A Discussion of the Development Process, Identification of Design Requirements, and Implementation of Improvements to a Point-of-Use Water Purifier in India

by

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ABSTRACT

Over 780 million people worldwide do not have access to clean drinking water. In India, one product that attempts to address this issue is the Tata Swach, a home purifier which makes water biologically safe to drink by neutralizing bacteria and viruses using silver nanoparticles. This thesis presents research which focuses on improving adoption of this life-saving technology. A holistic approach is followed which takes into consideration the product's technical performance as well as socioeconomic factors that may influence user acceptance. A mathematical model of flow through the purifier is developed and a design tool based on this model is created to allow the optimization of flow rate while maintaining purification efficacy. The development process used to design the Swach is analyzed and compared to literature to determine how this may have affected the product's ultimate success. The importance of incorporating the voice of the customer is emphasized. To that end, surveys among current Swach users are conducted and the responses are applied to Fishbein's Multi-Attribute Attitude Model to determine which design parameters are most important to the customer. "Quality of filtered water" and "ease of maintenance" are identified as the factors that most affect a user's overall satisfaction with the product. A technical issue that may affect these parameters — non-uniform flow through the purifier's porous medium — is identified and experimentally confirmed. Finally a design change to minimize the effects of non-uniform flow in the porous medium is suggested.

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CONTENTS

1 INTRODUCTION

Many millions of people around the world are affected by a lack of clean drinking water. According to the WHO/UNICEF JMP 2012 update, there are over 780 million people worldwide who do not have access to an improved drinking-water source [1]. This issue particularly affects the poor in developing countries and leads to many thousands of deaths each year due to water-borne illness [1].

Tata Chemicals Ltd. decided to address this problem by developing a point-of-use (POU) filtration system designed specifically for the Indian market. This product, the Tata Swach, provides bacteria- and virus-free water to households at an affordable price (approx. 25 USD).

Since its introduction to the Indian market in 2010, the Swach has achieved a limited degree of success and adoption. Many people are opting for other similar products from brands such as Kent, Unilever, PureIt, and Aquaguard. More importantly, a great number of people are still choosing to use no purifier at all.

This thesis attempts to address issues that may affect adoption of this potentially life-saving technology from a product design and engineering perspective. By partnering with Tata Chemicals, an investigation is made into all aspects of the product from original development to design changes for future iterations that may increase user satisfaction. Special emphasis is given to the voice of the customer and understanding how technical performance affects user acceptance. In this way, rigorous engineering and physics is combined with socioeconomic considerations to form a holistic view of the product and implement design changes.

This thesis is organized more or less chronologically, in the order that research was performed. It is divided into six sections. The rest of this section provides some background on prior art in water purifiers and explains why research into improving the Tata Swach is a reasonable strategy for addressing India's clean water crisis. Section 2 gives a general description of the product and provides an understanding of the physics behind its operation. Specifically, a mathematical model is developed which allows designers to predict the purification rate based on the physical characteristics of the purifier. Section 3 compares Tata Chemicals' product development process to processes advocated in literature and suggests improvements to better capture the voice of the customer. Section 4 presents original research by the author to elucidate and rank the importance of design requirements through collecting feedback from Swach users. Specifically, factors which most dramatically affect user satisfaction with the product are identified. It is hoped that this knowledge can be used to improve customer perception of the product and increase adoption. In Section 5, the results of Section 4 are applied by solving a particular technical issue that the purifier is likely experiencing. Finally, Section 6 summarizes the outcomes of this research and gives concluding remarks.

1.1 PRIOR ART IN WATER PURIFIERS

In past decades, many devices and schemes designed to provide clean water to the developing world have been deployed with mixed success. This section will briefly present a few of these projects as well as some evaluations of purification technologies that are particularly relevant to the topic of this research.

Barstow, Dotson, and Linden describe the development of a point-of-use (POU), UV purification device for developing contexts which achieves sufficient purification at 1L/min flow rates. At $63 per unit, the cost is prohibitive and the device also requires consistent access to electricity [2]. Ngai et al. describe the development and deployment of an arsenic filter in Nepal and state that there is a barrier to increased adoption of the technology due to difficulties in scaling up [3]. Ogunyoku et al. describe the deployment of several types of POU purification methods in Uganda. They face similar difficulties to Ngai et al. when scaling up and they highlight the importance of understanding customer-imposed requirements of a purification method [4].

Regarding the relative merit of several technologies, Sobsey et al. evaluate the sustainability of 5 POU purification methods: chlorination, chlorination-coagulation, SODIS (solar disinfection), ceramic filtration, and biosand filtration. Based on their scoring of 5 elements of sustainability, they find biosand and ceramic filtration to be the most promising of the methods evaluated [5].

Much research has also been conducted to understand why the many technologies available for clean water have not been adopted at scale. Jalan et al. show that awareness among consumers of the importance of water hygiene is a barrier to demand for clean water in urban India [6]. Also, Sobsey et al. describe several other barriers including cost, the ability of the technology to provide a sufficient amount of clean water for daily use, efficacy at treating water of different qualities and from different sources, required input effort of the user, and reliability and affordability of supply chains for maintaining the technology [5].

1.2 WHY WORK WITH THE SWACH?

Though many solutions have been proposed, it seems clear that there has not yet been a great breakthrough of the type desired by the development community, and further work developing clean water technologies and understanding barriers to adoption is required. This thesis attempts to contribute to this effort by understanding issues surrounding the Tata Swach and seeking ways to improve it.

Working with an established multinational corporation to improve an existing product holds certain benefits over developing a new purification technology and business from scratch. For one thing, Tata Chemicals has a well-developed supply chain and distribution channels as well as access to large amounts of capital. This will aid in the immediate deployment at scale of any improvements made to the purification technology.

The Tata Swach as a product is a good candidate for this type of partnership. The prior art in Section 1.1 show that common barriers to adoption include requiring access to electricity, difficulty in use, inability to provide sufficient amounts of purified water, and prohibitive prices. The Swach does not require electricity, is simple to use, provides enough purified water on a single cycle for a family of four for an entire day, and is the cheapest product among its competitors.

Considering this very reasonable baseline, improving this product to increase its adoption among consumers seems like a reasonable strategy for contributing to the effort to solve India's clean water crisis.

2 MODELING FLOW THROUGH THE TATA SWACH[1]

2.1 INTRODUCTION

One of the first steps taken in this research was developing a deeper understand of the physics that affect the filter's operation. Out of a desire to get the product to market as quickly as possible, Tata Chemicals designed the filter using an iterative approach, without mathematically modelling the flow characteristics. Components were prototyped and tested until an acceptable level of performance was reached. Now that there is a desire to optimize the product, it is necessary to understand the physical phenomena behind the filter's operation. This will allow designers at Tata Chemicals to improve the filter's performance, including increasing the rate at which it purifies water. A mathematical understanding of the filter's operation was also instrumental in the other research presented in this thesis including solving the issue of non-uniform flow in the porous medium (Section 5).

This section outlines the development of a mathematical model and design tool that can be used to optimize flow rate in the Tata Swach. A description of the filter's basic operation and key features is provided. The theory behind the mathematical model is also explained. A design tool is presented which allows filter designers to input certain physical parameters and predict the resulting flow rate through the filter. This design tool will be used to show that flow rate can be increased by 50% by making minimal changes to the design. Parameters for achieving the optimized flow rate are specified. Experimental results, which confirm the conclusions of the

[1] This section comes from a paper by Ricks et. al. [31] and contains text authored by Ricks, Lewandowski, and Lim.

design tool, are presented. Finally, the broader implications of this research are provided, and recommendations for future development are given.

2.2 FILTER OPERATION

The Swach operates without electricity or access to a running water source. As shown in Figure 2.1, dirty water is poured into the upper container through a mesh pre-filter. The static water creates a pressure head, which drives the water through the filter element, or bulb, where the purification takes place. Once it has passed through the bulb, the water is stored in the lower container until used by the consumer.

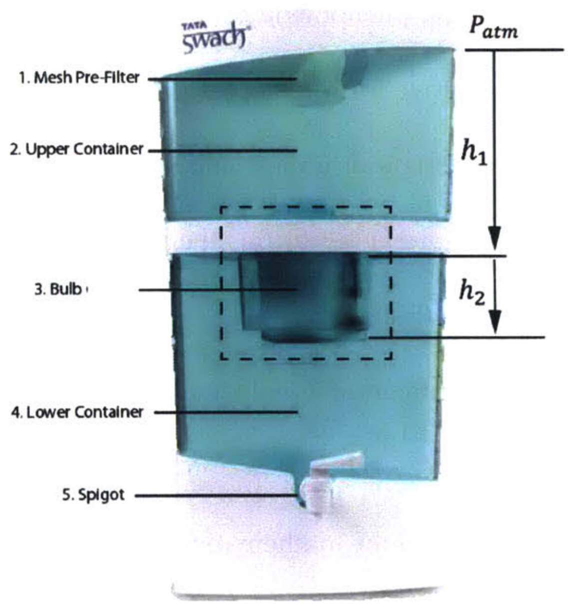

Figure 2.1. Basic Components of the Tata Swach water

Figure 2.2 shows the path that water takes as it passes through the bulb. First it enters the outer body of the bulb and flows to the bottom where it begins to filter up through the inner body. The inner body contains compacted rice husk ash (RHA), which has been infused with silver nanoparticles. As the water passes through the RHA, silver ions are released into the water, neutralizing viruses and bacteria. This process is time sensitive (i.e. the longer the water is in contact with the silver nanoparticles, the more ions will be released and the more microbes will be destroyed). For this reason residence time, defined as the amount of time the water spends within the RHA, is an important design parameter. After passing through the RHA, the water passes through a small nozzle (referred to as the flow-restricting nozzle) and enters the end-of-life (EOL) mechanism. The EOL has a water-soluble tablet that is designed to dissolve completely after 3 m^3 (3000 L), allowing a spring to close a valve and stop flow through the bulb. This is meant to provide a cue to the consumer that the effective life of the bulb is spent and the bulb requires replacement. After exiting the EOL, the water passes through a mesh post filter, which traps any RHA particles that escape from the bulb. Once through the post filter, the water enters the lower container and filtration is complete.

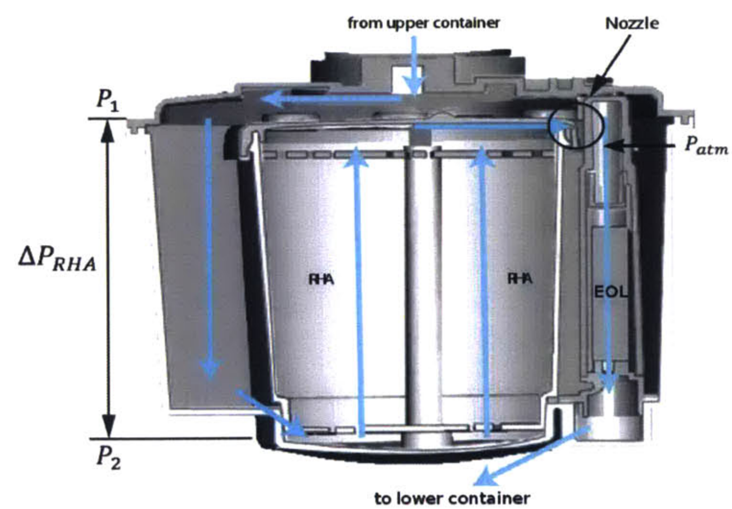

Figure 1.2. Tata Swach bulb and critical flow components.

2.3 PAST WORK

In order to ensure that the filter achieves a 6-log reduction of bacteria and a 4-log reduction of viruses (meeting or exceeding US-EPA standards), Tata Chemicals conducted extensive tests on their prototypes [7]. Given a certain amount of RHA in a prototype, an acceptable flow rate was determined experimentally without respect to residence time. The flow rate was controlled by the size of the orifice in the flow-restricting nozzle and successively lower flow rates were tested until the desired purification was achieved. The current design of the bulb yields a maximum flow rate of 1.67E^{-6} m^3/s (6 L/hr) when the upper container is full and the pressure head is at its greatest. By developing a physical understanding of how each element within the filter affects the flow rate and residence time, an optimized flow rate can be achieved while ensuring the same level of purification.

2.4 MATHEMATICAL MODEL

Flow through the bulb is analogous to current in an electrical circuit as shown in Eqs. (2.1) and (2.2). In an electrical circuit, current is equivalent to a potential difference divided by an electrical resistance; in a fluid circuit, flow rate is equivalent to a pressure difference divided by a flow resistance.

$$I = \frac{\Delta V}{R} \tag{2.1}$$

$$Q = \frac{\Delta P}{R} \tag{2.2}$$

The total pressure difference of the system is created by the hydraulic head above the bulb and is given by the hydrostatic equation:

$$\Delta P = P_1 - P_{atm} = \rho g h_1 \tag{2.3}$$

where P_1 is the pressure at location 1 (refer to Figure 2.2). The pressure just after the flow-restricting nozzle (inside the EOL) is atmospheric because vents in the side of the mesh post filter and the fact that the EOL never fills with water (flow is slow enough that water simply drips through the EOL) allow atmospheric air to reach the top of the EOL. In order to simplify calculations, h_1 is measured to the top of the bulb rather than the bottom (i.e. h_2 is neglected). The hydrostatic contribution of h_2 is compensated for by the fact that elevation gain through the RHA is also neglected.

There are several resistances that contribute to the total resistance of the system: the resistance of the RHA, major losses, and minor losses.

2.4.1 RHA Resistance

The resistance of the RHA can be determined from Darcy's Law for flow through a porous medium:

$$Q = \frac{kA\Delta P_{RHA}}{\mu L} \tag{2.4}$$

where k is the permeability of the RHA, A is the cross-sectional area of the RHA, ΔP_{RHA} represents the change in pressure across the porous medium, μ is the viscosity of the water, and L is the length of RHA. Note that this form of Darcy's Law assumes flow driven by pressure only (i.e. the elevation gain through the RHA is neglected). Comparing this equation with Eq. (2.2), it can be seen that the effective resistance of the RHA is given by

$$R_{RHA} = \frac{\mu L}{kA} \tag{2.5}$$

Because k is dependent on factors such as grain size and particle arrangement, which are difficult to determine, its value was chosen based on experimental results [8]. Several experiments were conducted (Section 2.6) during which flow rate and pressure were measured. With all other variables known, k was back-calculated to fit the data.

Note also that there are two mesh screens on either side of the RHA that prevent the medium from dispersing with the water. Since it was impossible to isolate these screens from the RHA without disrupting the RHA and therefore changing its permeability, it was determined to lump the resistance of these screens into the value of k. In other words, the RHA and the mesh screens were treated as one resistor with an experimentally determined permeability.

2.4.2 Major Losses

Major and minor losses are pressure drops across elements due to viscous effects [9]. These viscous effects create flow resistances that, for the sake of simplicity, we will refer to as major and minor loss resistances.

Major losses are given by the Darcy-Weisbach equation:

$$\Delta P = \frac{fL\rho v^2}{2D_H} \tag{2.6}$$

where f is the Darcy friction factor and is given by

$$f = \frac{64}{Re_D} \tag{2.7}$$

L is the length of the element in the flow direction, v is the velocity of water through the element and is given by

$$v = \frac{Q}{A} \tag{2.8}$$

D_H is the hydraulic diameter and is given by

$$D_H = \frac{4A}{Pe_w} \tag{2.9}$$

Re_D is the Reynolds number and is given by

$$Re_D = \frac{\rho v D_H}{\mu} \tag{10}$$

A is the area perpendicular to the direction of flow, and Pe_w is the wetted perimeter of the element. Substituting Eqs. (2.7), (2.8), and (2.10) into Eq. (2.6) yields

$$\Delta P = \frac{32L\mu Q}{D_H^2 A} \tag{2.11}$$

From Eqs. (2.2) and (2.11), it can be shown that the effective resistance associated with major losses, R_M, is given by

$$R_M = \frac{32L\mu}{D_H^2 A} \tag{2.12}$$

Since $A \propto D_H^2$, $R_M \propto D_H^{-4}$. Therefore, as D_H becomes large, the major loss resistance quickly becomes negligible. Table 2.1 shows the hydraulic diameter (or similar characteristic length) of several cross-sections within the system. Because the hydraulic diameter of the flow-restricting nozzle is much smaller than the hydraulic diameter anywhere else in the system (by at least an order of magnitude), major loss resistances can be neglected everywhere except in the flow-restricting nozzle.

Table 2.1. Hydraulic diameter of various components in system.

Component	Hydraulic Diameter, D_H (m)
Flow-Restricting Nozzle	0.001
EOL Tube	0.025
Bulb Inlet	0.034
Pre-RHA Tube	0.050
Bulb Outlet	0.190

Also, since Eq. (2.7) is only valid for laminar flow, care was taken to ensure that the Reynolds number did not exceed 2300 in the nozzle. For a flow rate of 1.67E^{-6} m^3/s (6 L/hr), the Reynolds number in the nozzle was found to be 1870 (note that the nozzle has a *square* cross-section of edge length .001 m).

An assumption was made that flow in the nozzle is fully developed. This is unlikely to be true since the nozzle length is only .005 m. However, it was determined that since the major loss over the nozzle is the smallest of the losses considered to be significant, any error associated with this assumption would be small when applied to the entire system.

2.4.3 Minor Losses

Minor losses are given by

$$\Delta P = \frac{K_L \rho v^2}{2} \tag{2.13}$$

where K_L is the minor loss coefficient and can be obtained from tabulated data. Substituting Eq. (2.8) yields

$$\Delta P = \frac{K_L \rho Q^2}{2A^2} \tag{2.14}$$

Comparing with Eq. (2.2) gives the minor loss resistance as

$$R_m = \frac{K_L \rho Q}{2A^2} \tag{2.15}$$

For the situation of contraction of the fluid into the nozzle, K_L = 0.48 and A is the area inside the nozzle [9]. Again, because the resistance is dependent on A^2, minor losses in other parts of the bulb can be neglected by the order of magnitude argument. Note that there is no corresponding resistance associated with expansion of the fluid after the nozzle. This is because flow stops after the nozzle and water simply drips through the EOL.

The only significant resistances in the system, then, are the resistance of the RHA, major loss resistance through the flow-restricting nozzle, and minor loss resistance due to contraction of the fluid into the nozzle. Because the fluid must pass through each of these resistances, they can be treated as resistors in series and summed to give a total resistance of the system. Thus,

$$R_{tot} = R_{RHA} + R_M + R_m \tag{2.16}$$

Finally, for any chosen nozzle geometry and RHA configuration (assuming permeability is held constant), Eq. (2.1) can be used to predict flow rate:

$$Q = \frac{\Delta P_{tot}}{R_{tot}} \tag{2.17}$$

Note that since R_m is dependent on Q, Eq. (2.17) is implicit and must be solved using numerical methods.

2.4.4 Residence Time

The residence time is the amount of time the water spends inside the RHA and in contact with the purifying agent (silver nanoparticles). This is given by

$$\tau = \frac{v}{L} \tag{2.18}$$

where v is the velocity of water through the RHA and L is the length of the RHA in the flow direction. Substituting Eq. (2.8) yields

$$\tau = \frac{Q}{V_{RHA}} \tag{2.19}$$

where V_{RHA} is the total volume of the rice husk ash. Because flow velocity may not be uniform throughout the cross section (see Section 5), this residence time must be considered an average rather than the residence time of a specific fluid element. It was assumed that as long as two prototypes had equivalent residence times, the purification level achieved by each would also be equivalent. Therefore, any increase in flow rate must correspond with an appropriate increase in V_{RHA}.

2.5 DESIGN TOOL AND OPTIMIZATION

The equations described in the previous section were used to create a design tool in Microsoft Excel. This tool allows designers to input the physical parameters of the bulb (nozzle dimensions, RHA properties, and fluid properties) and predict the resulting flow rate through the bulb. Resistances are calculated using Eqs. (2.5), (2.12), and (2.15), and Eq. (2.17) is used to give the flow rate for a given pressure head. Because R_m is dependent on the flow rate, an initial guess for Q is required, and the solver is used to ensure that the initial guess and the predicted value of Q converge to the same value. The residence time is also calculated so that designers can ensure that minimum purification requirements are met. Figure 2.3 shows a screen shot of the design tool.

Flow Calculator

Given Parameters		
Nozzle		
Edge Length	0.001	m
Length	0.005	m
Minor Loss Coefficient	0.8	
RHA		
Permeability	5.50E-11	m^2
Diameter	0.075	m
Length	0.032	m
Fluid		
Viscosity	8.90E-04	Pa*s
Density	1000	kg/m^3
Height (head)	0.15	m
Other		
Gravity	9.81	m/s^2

Calculated Quantities		
Nozzle		
Area	0.000001	m^2
Fluid Velocity	1.62	m/s
Reynolds Number (D_H)	1821	
Friction factor	3.51E-02	
Major Loss Coefficient	1.76E-01	
RHA		
Area	4.42E-03	m^2
Fluid Velocity	3.67E-04	m/s
Residence Time	87	s
Pressure Drops		
Nozzle Major	231	Pa
Nozzle Minor	1051	Pa
RHA	190	Pa

Resistances		
Nozzle Major	1.42E+08	$Pa*s/m^3$
Nozzle Minor	6.48E+08	$Pa*s/m^3$
RHA	1.17E+08	$Pa*s/m^3$
Total	9.08E+08	$Pa*s/m^3$

Initial Guess		
Flow Initial Guess	5.83	L/h
	1.62E-06	m^3/s

Results		
Flow Predicted	5.83	L/h
	1.62E-06	m^3/s
Convergence Check	YES	

Figure 2.3. The Excel design tool allows designers to input parameters for filter geometry and see what the resultant flow rate for the purifier will be. Gray boxes may be edited by the user.

This provides a snapshot of the flow at a single moment in time. In order to see how the flow behaves with respect to time, the dynamic pressure head must be taken into account (i.e. as water is filtered and passes to the other side of the bulb, the pressure driving the flow is reduced). To accomplish this, the calculated values are used as initial conditions for a step-wise solution where the resistances and flow rate are recalculated every five seconds. Automatically-generated figures based on these data allow designers to see how the filter will operate for an entire filtration cycle. Figure 2.4 shows an example of these figures. The design tool thus provides a convenient method for designers to virtually prototype various bulb configurations and observe performance without developing expensive physical models.

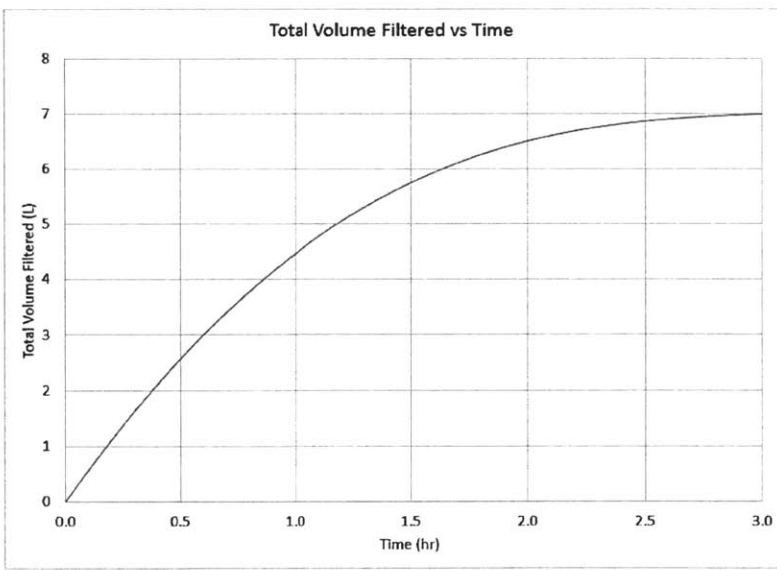

Figure 2.4. Automatically generated graph which shows the step-wise solution of volume filtered vs. time.

Once the design tool was complete, it was used to optimize the configuration of the Tata Swach bulb. The goal of the optimization problem was to reach a maximum flow rate with the constraints that the residence time could be no shorter than in the original bulb (to preserve efficacy) and the plastic body of the bulb could not be significantly altered (to preserve manufacturability and cost). Measurements of bulb dimensions showed that the current length of the RHA is 32 mm, and there is approximately 16 mm of empty space between the top of the RHA and the bottom of the nozzle. The RHA length, therefore, could be increased by 50% without changing the plastic body of the bulb. This means that the flow rate could also be increased by 50% while maintaining the current minimum residence time. With this objective in mind, the design tool was used to determine the nozzle parameters that would achieve the desired flow rate. It was determined that a nozzle orifice size of 4 mm would result in a new flow rate of $2.51E^{-6}$ m^3/s (9 L/hr), a 50% increase from the current flow rate of $1.67E^{-6}$ m^3/s (6 L/hr). Note that these flow rates are the maximum flow rate achieved when the upper container of the system is completely full. This was considered to be an optimized flow rate as it is the maximum allowable flow rate that can be achieved in the current embodiment of the bulb without altering residence time (efficacy) or manufacturability and cost associated with the plastic container.

2.6 EXPERIMENTAL VERIFICATION

Equation (2.19) shows that in order to increase volumetric flow rate through the bulb by a certain factor without changing residence time, the length of the RHA filtration element must be increased by the same factor (area held constant). This was the basis upon which a prototype was created.

The stock Swach bulb was first studied by measuring its total volume output at uniform time intervals, given 15 cm of initial pressure head, h_0, as measured in the upper container (refer to Figure 2.1). The same method was used to generate similar data for other Swach bulbs that were modified from the original. A prototype bulb was made by removing the flow-restricting nozzle (making it a 4.0 mm wide square hole), and adding RHA material to the inner bulb to increase its length by 50% (corresponding to a 50% increase in volumetric flow rate as per the logic above). Bulbs with different nozzle dimensions (1.3, 2.0, 8.0 mm side lengths) were fabricated by modifying nozzles of existing bulbs, and were tested in the same fashion as before. These experiments were performed to compare the original bulb with the prototype that was designed using the flow model described above, to demonstrate the sensitivity of volumetric flow rate to nozzle size when the nozzle is small (< 2.0 mm), and to demonstrate the significance of the nozzle resistance for large nozzle dimensions.

The manufacturing specifications and variation of the Swach bulb were measured for 5 samples and are shown in Table 2.2. Variation of measurement between these samples were used in the mathematical model to account for manufacturing error.

Table 2.2. Manufacturing specifications of RHA and nozzle.

Component	Specifications
RHA mass	100 ± 5 g
RHA length	35 ± 1 mm
Nozzle diameter	1.00 ± 0.05 mm

The permeability of the RHA was found by fitting the mathematical model to 4 experimental data sets with different nozzle and RHA dimensions (Table 2.3), but with the same RHA medium. This was found to be approximately $5.5E^{-11}$ m^2. The strong consistency between experiment and theory for all four data sets suggests the suitability of this model to the flow characteristics in the Swach bulb.

Table 2.3. Nozzle and RHA dimensions for experimental tests.

Test	RHA Length, L_{RHA} (mm)	Nozzle Hydraulic Diameter, D_H (mm)
1	32	1.15
2	50	4
3	32	4
4	32	8

The mathematical model was found to agree with experimental results for a stock Swach bulb (Figure 2.5) as well as a prototype bulb (Figure 2.6). Both the variation in nozzle size and RHA length due to manufacturing error have been accounted for in the theoretical model (the error bars in the graphs represent the model with minimum and maximum observed dimensions).

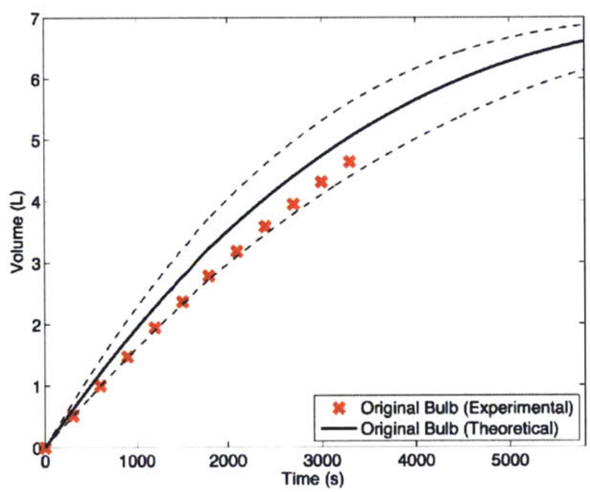

Figure 2.5. Theoretical flow model of original bulb with error bars and experimental validation.

A 50% increase in the maximum volumetric flow rate from the original bulb was achieved in the prototype bulb (Figure 2.6). Here, the flow restricting nozzle piece was removed to create a 4.0 mm square hole, which effectively removed this resistance. In order to maintain residence time, the RHA length was increased by 50% by adding 18 mm of RHA length to the original 35 mm.

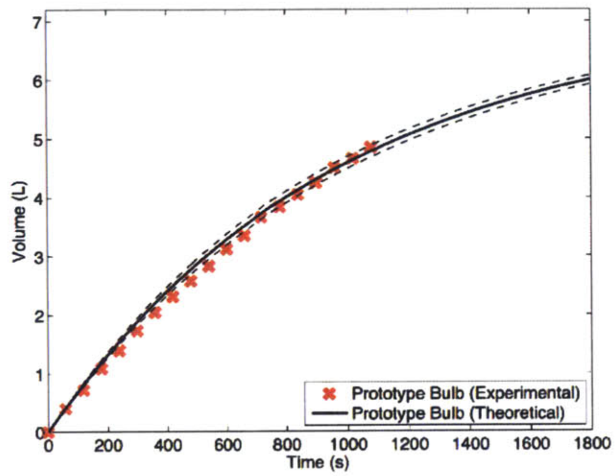

Figure 2.6. Theoretical flow model of prototype bulb with error bars and experimental validation.

Error bars are more pronounced for the stock bulbs (Figure 2.5) because changes in nozzle size when the nozzle is small led to magnified changes in flow rate. The sensitivity in flow rate to nozzle size was demonstrated experimentally in Figure 2.7, which displays tests performed for bulbs with nozzles of 1.3 mm and 2.0 mm side lengths. Flow rate in the mathematical model was shown to be very sensitive to nozzle size below a 2.0 mm dimension due to the dominance of the nozzle resistance in the electrical circuit analogy, which was consistent with experimental results.

On the other hand, the model shows that above certain nozzle dimensions (> 4.0 mm side lengths), the flow rate through the bulb is no longer sensitive. This was experimentally confirmed by testing bulbs with the same RHA length but with 4.0 mm and 8.0 mm sized nozzles (Figure 2.8). In this size range the nozzle resistance is negligible, so any changes in size and therefore resistance lead to minimal changes in flow rate.

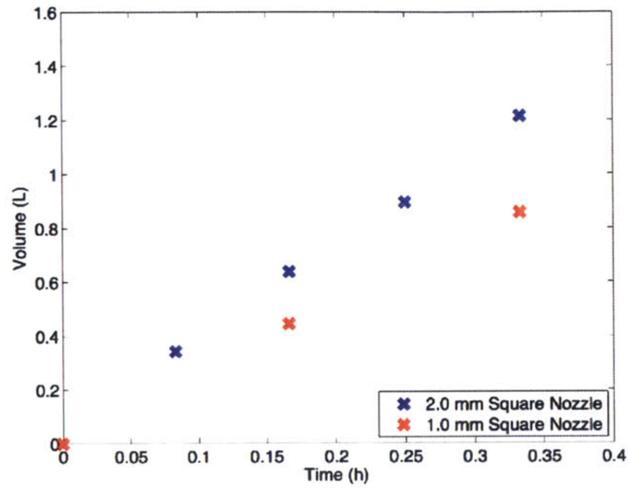

Figure 2.7. High sensitivity of the flow rate to nozzle size when the nozzle is small (<2.0 mm).

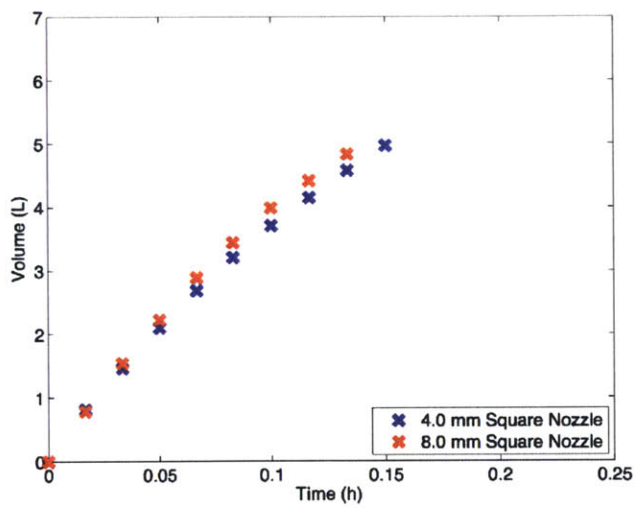

Figure 2.8. Nozzle resistance is negligible when the nozzle is large (>4.0 mm).

Let R_1 and R_2 represent two flow resistances, where R_2 is a flow-restricting nozzle (Figure 2.9). If $R_2 \gg R_1$ (e.g. where R_2 is a very small nozzle), then the system is very sensitive to R_2. Figure 2.7 demonstrates this sensitivity when the flow-restricting nozzle is < 2.0 mm. On the other hand, if R_2 is reduced and $R_2 \ll R_1$, then changes in R_2 will not affect the flow. Figure 2.8 demonstrates the low sensitivity of flow rate to nozzle size when the flow restricting nozzle is > 4.0 mm.

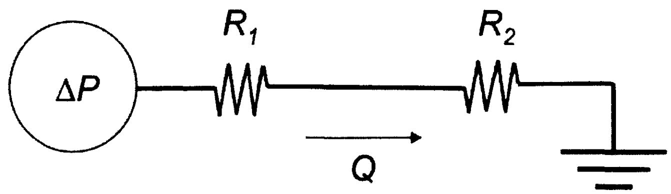

Figure 2.9. A depiction of resistances in the Swach bulb, where R_2 represents a flow-restricting nozzle.

The flow model was shown to closely track flow data from experiments performed using the Tata Swach. Its use as a design tool additionally describes sensitivities that Tata can now account for. It demonstrates that Tata may increase flow rate by increasing nozzle size while increasing RHA length. The existing dimensions of the Swach bulb allow this to be done without any drastic changes to geometry. At the same time, if nozzle sizes were increased beyond 4.0 mm, Tata may not need to improve manufacturing tolerances due to the reduced sensitivity of flow rate to nozzle size in this regime.

2.7 CONCLUSION

The impact of this work is manifold. First, by developing a mathematical model of the flow, the effects of certain features on filter performance are elucidated. For example, it is now apparent that flow rate is highly sensitive to the size of the orifice in the flow-restricting nozzle. The model shows that R_M and R_m are proportional to D_H^{-4}. This means that very small changes in orifice size can result in drastically different flow rates. The importance of tolerances is quantified and failure points are highlighted, allowing Tata Chemicals Ltd. to develop a more robust system.

Also, the design tool allows Tata Chemicals to create prototypes virtually before creating them physically. Concepts with poor performance can be ruled out before expensive building and testing occurs. This will reduce new product development times and costs.

The optimization methodology demonstrated here can be applied to other similar systems. Individuals or organizations interested in water purification or hydraulic systems can use a similar approach to characterize flow and optimize system performance.

Future work should focus on determining an accurate value for the permeability of the RHA. This should be left to Tata Chemicals as the value of k will be highly dependent on their standard packing and assembly procedure. At that point, it may also be useful to separate the effects of the two mesh screens from the permeability of the RHA. Finally, consideration of resistances that were neglected in this work may lead to greater accuracy, though researchers should bear in mind the relative magnitude of errors associated with each assumption as well as the ultimate purpose of the model in order to determine if such work is worthwhile.

3 THE DEVELOPMENT PROCESS

3.1 INTRODUCTION

The success of a product is strongly linked to the effectiveness of the process used to create it. For that reason, much research effort was dedicated to understanding the process that Tata Chemicals used to develop the Swach and how that ultimately affected its success in the market. In this section, an extensive review is given on literature about product design and development processes. Tata Chemicals' process is then described and compared to the literature. Finally, a discussion of potential improvements to their process is provided. As it is the foundation of Section 4, particular emphasis is given to the front end of the development process and identifying design requirements.

3.2 LITERATURE REVIEW

Product design and development has been a topic of academic and industry research for decades. Thousands of published and peer-reviewed works exist in the form of journal articles, conference papers, case studies, special-interest books, and texts. These publications teach various design methods and strategies for bringing products to market, a process which usually begins with understanding customer needs and translating them into design requirements. In their book, *Product Design and Development*, Ulrich and Eppinger approach product development from the perspectives of marketing, engineering design, and manufacturing, and provide a toolkit of product development methods that can be utilized by practitioners on development projects [10]. Specifically, the process of establishing design requirements is separated into two parts: (1) identifying customer needs and (2) establishing product specifications. The five-step process for identifying customer needs involves:

1. Gathering raw data from consumers
2. Interpreting the raw data in terms of customer needs
3. Ordering the needs into a hierarchy of primary, secondary, and sometimes tertiary needs
4. Establishing the relative importance of the needs
5. Reflecting on the results of the process

Methods for gathering raw data include conducting interviews and focus groups and observing the product in use. Once customer needs are identified, they are translated into the more technical and quantifiable language of product specifications. This multi-step process involves setting target specifications, benchmarking, and using technical and cost models to refine the specifications. Identifying customer needs and establishing product specifications are typically among the very first activities in Ulrich and Eppinger's development process. These ideas, however, are often revisited later in the process when new feedback from customers is received during the concept evaluation stage, and product specifications can be adjusted if necessary.

Pahl and Beitz also provide a text with general guidance on the design process [11]. The subject of identifying design requirements is treated in the section titled "Task Clarification" which describes a process of establishing a requirements list and using that list to direct later design activities. Similar to the hierarchy of needs discussed by Ulrich and Eppinger, requirements are classified as either demands or wishes. Tradeoffs or concessions that often must be made later in the project are governed by this classification. Little guidance is given on how to actually identify these requirements beyond suggesting a review of the documents provided by the customer with the design task (assuming the customer is involved in commissioning the project) and a series of introspective questions that the designer must ask himself regarding the use scenarios of the product. Attention instead is given to creating a useful documentation of the requirements that can be both binding and able to grow as new information becomes available.

Another well-established text on product design and development is provided by Otto and Wood [12]. The methodology for determining design requirements here is similar to that presented by Ulrich and Eppinger. It involves gathering customer needs through a variety of activities and then sorting and ranking those needs. Methods for gathering customer needs include interviews, questionnaires, focus groups, and "being the customer", an activity where design teams travel to the location where the product will be used and use a competitor's product to get firsthand experience. Methods for ranking the needs can be simple, such as counting the number of times a need is mentioned in customer interviews, or more complex, such as performing a conjoint analysis, a method where several needs are ranked together in order to account for interdependencies. Detail is also given on the different types of needs that can be uncovered including direct needs, latent needs, constant needs, variable needs, general needs, and niche needs.

In addition to the texts providing general product development principles, there are many papers emerging in recent decades that aim to customize the process of identifying customer needs when designing in the developing world. In their review of over 200 academic publications on product development research, Krishnan and Ulrich state that product development methodologies are "highly contingent on the market uncertainty and other environmental characteristics [13]." They conclude that "insights on customizing product development practices to diverse environments...should also help increase the relevance and applicability of the development literature."

Donaldson corroborates this opinion in her review of design practices in Kenya when she states, "It may not be appropriate to promote 'MIE-style' [more industrialized economy] design to LIEs [less industrialized economies] [14]." Citing Bucciarelli, Minneman and Leifer, Rittel and Smaili, she says that because design is viewed as "a social process" that is intermediately linked with culture, it is reasonable to believe that different cultures would have different design processes which are most effective for them [15][16][17][18]. Donaldson does not suggest what the appropriate design process should be for a less industrialized economy. Rather, her paper accounts the processes that were observed to be in use by large and small firms in Kenya without evaluating their efficacy. Notably, she states that "tarmac bias," a condition where product designers give preferential attention to consumers in urban areas, often neglecting the needs of potential consumers in rural areas, is a common issue in LIEs. She also says that prototyping, a tool often used in product development to receive feedback from consumers on design requirements, is seen by many firms in Kenya as "extravagance" and a waste of precious resources.

A similar paper by Vechakul and Agogino describes the product development practices used by two developing world design organizations: IDEO.org and the International Development Design Summit [19]. Like the paper by Donaldson, this paper does not claim to evaluate the methods used; it simply compares the practices of each organization and leaves the reader to determine which practices are more or less appropriate for a given design scenario.

The Human-Centered Design (HCD) *Toolkit,* a publication by IDEO.org, gives a specific methodology for designing products for emerging markets [20]. This resource divides the design process into 3 stages: (1) Hear, (2) Create, and (3) Deliver. It advocates close interaction with users throughout the process because consumers in emerging markets are assumed to have lifestyles and needs that are very distinct from those of the foreign designers that are often leading the product development process. Rather than relying on the intuition that designers bring to the project, methods are suggested which help the designers to develop empathy for users and give the users opportunities to directly contribute to the establishment of design requirements. In the Hear section of the toolkit, specific methods are given for elucidating customer needs. Some of these methods, such as interviewing and conducting focus groups, are the same as those discussed earlier in the general design texts. Other methods, however, are unique to this toolkit and may be especially suited to designing in emerging markets. Self-documentation, a method where potential users are given cameras or journals and asked to document their daily activities for a period of time, is used to help designers develop empathy and understand the possible use contexts of the products they are making. The Create stage also discusses the use of prototypes to elicit early feedback on the accuracy of design requirements. Throughout the HCD process, the necessity of immersion in the use context is emphasized.

The idea of immersion in the use context is also advocated in the book *Reverse Innovation* by Vijay Govindarajan [21]. This book discusses how to customize the product development process to emerging markets from an operations management perspective. Govindarajan says that multinationals designing for emerging markets should establish Local Growth Teams (LGTs), business units that live and operate in the country for which the product is being developed. He argues that it is impossible to correctly establish design requirements without gaining a deep understanding of the lives of the target consumers — an understanding which can only be gained by living in proximity to them. This idea of immersion could be compared to the "being the customer" exercise mentioned before by Otto and Wood [12], though unlike "being the customer", an activity which may be done in an afternoon, the kind of immersion and empathy development advocated by Govindarajan and the HCD Toolkit may require weeks, months, or even years.

3.3 TATA CHEMICALS' PROCESS

Through interviews with Tata Chemicals' engineers and business heads, a basic understanding of the process that they followed in developing the Swach was reached. This project was initiated when Ratan Tata, chairman of the Tata Group, announced a goal of providing clean water for the masses of underserved people in India somewhere around the end of 2009. Engineers at Tata Chemicals, in collaboration with other Tata subsidiaries, began brainstorming ideas for a purifier that could be both extremely affordable and effective at removing biological contaminants. In this early stage of the process, there was little interaction with customers. Instead of performing need-finding activities such as those suggested in much of the literature, design requirements were established primarily internally. In a process most similar to that described by Pahl and Beitz [11], engineers and marketing specialists established a list of requirements and ranked their importance primarily based on instruction that they were given in the design brief from upper management and their own intuition.

Once a design direction was established, engineers and industrial designers began making a series a prototypes and testing them internally, a process which culminated in the creation of a "green bulb" prototype which is similar to the current Swach filter element but does not include the upper and lower containers for storing water. Instead, the intention of the "green bulb" prototype was that it would be attached directly to clay matkas (traditional vessels for storing water) in the consumer's home which would serve the same purpose as the plastic containers seen in the current version of the product.

With this prototype complete, Tata Chemicals began seeking feedback from potential consumers. A pilot study was performed where the "green bulb" prototype was placed in approximately 300 homes for a month. Though it is unclear, it is likely that this pilot study occurred only in Mumbai (Tata Chemicals' HQ) among an urban population. After that, representatives from Tata Chemicals gathered feedback on what consumers liked and disliked about the product. A key outcome from this study was an understanding that the prototype may have missed the mark in several areas. First, consumers indicated that they were not interested in an ultra-cheap, "jugaad[2]" solution, but favored instead a more polished and complete product, even if it required a bigger price tag. They also learned that consumers were not satisfied with the level of purification that the prototype achieved which required Tata Chemicals to begin researching ways to improve the purification technology.

Armed with the knowledge gained during this pilot study, engineers at Tata Chemicals again began brainstorming ideas and creating prototypes. From this point on, most decisions were

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[2] Jugaad is a term commonly used in India to refer to a solution which is improvised or "hacked together."

made internally, and interaction with the consumer was very limited. Their prototyping and testing process eventually led to the creation of the product which was launched in April 2010.

Somewhere along this process, they also decided to shift focus away from creating an immediate clean water solution for the masses (meaning rural India) and instead focused on serving urban communities which were more accessible and where distribution channels were more established. The move made strategic sense for Tata Chemicals, and the hope was that after gaining a foothold in urban centers, the technology would percolate outwards toward the masses in rural areas.

Key events in this development process are outlined in Figure 3.1.

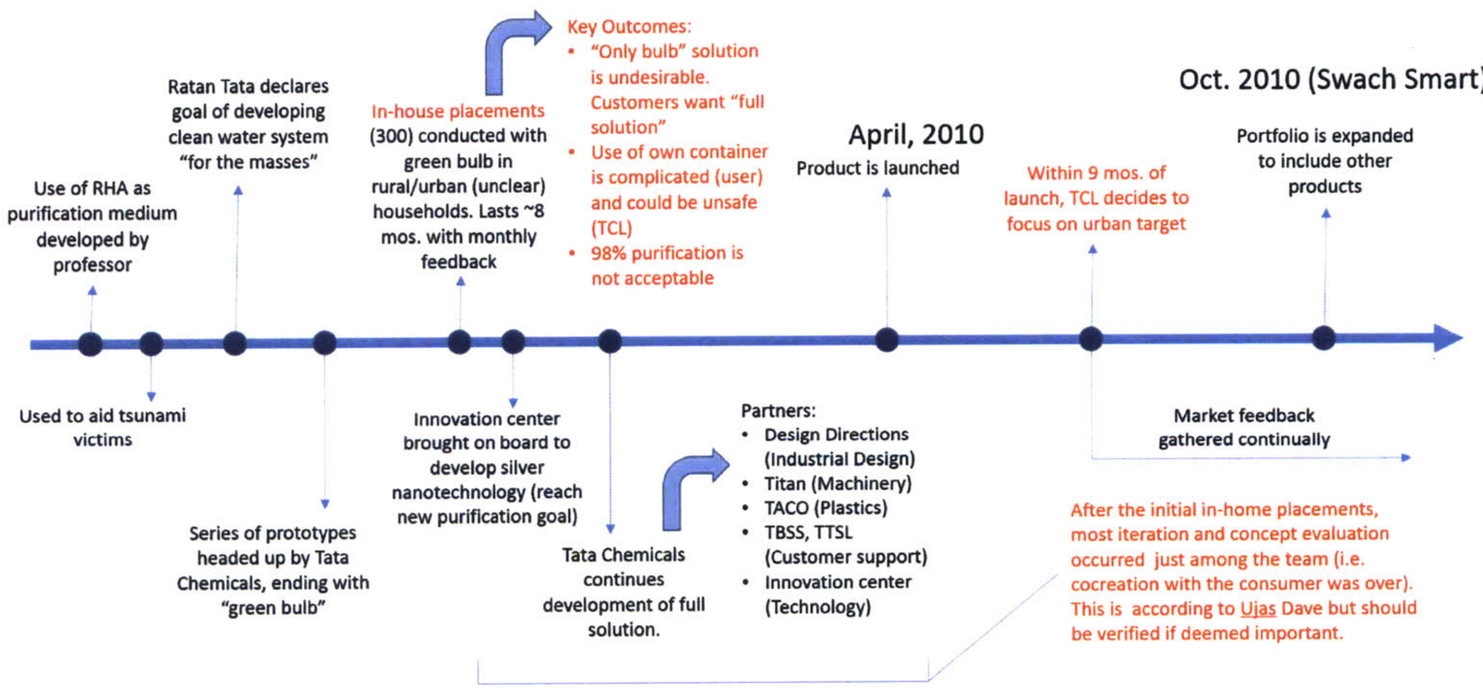

Figure 3.1. Key events surrounding Tata Chemicals' development process for the Swach

3.4 DISCUSSION

Information regarding the development process for the Tata Swach was collected several years after-the-fact and often from second-hand accounts. It is possible that this is not the most accurate representation of how events unfolded. That being said, if this is assumed to be an accurate representation of their development process for the Swach, there are several areas of improvement that can be discussed.

The most critical component missing from this development strategy is an ongoing connection with the consumer throughout the entire process. Though some feedback from consumers was obtained through the pilot study with the "green bulb" prototype, design requirements should have been identified and verified even earlier through activities such as observation, interviews, and surveys. Relying on one's own intuition at the beginning of the development process can lead to biases that persist even when new information from the consumer becomes available. This may especially be the case with the Swach considering a fully functional prototype was created before interaction with the consumer began. This represents a considerable investment of time and effort that may effectually lock designers into an incorrect design trajectory.

Also, assuming one group's opinions and priorities align with those of another group is always risky in product development. This is why design literature advocates interacting directly with the end-user to establish design requirements rather than relying on one's own understanding of what is important in a product. This may be especially true when a designer is making a product for consumers from a different cultural background. The disparity in beliefs and priorities between the designer and the consumer in this case may be particularly pronounced, and failing to get direct feedback from the consumer may cause the designer to miss the mark in a big way. Even though they are from the same country or even the same state in India, it would be a mistake for designers at Tata Chemicals to assume that their priorities for a water purifier align with those of others from a different social or economic class. Also, it may be a mistake to assume that a product which meets the needs of consumers in urban areas of India will also be acceptable to the rural masses and will be able to make that transition. All of this advocates the necessity of Tata Chemicals to do more need-finding throughout the development process and among different demographics.

3.5 CONCLUSION

This section has discussed product design and development processes in a conventional context as well as newer research on Design for the Developing World. The strategies advocated by literature have been compared to the process Tata Chemicals used when developing the Swach. While Tata Chemicals did many things right and were able to get a product to market very quickly, there is potentially room for improvement in the area of understanding the voice of the customer and establishing design requirements. The following section will describe work that the author did to rank design requirements according to what users of the Swach consider most important in a water purifier.

4 IDENTIFYING DESIGN REQUIREMENTS

4.1 INTRODUCTION

As emphasized in the last section, one of the key challenges of any consumer product development process is understanding design requirements imposed by the consumer. In order to create products which will meet user needs and be acceptable to the consumer, designers must understand which attributes of a product are valued by the consumer. When trade-offs need to be made during a development process, it is vital to know how changing each parameter of a product will affect its acceptability to the consumer.

To aid in this task, researchers have proposed a variety of models to represent how consumers evaluate products and make decisions. One of the earliest and most widely known models is Fishbein's Multi-Attribute Attitude Model which states that a person's overall attitude toward an object is the sum of his or her belief concerning each salient attribute of the object weighted by the importance of that attribute [22]. Represented mathematically, this is:

$$A_o = \sum_{i=1}^{N} b_i e_i \tag{4.1}$$

where A_o is the overall attitude toward the object, b_i is the strength of the belief that the object has attribute i, e_i is the importance of attribute i, and N is the number of salient attributes. In prior research, Fishbein's model has been applied to consumer products and used as a means of anticipating consumer brand preference [23]. In this section, Fishbein's model will be applied to consumer preferences surrounding the Tata Swach. Data on consumers' beliefs concerning 10 salient attributes of the purifier and a measure of their overall attitude toward the product will be used to back-calculate the relative importance of each attribute. Understanding the relative importance of each attribute will aid designers as they make future iterations of the product and attempt to improve overall acceptability to the consumer.

4.2 DATA COLLECTION PROCEDURE

4.2.1 Survey Administration

Data for this study were collected through the verbal administration of surveys by the researcher and a local translator in the homes of current Tata Swach users in India. The surveys were conducted in the language that the respondent was most comfortable speaking. Translators were local students or young professionals who were native speakers of the regional languages. They were trained by the researcher in the purposes of the study and coached in the manner in which questions should be asked in order to ensure consistency and minimize bias. Each interview was supervised by the lead researcher to ensure quality.

4.2.2 Survey Description

Each survey contained approximately 65 questions (the use of some questions was dependent on responses to previous questions) and required about 25 minutes to complete, though some interviews lasted as long as 40 minutes depending on the level of detail provided by respondents. Questions were primarily short answer and multiple choice and covered topics from basic water-use habits to product-specific feedback to demographics. The 11 questions pertinent to this analysis are shown in Table 4.1.

All of these questions were asked with respect to the Tata Swach which respondents were currently using (or had been using in the recent past) in their homes. The survey was administered to a total of 39 participants, though only 35 participants provided answers to all 11 of these questions and could therefore be included in this study.

Table 4.1. Survey questions

Question	Options Provided
1. How would you rate the quality of your *filtered* water?	(1) Very Bad, (2) Bad, (3) Adequate, (4) Good, (5) Very Good
My water filter:	
2. Filters water quickly.	(1) Agree, (2) Disagree, (3) No Opinion
3. Has a good storage unit size.	(1) Agree, (2) Disagree, (3) No Opinion
4. Is easy to maintain.	(1) Agree, (2) Disagree, (3) No Opinion
5. Is easy to get parts for.	(1) Agree, (2) Disagree, (3) No Opinion
6. Replacement parts are affordable.	(1) Agree, (2) Disagree, (3) No Opinion
7. Is durable/does not break.	(1) Agree, (2) Disagree, (3) No Opinion
8. Improves my water's taste.	(1) Agree, (2) Disagree, (3) No Opinion
9. Improves my water's color.	(1) Agree, (2) Disagree, (3) No Opinion
10. Improves my water's smell.	(1) Agree, (2) Disagree, (3) No Opinion
11. How would you rate the product as a whole?	Score out of 5

As will be described in Section 4.3, each of the questions 1 through 10 describes a particular attribute which will be considered salient to determining the respondent's overall attitude towards the product. The inclusion of these particular attributes and the exclusion of others is the result of a couple of factors. First, an exploratory study was performed by the researcher in the months preceding this study with the aim of identifying salient attributes. In the exploratory study, four individuals of Indian origin who were living in the Boston, Massachusetts, USA area were given a Tata Swach to use in their homes for a week. The researcher met with each participant at the beginning of the study to observe as he or she attempted to assemble the product and use it for the first time without guidance and again at the end of the study to interview the participant about his or her background and experience with the product. Each of these interviews lasted approximately 40 minutes and was very open-ended, asking participants to describe the product and comment on any problems they may have had with it throughout the week. The interviews were recorded, transcribed, and analyzed qualitatively to find attributes which the participants considered important. Second, a portion of this current study was performed in partnership with the Comprehensive Initiative on Technology Evaluation (CITE) at the Massachusetts Institute of Technology (MIT). CITE researchers prepared a survey to evaluate filter use in India, and upon comparison with results from the exploratory study, this researcher found that most emergent themes in the qualitative data were covered in CITE's survey. In the end, this researcher determined to move forward with a slight variation of CITE's survey in order to facilitate information sharing across studies. Each of the questions from Table 4.1 are found in CITE's survey.

Open-ended questions included in the survey such as "What do you like/dislike about the filter?" yielded rich qualitative data that will likely lead to the identification of other salient attributes in the future. Analysis of these data could not be included in this study, however, because they are not consistent across respondents (e.g. though many commented on the portability of the product, it cannot be analyzed in a meaningfully quantitative way because it was not identified beforehand as a salient attribute and was therefore not asked explicitly of every respondent).

4.2.3 Survey Location

Surveys were administered in two geographic locations in India: Ahmedabad, Gujarat and Mumbai, Maharashtra. Of the 35 respondents included in this analysis only one was in Ahmedabad so the effect of geographic location on overall results should be minimal. Nevertheless, for the sake of completeness, a short explanation of the difference in use context between these two locations is provided.

Ahmedabad experiences a level of groundwater salinity that is much greater than that experienced by Mumbai. As shown in Figure 4.1, Mumbai experiences total dissolved solids (TDS) levels below 480 mg/L whereas Ahmedabad experiences TDS levels greater than 1920 mg/L.

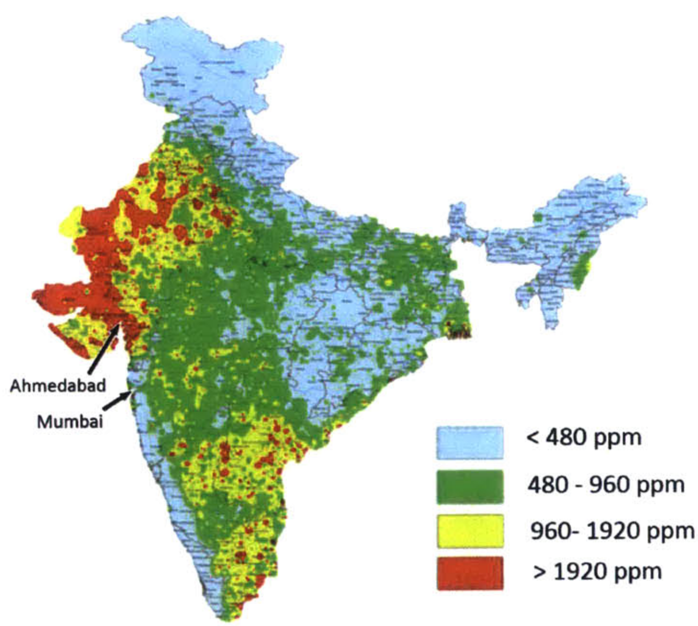

Figure 4.1. Groundwater salinity in India. From Central Ground Water Board [24]

In addition, the provision of treated water from the municipality was ubiquitous in Mumbai, whereas many people in Ahmedabad obtained their water from an untreated source provided by a third party such as a private bore well. Survey respondents in Ahmedabad would often describe their water as salty, and as a result, the use of reverse osmosis filters (which have the ability to remove dissolved solids) was much more dominant in Ahmedabad as compared to Mumbai. As the Tata Swach is not a desalinating purifier, it would possibly experience a disadvantage in questions 1 and 8 with respect to an equivalent evaluation in an area which does not have issues with high TDS levels.

4.2.4 Identification of Participants

Survey participants were identified through Tata Chemicals which provided the contact information for Swach users who had recently contacted the customer support center. These are individuals who were requesting service for their product either because they were experiencing a problem or because it was time for their regularly scheduled filter element replacement. These individuals were then contacted by the researcher and asked if they would be willing to participant in the survey. This selection process incorporates a definite bias since these individuals are much more likely to have experienced a recent malfunction of the product than the average user. It would not be valid, therefore, to claim that the *experiences* of these individuals is representative of all Swach users. However, this researcher believes that it is fair to claim that the *preferences* of these individuals with regard to attributes can be representative of a greater population of Swach users. In any case, this bias should be considered by anyone who seeks to apply the results of this study to a population.

4.3 ANALYSIS AND RESULTS

4.3.1 Choice of Proxies

Fishbein's Multi-Attribute Attitude Model says that a person's overall attitude toward an object is the sum of his or her beliefs regarding each of its salient attributes multiplied by that attribute's respective importance [22]. In this study, responses to questions 1 through 10 are considered to be the respondent's beliefs regarding 10 different salient attributes of the filter (b in Equation 4.1). There are most likely other salient attributes which are not captured in those questions, however reliable quantitative data for other attributes are not available in this data set and must therefore be ignored.

The response to question 11 is considered to represent the respondent's overall attitude toward the product (A_o in Equation 4.1). This is a reasonable assumption as long as respondents answered honestly and thoughtfully. Researchers may be tempted to use responses to other questions regarding purchasing or recommendation behavior as proxies for overall attitude towards the product (e.g. if the respondent has recommended the product to friends, it is an indication that his or her attitude towards the product is positive), however this practice would be incorrect. It has been emphasized in the literature that attitudes toward an object must be distinguished from attitudes toward *using* (or recommending, for that matter) an object because different salient attributes may apply to each [25]. Thus, because this study seeks to quantify each respondent's attitude toward the product, it is most appropriate to use a proxy which points directly at the product, as in question 11.

Calculation of the importance of each salient attribute (e in Equation 4.1) is the subject of this analysis.

4.3.2 Quantifying the Data

In order to apply the data to the Multi-Attribute Attitude Model, it is necessary to convert the data from qualitative statements of belief about each attribute (e.g. "I agree that my filter is durable") to numerical values. This is fairly straightforward for questions 2 through 7. Table 4.2 shows the possible responses and their corresponding numerical value.

Table 4.2. Numerical assignments for responses to questions 2 through 7

Response	Numerical Value
Agree	1
No Opinion	0
Disagree	-1

This is consistent with value schemes used by other researchers [26].

A similar scheme is used for questions 8, 9, and 10 except that all responses of "Disagree" are counted as "No Opinion" (i.e. valued 0). This is because most respondents who answered "Disagree" qualified their responses to those questions by saying that their water was already within acceptable bounds with regards to color, taste, and smell so they did not expect it to change. It became clear that their responses were meant to be neutral rather than an indication that a wanted attribute was missing.

For question 1, the responses are first remapped to a -2 to 2 scale and then normalized to have an equivalent range to the other attributes. The reason for normalizing is to ensure that weighting factors calculated for each attribute are comparable. The resulting value scheme is shown in Table 4.3.

Table 4.3. Numerical assignments for responses to question 1

Response	Numerical Value
Very Good	1
Good	0.5
Adequate	0
Bad	-0.5
Very Bad	-1

For question 11, the overall satisfaction score out of 5 is remapped to a -2 to 2 scale for the sake of symmetry between the attributes and the overall attitude. It is allowed to retain its wider range in order to provide resolution in the final attitude score which will be calculated. The resulting value scheme as well as a descriptive interpretation of the attitude score is provided in Table 4.4.

Table 4.4. Numerical and descriptive assignments for responses to question 11

Response (Score out of 5)	Numerical Value	Description
5	2	Very Satisfied
4	1	Satisfied
3	0	Neutral
2	-1	Dissatisfied
1	-2	Very Dissatisfied

Because the respondents were only asked for a score out of 5 and were not asked to describe in words their overall opinion of the product (e.g. "Satisfied", "Dissatisfied", etc.), an important assumption is made here that a respondent would equate a score of 3 out of 5 to an indication of neutrality and likewise with the other scores. This may be a valid assumption to make when the survey respondents are familiar with using a Likert scale. If they are not, it may not be a valid assumption, and the numerical values should not be translated to words. In any case, it must be understood that a score of 0 out of 5 is not a valid response.

4.3.3 Calculation of Attribute Importance

In order to calculate the importance of each attribute, a critical assumption must be made that an attribute's importance is constant across all 35 respondents. This is, of course, untrue as each respondent has unique preferences and would allocate importance in a unique way. However, since the goal of the study is to understand preferences *in aggregate* it makes sense to make this assumption. Results therefore represent the importance that an *average* consumer assigns to each attribute. Using Matlab, a least squares regression was performed across 35 linear equations of 10 independent variables. The resulting coefficients are the importance values of each attribute and are summarized in Table 4.5.

Table 4.5. Average Importance of each attribute

Attribute	Importance
1. Quality of filtered water	1.45
2. Filters water quickly	0.22
3. Has good storage unit size	0.30
4. Is easy to maintain	0.43
5. Is easy to get parts for	0.24
6. Replacement parts are affordable	0.00
7. Is durable/does not break	-0.18
8. Improves the taste of water	-1.02
9. Improves the color of water	0.20
10. Improves the smell of water	-0.01

These values, then, represent the relative weight that the average user places on each salient attribute when determining overall attitude toward the product.

4.3.4 Analysis of Fit

To evaluate the accuracy of these values, they are substituted back into Equation 4.1 and used to predict an overall attitude score for each respondent. This score is compared with the score the respondents reported (i.e. their responses to question 11 remapped as in Table 4.4) to determine if overall attitude was consistently predicted by responses to questions 1 through 10 and the calculated importance factors. Figure 4.2 shows this comparison where the data have been sorted from lowest reported score to highest in order to facilitate visually interpreting the fit.

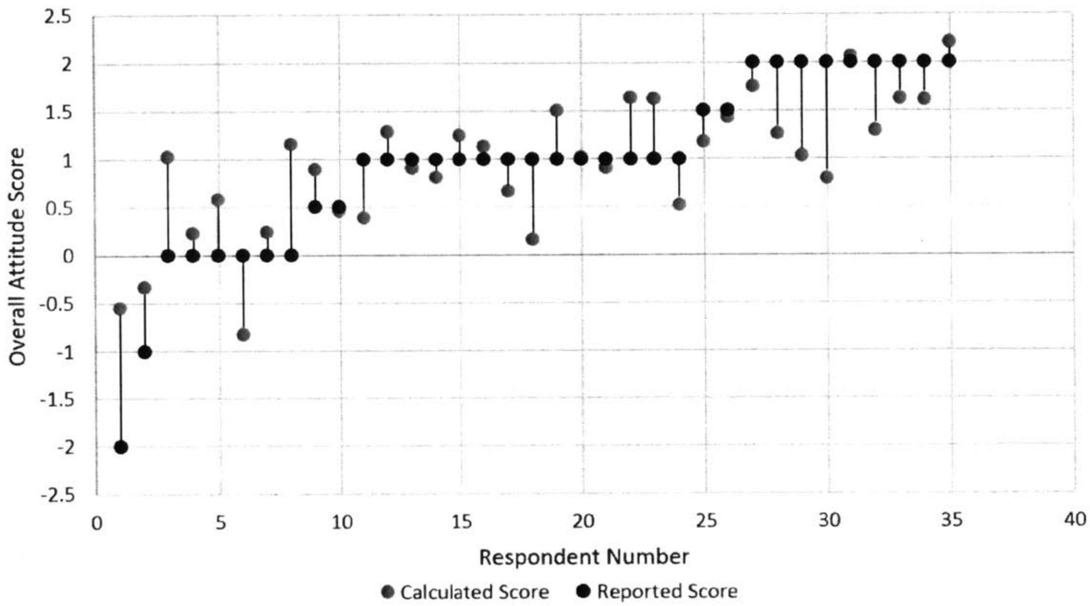

Figure 4.2. Comparison of overall attitude scores reported by respondents and calculated using experimentally determined importance factors.

As can be seen from the figure, Fishbein's model using the calculated weights is able to predict overall attitude fairly accurately in many instances. The average of the absolute (unsigned) error is 0.49 and the standard deviation of the same is 0.37. In some instances, however, the prediction was not very accurate, and the maximum error observed in this data set is 1.45.

4.4 DISCUSSION

4.4.1 Significance of weights

The values in Table 4.5 reveal some interesting insights. First, "quality of filtered water" scored an importance rating of 1.45 which was significantly larger than all of the other importance ratings. This means that according to this analysis, the filter's efficacy in improving water quality has a greater impact on overall attitude towards the product than any other attribute. This would suggest that designers should focus their efforts on improving the technical performance of the filter, though further inquiry may be necessary to determine which factors consumers consider to determine the quality of the water (e.g. expected contaminant levels, aesthetics, etc.).

The second most important attribute is "ease of maintenance" with a score of 0.43. From the qualitative data, some factors that were mentioned that could affect attitude toward this attribute are:

1. Ease of cleaning the microfiber mesh filter
2. Resistance of plastic parts to algae growth
3. Number of parts
4. Life of filter element

These represent potential areas for design improvements that could have a significant impact on overall satisfaction.

Another interesting finding is that the attribute "replacement parts are affordable" scored an importance rating of 0. This would suggest that this attribute has no connection to overall attitude toward the product, a finding which was not expected. One possible explanation for this is that respondents to the survey may have not yet experienced a need to replace any parts and therefore did not consider this a salient attribute. Though nearly all of the respondents had replaced a filter element at some point, it is possible that they did not associate this disposable part with a "replacement part" because it was something that was merely used up rather than something that broke and had to be replaced.

The fact that three importance ratings came out negative ("is durable", "improves taste", and "improves smell") is a problem. Though Fishbein's model does allow the existence of negative weights, these weights should be associated with negative attributes so that the lack of such an attribute contributes positively to overall attitude. In this case, common sense indicates that durability and improved water aesthetics should not be considered negative attributes. The score for "improves smell" is nearly zero so it can perhaps be discounted, however the other two scores are not so easily ruled out. One possible explanation is that there is an extraneous variable that is not being considered which is leading to the correlation. For example, though unlikely, it is possible that there exists a positive feeling among the respondents associated with fixing something that could lead respondents who have experienced breakages to have a more positive overall attitude toward the product because they have fixed it. A more likely explanation is that salient attributes are missing from the analysis which, when included, would drastically change the allocation of relative importance. If this is the case, it calls into question the validity of all of the other importance ratings as well. A third possible explanation is the sample size may not be large enough and the negative weights could be the result of randomness. In any case, it is obvious that further analysis is necessary before conclusions can be reached with confidence.

4.4.2 Improving Existing Model

To improve the model, more data should be collected in order to increase the sample size and decrease the effects of randomness. At that point, a more robust statistical analysis could be performed to determine the statistical significance of the several identified salient attributes. A second round of data collection would also allow the addition to the model of new salient attributes that were identified in the qualitative portions of the survey but were not able to be included in this analysis. It is anticipated that this would increase the accuracy of the calculated importance factors.

4.4.3 Model Limitations

There are a few limitations which are inherent to the application of the Fishbein model to a product. First, the Fishbein model does not include a constant term. This term would account for any offset in the reported overall attitude that is constant across respondents. This is especially important when considering the difference between *reported* attitude and *actual* attitude (i.e. respondents may tend to report overly positive attitudes if they anticipate that the survey administrator is in some way associated with the product).

Second, the Fishbein model assumes a linear relationship between salient attributes and overall attitude. This is in disagreement with other models such as the Kano model which suggests that some attributes (namely "attractive qualities" and "must-be qualities") relate to customer satisfaction in an exponential way [27]. If any of the salient attributes investigated in this study fall into the "attractive" or "must-be" categories as defined by Kano, the effect would be missed and the fit of the model would be negatively impacted.

4.4.4 Future Work

Future work should focus on improving the statistical robustness of the analysis so that conclusions may be reached with greater confidence. This involves collecting more data to increase the sample size as well as quantifying the new salient attributes identified in the qualitative portions of the survey.

Another interesting line of inquiry would be to investigate the effect of demographics on filter users' allocation of importance. Do users from different economic classes consider different attributes to be most important? This data set is too small to investigate this question with any statistical significance, but with a larger data set, this question could be investigated by backcalculating importance factors for different subsets of individuals. This could lead to interesting insights into how to target different market segments.

4.5 CONCLUSION

This section has shown how the Fishbein Multi-Attribute Attitude Model can be applied to a data set for users of the Tata Swach water purifier. Using respondent's answers to 11 questions (10 regarding salient attributes and 1 regarding overall attitude toward the product), the relative importance of each salient attribute was calculated by least squares regression. Though the results are inconclusive, there is some indication that "quality of filtered water" and "ease of maintenance" are important attributes from the customer's perspective. After collecting more data to verify these findings, this information may be useful to designers because it can help them understand customers' prioritization of design requirements and inform design decisions for future iterations.

5 APPLYING DESIGN REQUIREMENTS

5.1 INTRODUCTION

Based on the findings of the previous section, it was determined that a design change resulting in improvement of the quality of the filtered water or in a reduction of the required maintenance would lead to greater satisfaction among consumers. This section describes how such a design change was identified and addressed.

Through meeting with the purifier's manufacturer, it was determined that water could potentially be flowing non-uniformly through the purifier's porous medium. Preferential flow in porous media is a well-documented phenomenon (see Section 5.2 for a review of the literature) and could cause water to flow more quickly through certain paths in the porous medium of the filter element than through others. This could have two significant results related to the design requirements mentioned above:

1. Because the purification process is dependent on the length of time the water spends in contact with the silver nanoparticles (contact time), preferential flow could lead to some water being underexposed and therefore affect the level of purification achieved. This is directly related to the quality of the filtered water.

2. Preferential flow could lead to uneven expenditure of silver nanoparticles in the porous medium. In areas where the water is flowing more quickly, the silver nanoparticles will leach out more quickly, causing some areas of the medium to expire before others. Addressing this issue so that all areas of the medium expire at the same time could lead to longer filter element life. This is simultaneously an issue of ease of maintenance and recurring cost to the consumer.

The rest of this section provides a review of previous research related to preferential flow and a description of experimental work that was performed in order to confirm the existence of preferential flow in this purifier. Finally, a design change is proposed which should decrease the prevalence of preferential flow in the purifier and therefore lead to improvements in the quality of the filtered water, ease of maintenance, and recurring cost.

5.2 LITERATURE REVIEW

Preferential flow in porous media has been a topic of some research in the field of civil and environmental sciences as it often can lead to the transport of contaminants in groundwater. Booltink and Bouma observe preferential flow using tensiometers and methylene blue and show that water flows quickly through macropores and redistributes from discontinuous pores into the surrounding matrix [28]. Pouya et al. provide a theoretical solution to flow around an unsaturated crack in an infinite porous medium, in two dimensions, and under simplifying assumptions [29]. Nimmo shows that preferential flow can happen in unsaturated conditions as well as saturated conditions and states that more research is needed to identify appropriate types of measurement relevant to preferential flow [30].

Though research does exist in this area, it is often either highly theoretical and simplified or else it is experimental and specific to a particular application. For this reason, finding a reliable analytic solution to the flow phenomenon occurring within the Swach is challenging, and instead a combination of experimentation and simulation is attempted to describe the phenomenon and suggest a solution.

5.3 PRELIMINARY EXPERIMENTATION

Experimentation occurred in two stages. Before the final experimentation described in Section 5.4 occurred, some quick, preliminary experiments were performed to get a basic understanding of what was happening inside the filter element. In these experiments, food coloring was used to see if preferential flow would lead to dyed paths in the porous medium that could be viewed after disassembling the filter element.

These experiments were inspired by similar experiments performed at Cornell University to observe preferential flow in topsoil and in a column of sand (cite Cornell website). Figure 5.1 shows pictures from their website where a blue dye was used to show macropore flow in topsoil. Also, dye paths in a column of sand were frozen to observe fingered flow in three dimensions.

Figure 5.1. Preferential flow experiments performed at Cornell University. Accessed from: http://soilandwater.bee.cornell.edu/Research/pfweb/educators/intro/fingerflow.htm

Tata Chemicals provided pictures showing similar experiments that they had performed. In these experiments, technicians at Tata Chemicals created several filter elements that contained a white porous material (rather than the dark RHA which is normally used). Next, they ran water containing a dye through the filter for several complete cycles. Finally, they opened the filter elements and dumped out the porous material to observe the dyed paths in and around the material. Figure 5.2 shows the pictures that they provided of their experimental results.

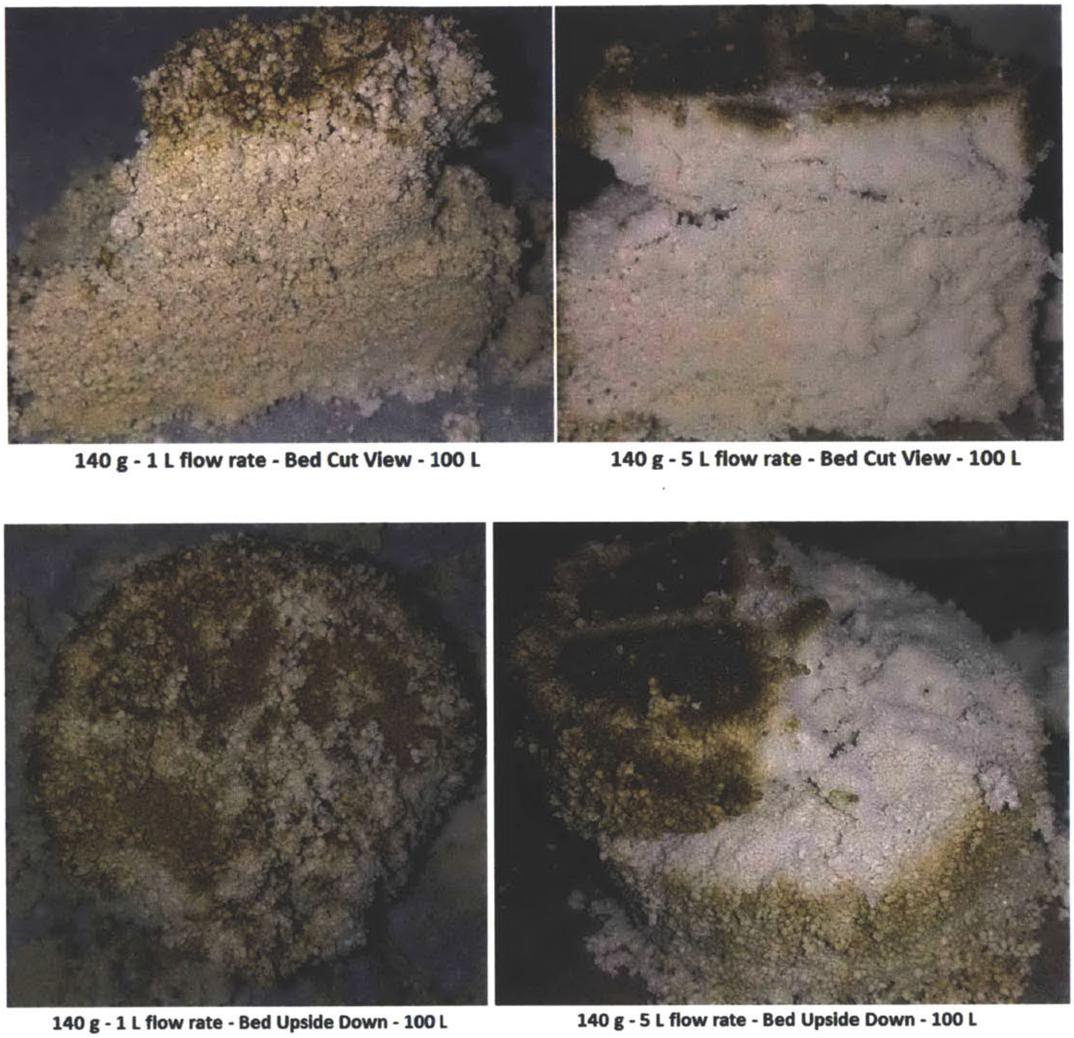

Figure 5.2. Tata Chemical's preferential flow experiments

The pictures appear to show that dye has permeated only the very bottom of the porous material and all along the outside edge. This is what originally led engineers at Tata Chemicals to believe that preferential flow was occurring. There are several reasons, however, why these results may not be comparable with what is actually happing inside the filter element. First and foremost, the porous material was changed from RHA to this white (unidentified), material in order to allow visibility of the dye. This would undoubtedly change the properties of the porous material such as porosity, permeability, particle density, and particle shape. Many of these properties may affect the characteristics of flow through the material so this change may have invalidated the results. Also, it is possible that the dye which they used had too large of a particle size and was simply filtered out quickly by the porous material. This would explain why the dye is only visible at the boundaries but does not give an accurate depiction of what the water is actually doing.

It was the goal of the preliminary experiments presented in this section to replicate the results of Tata Chemical's experiments using the original porous medium and an appropriate dye so that the problems of comparability could be overcome.

5.3.1 Methodology

Two different tests were performed. In the first test, 9 L of water containing red food coloring were run through the filter simulating a normal cycle. After the cycle was complete, the top of the filter element was removed and the porous material was dumped out. It was expected that the damp material would stick together, and distinct paths containing red dye would be visible in portions of the material.

In the second test, again 9 L of water containing red food coloring were run through a new filter element. After the cycle was complete, the filter element was placed in the freezer to allow the damp portions to congeal. After freezing, the top of the filter element was removed and the porous material was inspected. The hope was that congealed paths would be visible in the porous material similar to what was observed in Figure 5.1.

5.3.2 Results

Neither experiment revealed very interesting results. Figure 5.3 shows what was observed while inspecting each experimental filter elements. The porous material from the first test was wet throughout, but the red dye was not visible in the dark porous material. In the second test, again the material was wetted throughout. In fact, the entire filter element was frozen solid to the end that it could be cut in half by a band saw without any of the material being disrupted.

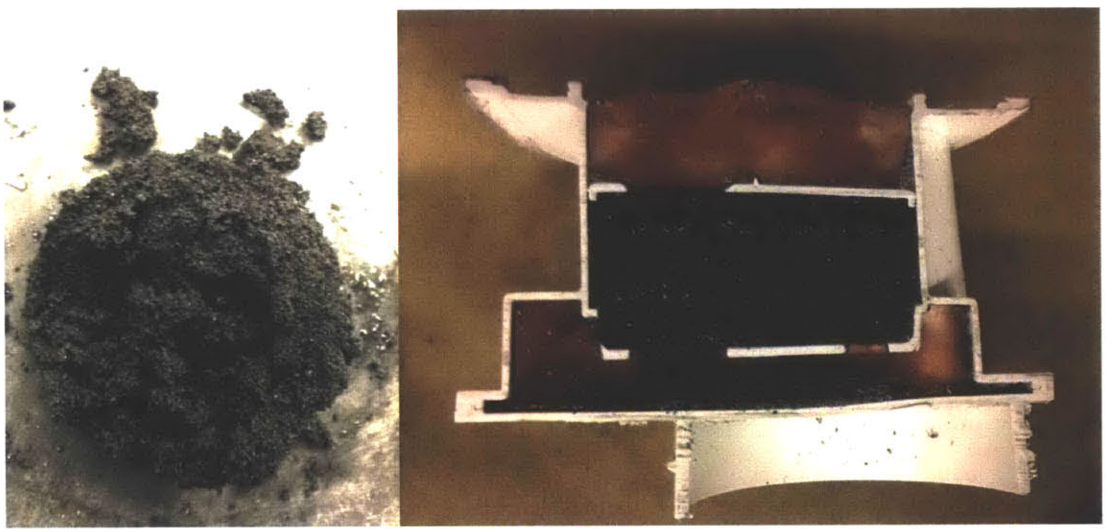

Figure 5.3. Results of Preliminary Experimentation. On the left, results of the first test show that the material is wetted throughout. On the right, the filter element from the second test is cut in half showing ice throughout the entire cross section.

5.3.3 Discussion

Although both preliminary tests showed that the material was wetted throughout, this is not an indication that preferential flow was definitely not occurring within the filter element. It is still possible that water was flowing more quickly through some paths than through others. These tests just showed that the water eventually permeated the entire porous material. To see if water is flowing uniformly throughout the cycle, it is necessary to conduct an experiment which allows the flow characteristics to be observed during operation. This is the focus of the following section.

5.4 FINAL EXPERIMENTATION

Another round of experimentation was performed in order to see what the flow characteristics look like throughout a cycle. This was accomplished by observing the movement of a fluorescent tracer (highlighter ink or fluorescein disodium salt) through the porous medium as the purifier is in normal operation. As the tracer diffused throughout the filter element, it was observed qualitatively that it moved more quickly through some areas than through others, indicating that non-uniform flow is occurring.

5.4.1 Experimental Setup

In order to allow visualization of the porous medium during operation, a vertical cross section of the filter element was taken, and a piece of clear acrylic was adhered to it using silicone. Care was taken during this process to disrupt the internal nature of the filter element as little as possible. This included ensuring that the packing fraction of the porous medium was kept as close as possible to its original state and taking the vertical cross section in such a way that essential elements such as the channel preceding the porous medium, nozzle, and end-of-life mechanism were still included. Figure 5.4 shows the experimental filter element.

The experimental filter element was fixed to the purifier as it would be in normal operation. Some material was removed from the lower container so that the experimental filter element could be viewed more easily (See Figure 5.5).

For initial tests, highlighter ink mixed with water was used as a tracer. Black light (352 nm wavelength) was used to fluoresce the tracer. For later tests, fluorescein disodium salt was mixed with water (1 g/mL) and blue light (460 nm wavelength) was used to fluoresce the tracer.

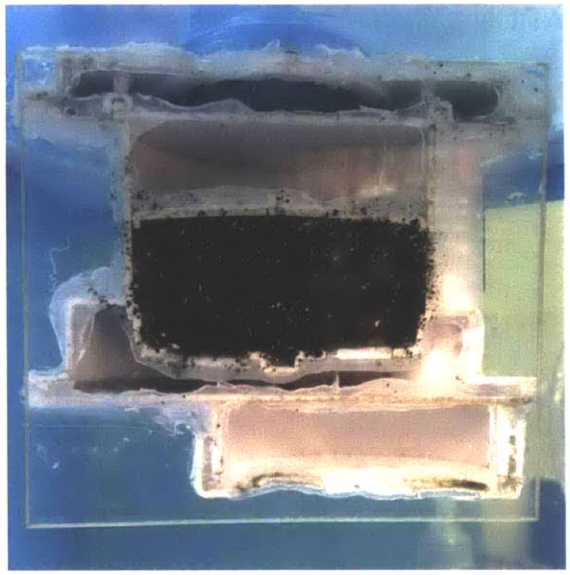

Figure 5.4. The experimental filter element. It has been cut in half and a piece of transparent acrylic is attached using silicone.

Figure 5.5. Experimental filter element attached to purifier

5.4.2 Methodology

Several trials were performed to see if preferential flow could be observed under different conditions. Trials began with the filter element in a pre-wetted state, i.e. clear water was present throughout the filter element, from the channel preceding the porous medium to the nozzle. A certain amount of water with premixed tracer was added to the upper container to achieve a desired input pressure head (2.25-2.63 inches H_2O for low-pressure trials, 4.13 inches H_2O for medium-pressure trials, and 8.25 inches H_2O for high-pressure trials). In order to minimize the amount of mixing required before the tracer reached the bottom of the porous medium, the upper container was either empty or nearly empty before tracer was added. The tracer was then observed as it diffused throughout the porous medium, and particular attention was paid to where the tracer first exited the porous medium. A trial ended when the tracer had diffused to such a degree that flow characteristics were no longer visible. Each trial was video recorded for subsequent analysis.

5.4.3 Results

A total of six trials were performed, three at low pressure, two at medium pressure, and one at high pressure. Three trials used highlighter as a tracer and three used fluorescein disodium salt. Both tracers worked suitably well; they each mixed well with the water and fluoresced brightly enough to be visible within the porous medium, though the fluorescein disodium salt fluoresced more brightly.

Each of the six trials showed signs that preferential flow may be happening within the filter element as distinct paths of tracer initially appeared within the porous medium (Figure 5.6). Figure 5.7 shows how these paths eventually became indistinct as tracer permeated the entire porous medium over time. This was consistent across all six trials. Of particular interest are the results of Trial A which was performed at 2.63 inches of H_2O pressure head and used highlighter as a tracer. Before tracer was visible within the porous medium, four distinct streaks were observed exiting the top (Figure 5.8). This was the clearest indication of all of the trials that non-uniform flow was occurring within the porous medium because it showed that the tracer had permeated the porous medium in four vertical paths much more quickly than anywhere else in the medium. An explanation for what could have caused these four paths to be especially permeable is included in the discussion to follow.

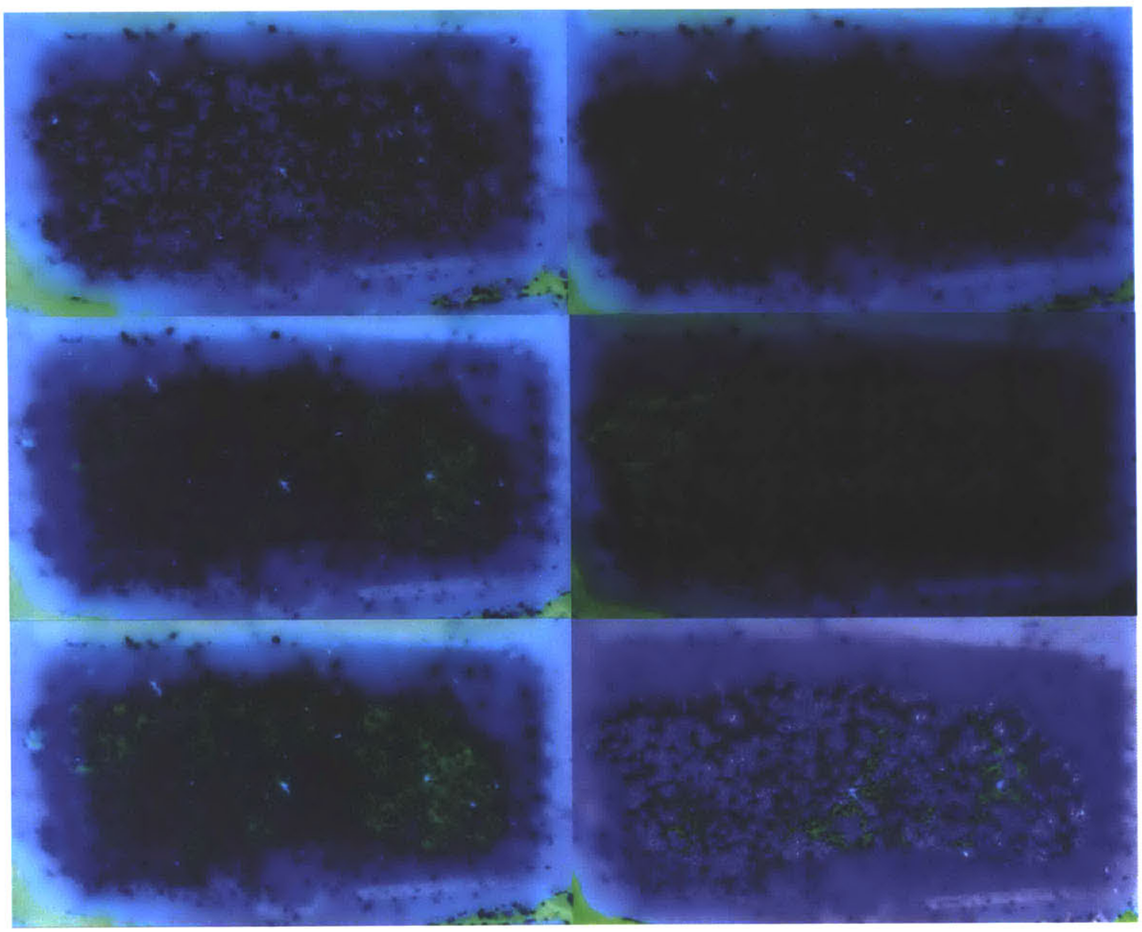

Figure 5.6. Preferential paths observed in each of six trials

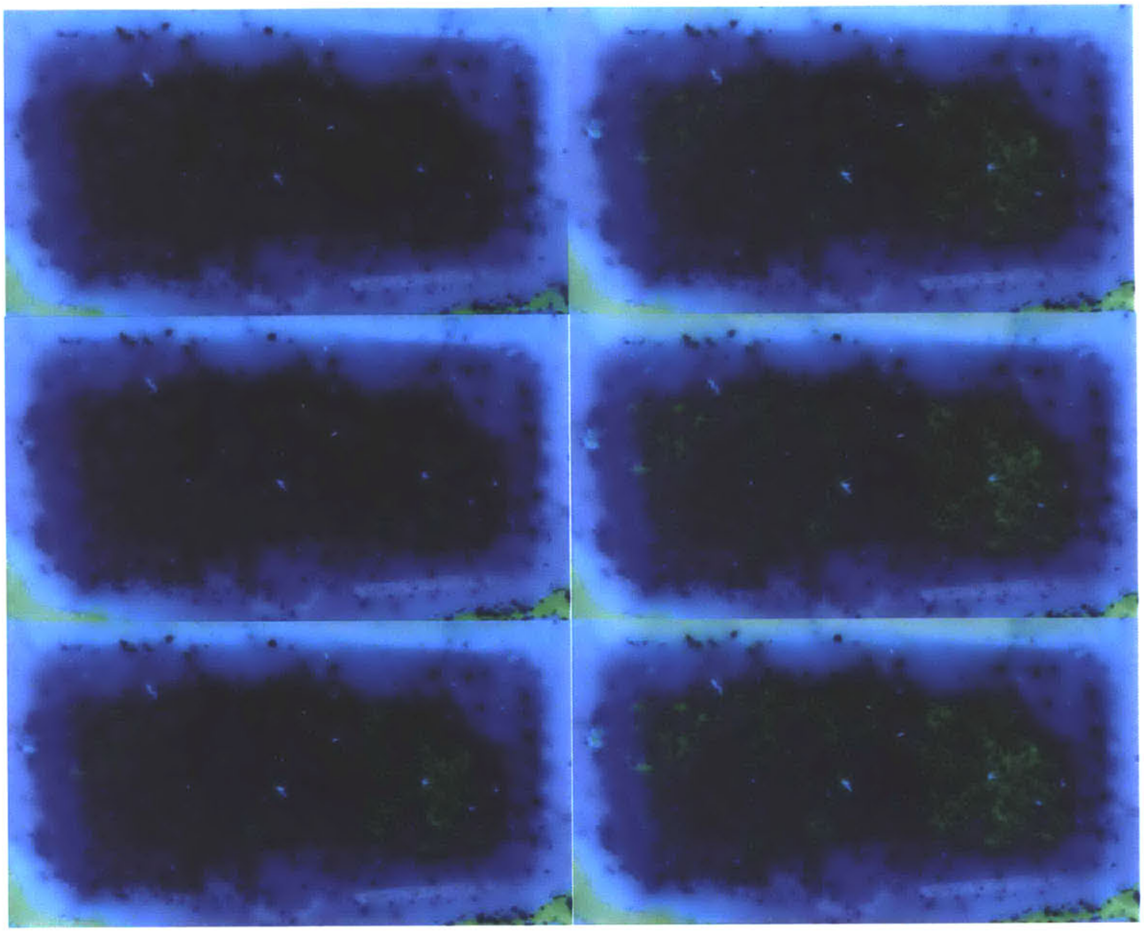

Figure 5.7. Progression of a single test

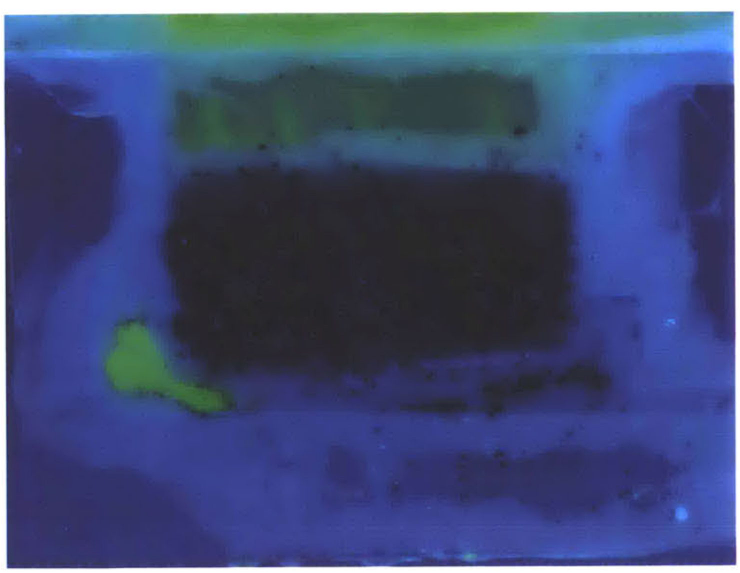

Figure 5.8. Distinct streaks of tracer seen exiting the porous medium at the beginning of Trial A

5.4.4 Discussion

A potential cause of the non-uniform flow in the porous medium is the boundary condition imposed by filter element geometry. There are two circular mesh plates, one above and one below the porous medium, that keep the porous material from washing away with the water. These are divided into quadrants by impermeable plastic bars which provide structural support to the plate and a surface on which to adhere the permeable mesh (Figure 5.9). The lower mesh plate is integral to the plastic housing of the filter element. During manufacture, the porous material is added to the plastic housing (above the lower mesh plate) and then the upper mesh plate is dropped into place to hold the material secure. The orientation of the plastic bars of the upper mesh plate is considered arbitrary, so it rarely aligns with the plastic bars of the lower mesh plate.

Figure 5.9. The upper mesh plate. Seen when the top of the filter element is removed

Because the plastic bars are impermeable, water has to flow around them upon entering and exiting the porous medium. Viewed from above, there are eight distinct regions where the water can flow directly through the porous medium without encountering a plastic bar at the top or at the bottom (two misaligned mesh plates, each with four quadrants). These "free paths" provide lower resistance to the water passing through them which results in a higher flow rate. Figure 5.10 shows a top view of the mesh plates as they are aligned in the experimental filter element and the line along which the vertical cross section was made. It appears that the four "free paths" in the experimental filter element coincide with the four streaks of tracer material that were observed in Trial A.

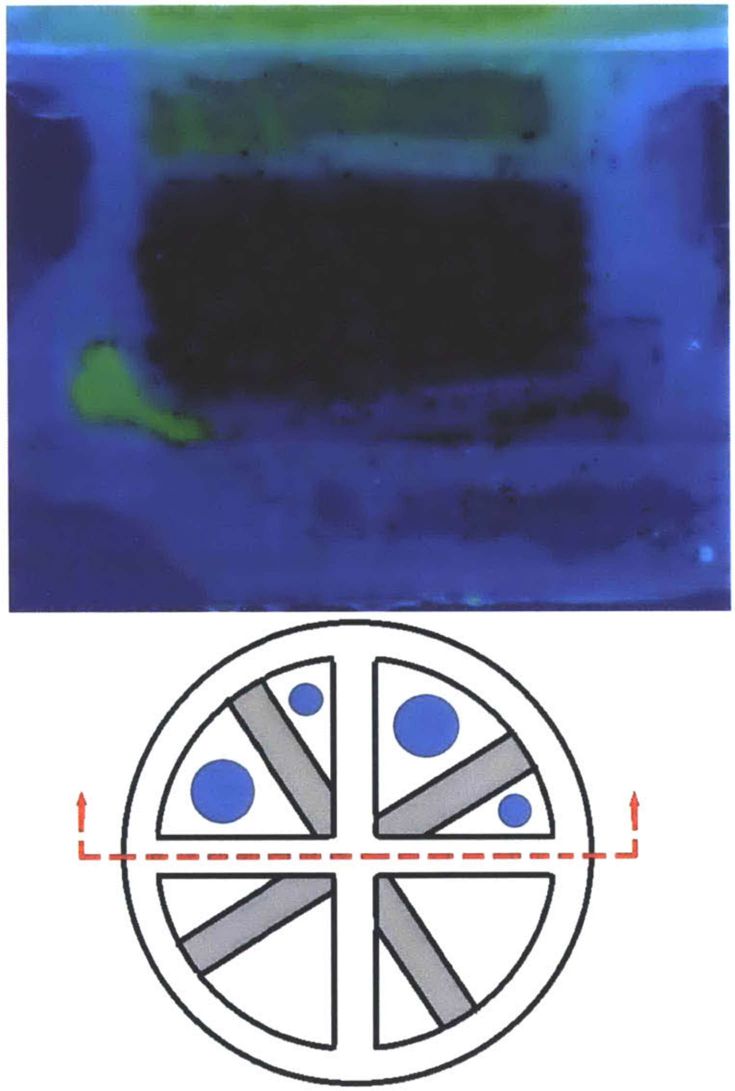

Figure 5.10. Mesh plate arrangement in the experimental filter element as seen from above. Grey bars are from the lower mesh plate and white bars are from the upper mesh plate. The red line shows where the cross section was taken and the blue circles represent potential "free paths." Notice how they align with the tracer streaks observed in Trial A.

Another important discussion point involves the relatability of experimental results to conditions in an untampered purifier. If a particular flow phenomenon is observed in the experimental filter element, is it reasonable to conclude that the same phenomenon would occur in an untampered filter element under normal operating conditions? It was assumed that the important condition for relatability between the experimental filter element and an untampered filter element is the Reynolds number in the porous medium, given by:

$$Re = \frac{\rho v_s D}{\mu} \tag{5.1}$$

Where v_s is the superficial velocity and D is the diameter of a particle. The only variable which can change in this case is the superficial velocity. Using a previously determined fluid dynamics model for the filter element, it can be shown that the superficial velocity is equivalent for the experimental filter element at 2.63 inches H_2O input pressure (as in Trial A) and an untampered filter element at 6.97 inches H_2O input pressure [31]. It is therefore reasonable to conclude that the non-uniform flow observed in Trial A is likely to occur in an untampered filter element at approximately 7 inches H_2O input pressure, a condition that occurs during normal operation (the purifier sweeps from 8.25 inches H_2O to 0 inches H_2O input pressure during a cycle).

5.4.5 Limitations

One limitation involves the uneven distribution of tracer material at the beginning of a test. Because tracer is introduced into the upper container of the purifier, it must diffuse down the experimental filter element through the channel preceding the porous medium. Because this channel is located toward the left side of the experimental filter element, tracer is first introduced at the bottom of the porous medium on the left and then slowly diffuses to the right. The time required for the tracer to become ubiquitously present at the bottom of the porous medium must be considered when qualitatively analyzing the speed of its movement upwards through the porous medium. A clearer understanding could be achieved by directly introducing the tracer material evenly across the bottom of the porous medium at the beginning of test. This could be accomplished by modifying the experimental apparatus and is left for future work.

5.5 SUGGESTED DESIGN CHANGE

If the cause of preferential flow in the filter element is in fact the obstruction of the plastic bars in the mesh plates, a few simple design changes could help mitigate the effect. First, the plastic bars may be removed entirely so that a single mesh provides a uniform boundary condition across the entire cross section. This will eliminate the existences of distinguishable "free paths" that have a higher permeability than the surrounding areas. This may be difficult to implement if the plastic bars are considered a necessary structural element for supporting the mesh or for ease of assembly during manufacture. In that case, a second solution could be to make the plastic bars thinner or fewer in number. In this way, the effect of the boundary condition imposed by the plastic bars is minimized. A third solution, which requires the least amount of change to manufacturing equipment but perhaps provides the least amount of benefit, is to ensure that the plastic bars of the top mesh plate are always aligned with the bottom mesh plate. This creates four large regions of unobstructed flow rather than eight smaller regions, thus increasing the percentage of the cross section that experiences unobstructed flow. This can also be combined with the previous solution for even greater benefit. Each of these solutions is depicted in Figure 5.11.

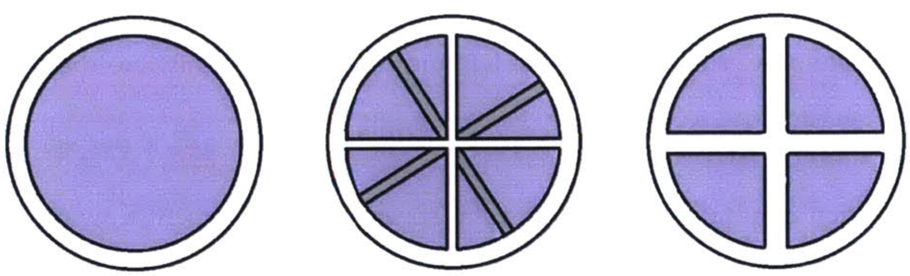

Figure 5.11. Possible design changes to the mesh plate that could reduce the effect of preferential flow in the filter element

A sensible next step would be to create a prototype which incorporates these design changes and experimentally observe the benefit obtained. This is left for future work.

5.6 CONCLUSION

Non-uniform flow in the porous medium could lead to water that is not purified properly as well as the filter element expiring prematurely or with unused material going to waste. Because the quality of the filtered water and the ease of maintenance of the purifier were identified in Section 4 as the two biggest factors affecting user satisfaction, this is an important issue to address. This section has shown experimental evidence that preferential flow is likely occurring in the Swach filter element. It has also proposed several design changes that can be implemented to reduce the occurrence of preferential flow in the Swach.

6 CONCLUSION

Developing clean water technologies that scale and can meet the needs of consumers in developing countries continues to be a difficult problem for the development community. There is not one solution that will work everywhere around the world. There is not one solution that will work even everywhere in India. Instead we must continue to develop a portfolio of solutions and seek to constantly improve them. If we do this, we will eventually see this problem eradicated.

The goal of this thesis has been to better understand and to address issues surrounding adoption of one of these technologies — the Tata Swach water purifier. This research has contributed in several ways. First, a physical understanding and mathematical model of the purifier's operation has been identified. This will allow designers to optimize the flow rate while maintaining purifier efficacy. A design tool based on this model has been developed and demonstrated to aid in the design of future iterations of the product. Next, an analysis of Tata Chemicals' design process and a comparison to literature has identified process improvements that can facilitate better incorporating the voice of the customer. This will hopefully lead to more success in the development of future products or future iterations of the Swach. It also serves as a case study for other designers working in similar contexts. Also, original consumer research was performed to identify which design requirements are most valued by users of the Swach. By applying Fishbein's Multi-Attribute Attitude Model, it was shown that "quality of filtered water" and "ease of maintenance" are the characteristics that have the greatest impact on overall satisfaction. This is essential knowledge for Tata designers as they make decisions for future iterations and decide where to focus their efforts. It can also be informative for other designers who are seeking to create purification technologies, especially in India. Finally, experimentation confirmed the likely occurrence of preferential flow in the porous medium of the filter element, and it was explained how this can affect the quality of the filtered water and the purifier's ease of maintenance. A design change was suggested to minimize the effects of preferential flow.

Some of these contributions have already had a direct impact on Tata Chemicals' operations. It is the hope of the author that this research will continue to be applied by Tata Chemicals to improve this product and bring this life-saving technology into the homes of more people.

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