Reducing the Power Required for Irrigation: Designing Low-Pressure, Pressure-Compensating Drip Irrigation Emitters and High Efficiency Solar-Powered Pumps for Emerging Markets

by

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ABSTRACT

This thesis presents a mathematical model investigating the physics behind pressure-compensating (PC) drip irrigation emitters and a design of a highly efficient solar-powered centrifugal pump for small-acreage farmers drawing from shallow groundwater.

The global community is facing a worsening crisis with regards to the water-energy-agriculture nexus. Irrigation is a proven way to increase the agricultural productivity of a plot of land; however, with a growing population, it will be necessary to invest in methods of irrigation that are both energy- and water-efficient, and intensify the agricultural output per unit of land. Drip irrigation, a method of irrigation where water is delivered directly to the plant roots through a network of tubes and valves, is a highly water-efficient method that gives high yield per unit area. The current challenge to adoption facing drip irrigation is the high capital and operating costs. It is possible to cut these costs by developing a valve, called an emitter, that gives the desired flow rate at a lower pressure. This lower pressure in turn requires less energy from the pump, allowing for a smaller and less expensive pump, and even making a solar-powered system affordable for small-acreage farmers.

In coming decades, it will become increasingly necessary to switch from fossil-fuel based energy to renewables, such as solar. For small acreage farmers in the developing world, this switch will not only alleviate the pains of paying the recurring and volatile costs for diesel fuel, it will also help to lighten the load on the electrical grid by those using electric pumps.

Thesis Supervisor: Amos G. Winter, V
Title: Assistant Professor of Mechanical Engineering

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1. Introduction

1.1. Background and Motivation

1.1.1. Scope of Problem

The world is facing a growing crisis surrounding the energy-water-agriculture nexus. Currently, agriculture accounts for 70% of global freshwater use. By 2050 the world's population is predicted to exceed 9 billion. Feeding these 9 billion people will require increasing global food production by 70% [1].

Along with available freshwater, there is only a certain amount of arable land on earth. Currently, cropland makes up 11% of the total land on earth. It is estimated that there is another 25% of the land on earth that is suitable for crop production [2]; however this land is also under demand for urban development and industrial use. In order to meet the needs of a growing global population, it will be necessary to intensify agricultural production.

Out of the land that is currently used for cropland, only 18% of it is irrigated at any point during the year [2]. Irrigation has been shown to increase the yield per acre; the Food and Agriculture Organization of the United Nations published a report stating that the "highest yields that can be obtained from irrigation are more than double the highest yields that can be obtained from rain-fed agriculture" [3]. However, irrigation requires energy to move the water.

Most commonly, farmers use pumps that run on diesel or electricity from the grid to irrigate. These two options are problematic; diesel is a non-renewable resource, which is volatilely priced and degrades environment; electricity is mostly generated from the burning of non-renewable coal and there are 2.4 billion people who have no or unreliable access to the grid [4].

India, the country of focus for this paper, is home to 17% of world's population, but has only 4% of the world's freshwater resources [5]. By 2050, India's population is expected to be the largest in the world, 1.6 billion, and the country's water demand will have exceeded its supply [6]. As of 2012, 61.4% of the land in India was cropland, but only 35.1% of that land was under irrigation at any point during the year [7]. Not only is it important to increase the agricultural output to feed the growing population, it is also essential in supporting the rural agrarian-based economy. Currently, the rural economy sustains two-thirds of India's 1.2 billion citizens [6]. If India is going to feed it's growing population without depleting its water resources in an economically viable fashion, it will need to invest in water- and energy-efficient forms of irrigation, preferably using renewable energy resources.

1.1.2. Technological Opportunity

It is possible to make irrigation water-efficient and energy-efficient, while keeping it as an economically an accessible option for even the poorest farmers through combined policy, financing and technological advancements. The following thesis will discuss two technological approaches for reducing the power needed to irrigate with a highly water-efficient technique, powered by renewable energy.

1.2. Proposed Solution

1.2.1. Dripper

Drip irrigation is a highly water-efficient type of irrigation, meaning that the same amount of water gives a much greater yield per acre than other types of irrigation. Drip irrigation refers to a system where water is pumped through a network of tubes to valves that deliver a regulated flow of water directly to where it is needed, the plant's roots. These valves are called "emitters" or "drippers". Figure 1-1 shows a typical drip irrigation setup.

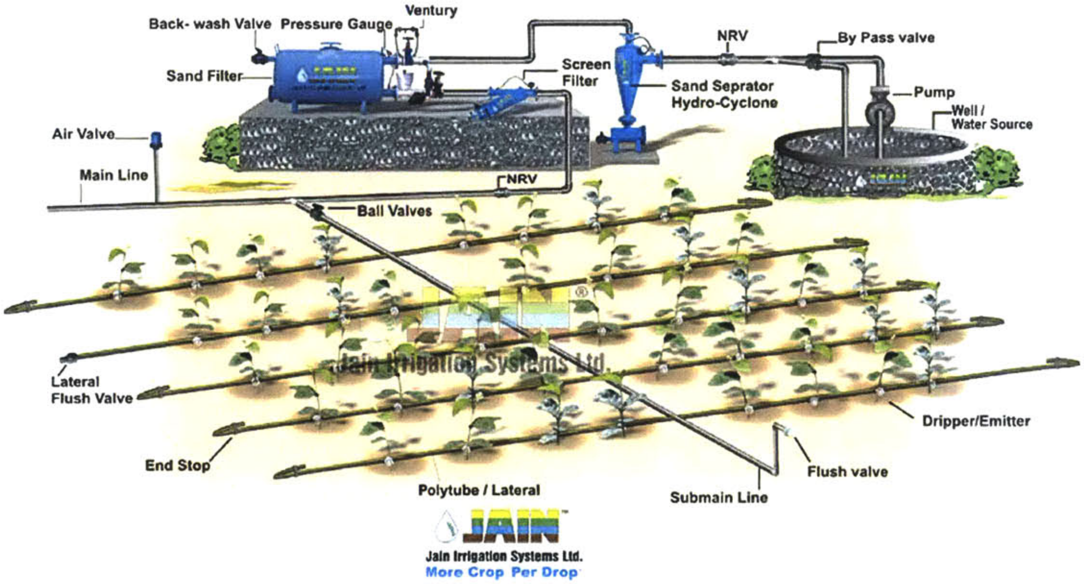


Figure 1-1: Typical Drip Irrigation Setup
www.jains.com

The reason that drip irrigation has a higher yield than other types of irrigation is that the flow rate of water let through the emitters and the spacing between the emitters and between the lateral tubes are prescribed based on type of plant and soil. In drip systems that use a pump with unsteady flow or fields with inclined terrain or a large network of tubes, a specific type of emitter, called a pressure-compensating (PC) emitter, is needed to ensure that the same flow of water is delivered through all of the emitters; the PC behavior of an emitter means that for flows within a range of pressures entering the emitter, the same flow rate exits the emitter. The low end of the range of pressure at which the dripper exhibits PC behavior is called the activation pressure.

While the main strength of drip irrigation are water conservation and increased yield, the main weakness of drip lies in its cost, which is often prohibitive for small-acreage farmers. There is the upfront capital cost for the pump, network of tubes and emitters, but there is also the operating cost of pumping the water at a relatively high pressure. It is possible to reduce both the capital and the operating costs by developing an emitter with a lower activation pressure. If said emitter can activate the desired PC behavior at a lower pressure, then there is lower pressure needed in the lateral line, thus lower pressure needed in the main line and thus lower pressure needed out of the pump. Since the power of a pump is the product of the flow rate and pressure, this lowered pressure requirement directly lowers the power requirement of the pump. A lower power pump is less expensive, cutting the capital cost of the system, and requires less fuel. With the lower power requirements, it is even possible to use solar to power the pump.

Thus, the key to overcoming this economic barrier is to develop a PC emitter that has a lower activation pressure.

1.2.2. Pump

Globally, 72% of the farms on earth are less than 1 hectare, and more than 90% of all farms are run by an individual or a family [8]. Thus it is surprising that with dwindling fossil fuel resources, there is no commercially available solar pump that has been designed with these small-acreage farmers in mind. There are pumps that are fit for large farms or collectives of farmers, but none with flow rates fit for small farms that are efficient enough to make solar an economically viable option.

This thesis discusses the development of a highly efficient centrifugal pump that is the cornerstone of a solar-powered irrigation system that is tailored for small-acreage farmers drawing from shallow groundwater.

2. Dripper

2.1. Introduction

2.1.1. Motivation

Climate change and the growing global population is increasing water scarcity, creating a serious challenge to agricultural development and growth. With dwindling freshwater resources, and a growing global population, it will be necessary to produce more food while conserving non-renewable resources. One proven method of increasing crop yields and decreasing water usage is drip irrigation. Currently, the most common method of irrigation in the developing world is flooding, which is labor intensive, but requires no capital. Compared to flood irrigation, drip irrigation reduces water consumption by up to 70% and increases crop yields by 20-90%, depending on the crop [9]. Drip irrigation allows for the cultivation of higher value crops, which are more sensitive to water and fertilizer application rates. The ability to grow more and higher value crops is essential for small-acreage farmers to raise their families out of poverty.

The greatest barrier to adoption of drip irrigation by smallholder farmers is the recurring cost of the power required to pump water through the system at the presently necessary, relatively high pressure. For example, in order to power the pump for 1-acre of drip irrigation around $2000 worth of solar panels are required [10]. We propose a model that could lead to the design for a pressure-compensating emitter that activates at 1/10th of the current required pressure. By lowering the activation pressure, we lower the required pumping pressure, and thus the power to move the water. It would be ideal to make the system able to use solar power, so that it could be used by the 2.4 billion people who have no or unreliable access to the grid [11]. The decreased pumping power requirements would make solar powered drip irrigation systems an affordable option for smallholder farmers across the developing world, including tens of millions of small-scale subsistence farmers in India, the primary country for this research project. In India, as in much of the developing world, many farmers do not have access to the power grid. Solar powered irrigation would not only give these farmers access to drip irrigation but would also ease the load from the farmers who are on the grid and who currently account for 1/4 of the electrical consumption in India.

In "Looking Back to Look Forward" [12], Duarte et al. examine the connection between economic growth and the colossal rise in water use in the past century due to the expansion of agriculture and irrigation. By analyzing trends in water use on both a global and regional scale, along with economic and demographic trends, the authors disentangle the relationship between the major drivers responsible for the changes in water use and in water use intensity. Globally, agriculture accounts for 66% of freshwater withdrawals and 85% of freshwater consumption. Duarte et al. discuss the tenuous balance between economic and income growth, economic development and agricultural intensification with structural change. The authors state that in order to avoid a drastic global water crisis, there needs to be both technological improvements yielding efficiency gains as well as demand management policies and pricing. They emphasize that this will be particularly important in developing countries where significant increases in population and affluence are predicted.

Postel et al. [13] agree that technological developments will be moot if other ancillary but critical issues are not resolved, such as the farmers' access to markets and micro-credit. However, the authors make an argument that making drip irrigation available to small farmers is key to alleviating rural hunger and poverty. They estimate that making low-cost drip available to poor farmers in Africa, Asia and Latin America by way of private microenterprise could "boost the annual net income among the rural poor by some $3 billion per year" [13].

Looking specifically at India, it is apparent that it is a country that has a significant unmet demand for affordable water-efficient irrigation on small farms. In "Drip irrigation in India: can it solve water scarcity?" Narayanamoothy [14] argues that water use efficiency and increasing the productivity of crops is paramount in India due to the rapid population growth, decline of available ground water and increasing population. By conducting experimental trials in the state of Maharashtra the author shows that by converting from flood irrigation to drip irrigation, water savings of between 12-84% can be achieved depending on the crop, and estimates these water savings could irrigate an additional 24.12 million hectares in Maharashtra alone.

2.1.2. Stakeholder Analysis

The stakeholders discussed are divided into primary and secondary stakeholders. Here, primary stakeholders are defined as those who are directly affected by and who directly influence the project, whereas secondary stakeholders are defined as those who are indirectly affected. Of course there is some overlap in these categories, but they are simply meant to help illustrate the importance of each stakeholder. The primary stakeholders considered are the farmers who would use the drip irrigation system, Jain Irrigation Systems, and agencies within the state and federal government. The secondary stakeholders considered are the farmer's family, the neighboring farmers, and the suppliers of raw material to Jain Irrigation.

2.1.2.1. Primary Stakeholders

The farmers are the target customer and the end users of the drip irrigation system. They have a vested interest in some of the advantages provided by drip irrigation over alternate methods of irrigation. These alluring advantages include the ability to grow higher quality and higher value crops, the reduction in daily labor and the ability to use poorer quality water. However, for the farmer, there are some disadvantages in using a drip irrigation system. The cost of purchasing a drip irrigation system, the possibility for theft, and the increased complexity of operation and maintenance are all considerations for the farmer. Jain Irrigation has attempted to address the problem of theft by designing anti-theft mechanisms for solar panels and pumps to be used with the system. They also have addressed the increased complexity by conducting training courses on solar panel maintenance and drip irrigation operation, such as routine flushing of the system to remove clogs. If the desired price and operation requirements can be achieved, this low-pressure drip irrigation system has the possibility to be a crucial aid to farmers caught in a poverty trap. However, as with all new technology, there is chance the farmers may resist adopting the drip irrigation system out of an affinity for tradition or a trust in the traditional methods. It is also possible that farmers may be concerned about this technology affecting their employment and livelihood.

As the product develops through the iterations of prototyping, the farmers' input will be invaluable. They will be able to inform the design with their personal and comprehensive first hand experience. They will provide information on the ease of use of the prototype, on whether or not the financing is realistic, and in later trials, on the efficacy of the system for growing higher value crops.

Jain Irrigation Systems, the world leader in supplying drip irrigation systems to small-scale farmers, is another primary stakeholder. Jain Irrigation is a well-established company that is in charge of the manufacturing, distribution, sales and training for their farming products. Jain has over $1 billion in annual revenue [15]. In this project, Jain Irrigation will be in charge of the technology transfer from the shovel-ready emitter prototype to taking it to market. This is a very exciting opportunity for Jain, since it would open up a whole new sector of the market to them: subsistence farmers who currently cannot afford their drip irrigation technology. Also, since it is such a disruptive opportunity, it may allow them to expand overseas more effectively, including markets in the developed world. Some considerations regarding this project for Jain include whether or not they'd have to develop a new financing scheme for subsistence farmers, whether or not they'd need to put capital into expanding their training forces or if they would hire consultants and if this new technology would cannibalize some of their current drip technology.

Jain greatly influences the technical design of the emitter and its manufacturability. Jain, along with Professor Winter, was in charge of determining the performance and price metrics. For Jain, it would be optimal if the emitter could be manufactured using machines and subsidized materials that they currently own. For Jain, the design of a pressure-compensating emitter that would cost $0.025 is very exciting since their current pressure-compensating emitter costs about double that, in no small part due to a silicone membrane purchased from an outside company that alone costs $0.025. Thus Jain also influences the materials choice for the emitter. Morgan Stanley recently commented that "profitability in Jain's micro-irrigation business would remain under pressure over the medium term due to a 'sharp' rise in input costs" [16]; thus cutting the input cost in half, and cutting out purchasing from another outside source would help Jain's profits and is of great interest to them.

Agencies within the state and federal government are another group of primary stakeholders to be considered here. One pertinent federal agency is the Central Board of Irrigation and Power (CBIP), which "is a knowledge bank and an exchange for dissemination of experience and technical knowledge" [17]. The CBIP, along with the Department of Agriculture Research and Development, can influence the design of the prototype by sharing their gathered knowledge on agricultural technology in India. These two federal agencies have connections throughout the agricultural chain, from government bodies that set subsidies to researchers who gather data from farmers across the Nation. They would also most likely be very interested in a device such as this that would alleviate water usage issues and lead to more intensive land use. The Ministry of Agriculture is another federal agency that would be informative in our design, and also highly invested in its success because the use of drip irrigation can allow for higher quality and value crops to be grown, which could raise the GDP and alleviate nutrition issues. The Department of Power would benefit from the success of our technology; since it allows for the use of solar power, it will lessen the load on the grid from farmers. Water resources are managed both by state, through the State Water Missions, and by the federal government, through the Ministry of Water Resources. Both of these agencies would advocate the spread of affordable drip irrigation in order to aid in water conservation, which in turn helps the country in terms of water security.

2.1.2.2. Secondary Stakeholders

While the farmer's family has been characterized here as a secondary stakeholder, it is understood that in India farming is often a family business and thus the family all would fall under the primary category. Even if not, the family would benefit or be disadvantaged by this project in similar ways to the farmer. It is possible this technology could aid in breaking a family's cycle of poverty. It is also possible that the initial investment could be detrimental if the equipment were stolen or if right after purchase, someone fell ill or money was needed for another emergency.

The neighboring farmers, or local farmers who grow similar crops, are another group of secondary stakeholders to consider. If the farmers who have enough money to buy the drip irrigation system are successful, it is possible that they would push those farmers, who used to be competitors and who are still unable to afford the technology, deeper into poverty. On the other hand, perhaps the success of the farmers using the drip irrigation technology would empower and enable them to form some sort of union, which could in turn benefit the farmers still using methods such as flood irrigation.

The companies who supply raw materials to Jain Irrigation are another group of secondary stakeholders to consider. The success of our design would be challenging to the company that currently supplies silicone to Jain for their more expensive pressure-compensating drippers. However, there may be companies that benefit by being the sole suppliers or by supplying more of the same material to be used in the design.

This stakeholder analysis is limited due to the researcher's growing, but still not yet comprehensive, understanding of life in India. This understanding will surely continue to grow through academic research and in future visits to India. The analysis is also limited due to the inability to speak directly to many of the stakeholders, which also may be alleviated in coming visits and with further research.

2.1.3. Method

The method of approaching this research problem is to understand the full power requirements of a drip irrigation system, to isolate where a key change could be made, and to develop a parametric model of the current emitter design, so as to fully understand the underlying physics and be able to manipulate the mechanisms to meet the desired design specifications.

The overall goal is to lower the amount of power needed by the pump, so that it becomes an affordable option to use solar power for the pump. The definition of power is:

$$Power = Flow\ rate * Pressure \qquad [1]$$

Since the daily flow rate is determined by the type of crop and type of soil, the pressure is the factor that can be manipulated to lower overall power. The pressure losses occur across the filter, through the main pipe, through the lateral tubes and across the emitters. In section 2.4.1. a flow model is developed to back calculate the power required at the pump, starting from the activation pressure required at the dripper farthest from the pump. The losses across the filter are a function of the flow rate. The losses through the main pipe and lateral tubes are frictional line losses, and are taken into account by the drip company when laying out a system by setting the length and diameters of the tubes and the main pipe [18]. Thus the real opportunity for lowering the overall power needed by the pump is to lower the activation pressure of the emitters.

In order to lower the activation pressure of the emitter, a parametric model is developed in an effort to understand the underlying physics behind the behavior of the emitter and the accompanying geometric and material sensitivities. With this knowledge, it may be possible to manipulate the geometry or material of the emitter, or to develop a new architecture that exhibits similar behavior, to meet the design specifications.

2.2 Prior Art

2.2.1. Evolution of Drip Irrigation

The creation of drip irrigation occurred in the 1950's due to a confluence of factors and one curious man. The first important factor is that due to the scarcity of rubber during World War II, American scientists had put a great deal of work into developing different types of plastics, namely polypropylene and polyethylene, to feed the war machine [19].

Secondly, the end of World War II in 1945 and the declaration of Israel's independence in 1948 brought floods of Holocaust survivors from Europe and Russia to Israel. In order to support the refugees, David Ben-Gurion, the first Prime Minister of Israel, felt that the future of Israel was dependent on "making the desert bloom" [20].

In an attempt to answer this challenge, Simcha Blass, a Polish born Jewish engineer, worked as a hydraulic engineer in the Palestine desert. As the story goes, one day Blass ate lunch under a fig tree. As he was eating, he wondered at how the tree had grown so tall since the only sign of moisture was a pipe coupling next to the tree that was perpetually dripping. Curious at how such a large tree could be supported by such a small amount of water, Blass dug around the roots of the tree to find an onion shaped wet zone that perfectly matched the tree's roots system. Blass understood that the tree remained moist due to the lack of surface evaporation. After this fortuitous day, Blass worked diligently to design and manufacture plastic drippers that would be the first drip irrigation emitters on the market [19].

Currently drip irrigation emitters exist in three main forms: online (Fig 2-1) inline (Fig 2-2) and drip tape (Fig 2-3).

Figure 2-1: Online Emitter
www.jains.com

Figure 2-2: Inline Emitter
www.toro.com

Figure 2-3: Drip Tape
Irrigationexpress.co.nz

Online emitters are attached to the drip tube after the tube has been extruded and cooled. Inline emitters are attached during the process of extrusion. Drip tape is a strip that is affixed inside the tube, along its entire length, during extrusion. All three types of emitters can come in designs that give different degrees of pressure compensation.

Online emitters, inline emitters and drip tape have the same basic mechanisms to achieve PC flow restricting behavior; they have one fixed resistance, whether it be a gap that uses the venturi effect or a labyrinth to provide frictional resistance, and one variable resistance. In the online and inline drippers, the variable resistance is a silicone membrane that deflects with varying pressure and causes the flow restriction. The problem with these silicone membranes is that they are expensive and that there are bounds on how thin they can be due to fatigue and pinning. In the drip tape, it is the tape itself, which is not fully connected through the labyrinth, which provides the variable resistance. With higher pressure within the drip tube, the tape is pushed up and the labyrinth is pushed against the top of the tube, providing increased resistance. With lower pressure in the drip tube, the tape is sucked down, a gap between the labyrinth and the tube develops and the resistance is lowered. However, again due to the trade-off between flexibility and fatigue, the drip tape has limits on the lower bounds of pressure that allow it to exhibit PC behavior.

One of the early designs of a pressure-activated flow control device was by Robert Rosenblum in 1946 [21]. Rosenblum created a device, shown below in Fig 2-4, that was comprised of an insert with an orifice that provided a fixed resistance, and an annular flexible membrane, which provided variable resistance.

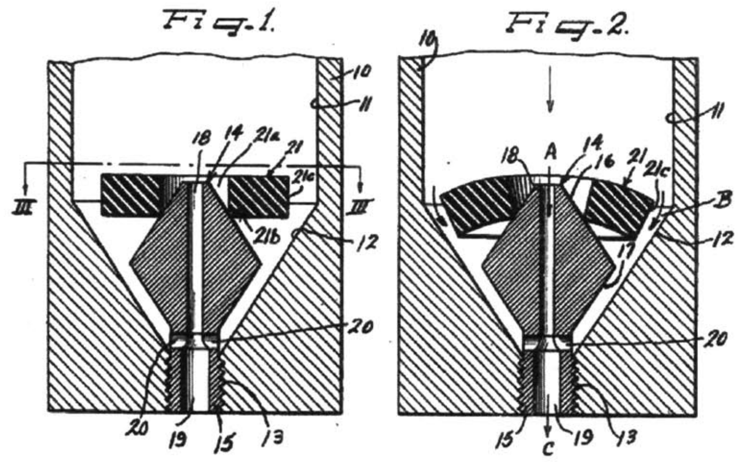


Figure 2-4: Patent Sketch of Rosenblum's Flow Control Device [16]

In Rosenblum's device, the orifice was through the insert, which could be screwed to raise or lower the height, thus changing the distance from the flexible membrane to the sides of the annular flow channel. While this design was not directly used for drip irrigation, it is cited in many PC drip patents.

The current design of most online PC emitters on the market resemble the PC emitter designed by James Hardie Irrigation, Inc. [22]. This emitter has a flow channel in the housing that provides a fixed resistance and an elastomeric disk that provides variable resistance.

2.3. Concept and Theory of Dripper Performance

It is possible to create a parametric model of a dripper to understand its material and geometric sensitivities. In order to do so, it is important to understand the mechanisms behind the two main functions of the emitter, flow limitation and pressure compensation, and the parameters that influence these functions.

Below, Fig 2-5 shows the parameters that influence the emitter's performance. The parameters of interest with regards to the membrane are: the material properties, thickness and diameter. The parameters of interest with regards to the rigid emitter are: the orifice dimensions, the land diameter, the channel dimensions, the maximum height of deflection of the unstressed membrane, and the outlet diameter.

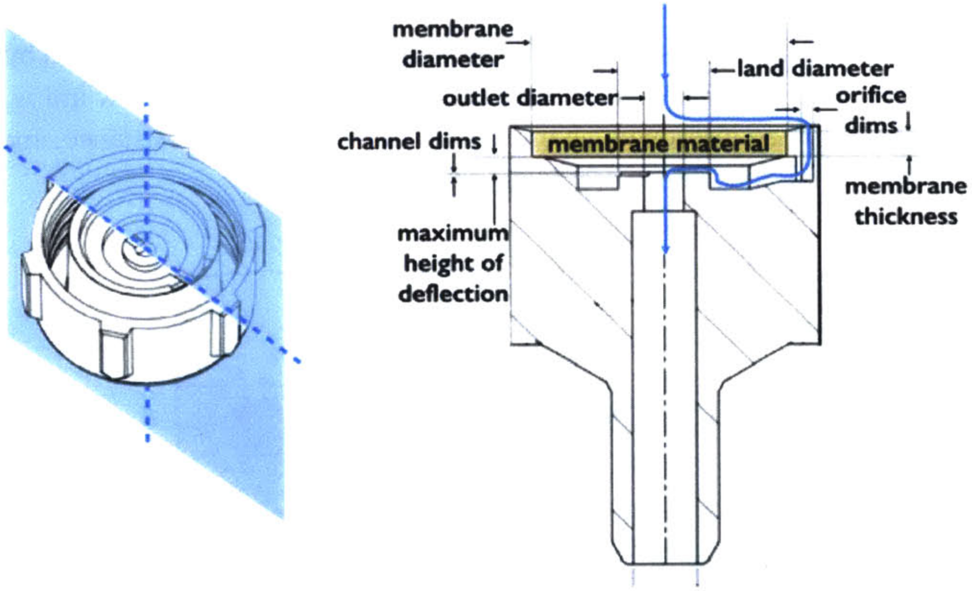


Figure 2-5: Parameters of Interest in Emitter

Image Source: http://www.jains.com/

Figure 2-6 depicts the cycle of pressure compensation and shows the fluid flow path through the cross section of the emitter.

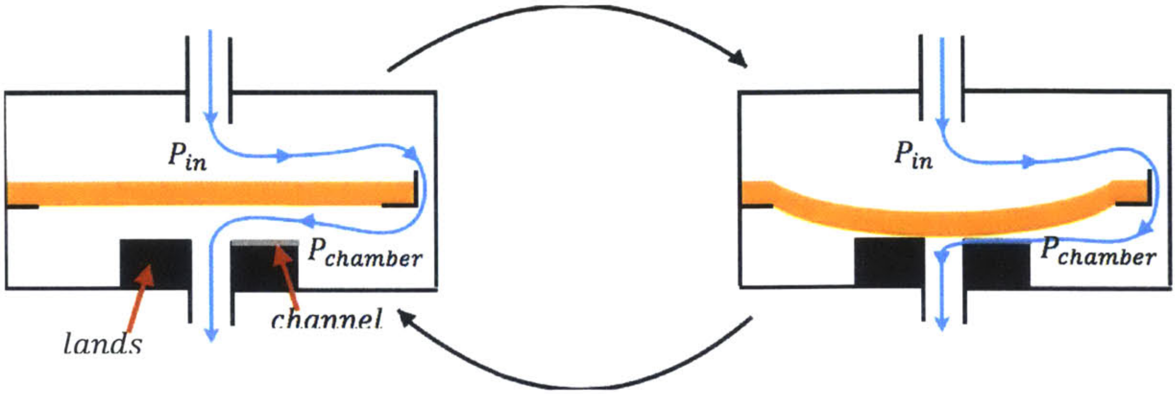


Figure 2-6: Cycle of Pressure Compensation

The cycle of pressure compensation goes as follows: fluid flows into the emitter at an inlet pressure equivalent to that in the lateral tube at the emitter location and then flows into the bottom chamber under the membrane through an orifice which leads to a pressure loss; when the incoming pressure in the upper chamber, P_{in}, is greater than the lower chamber pressure, $P_{chamber}$, the membrane deflects down and restricts flow; the lower chamber pressure and upper chamber pressure eventually equalize, and the membrane pops back up; the fluid can then out of the emitter over the lands, until the incoming pressure is again greater than the lower chamber pressure, in which case the cycle begins again.

2.3.1. Flow Limitation

The main function of any drip irrigation emitter, PC or not, is to limit the flow coming from the lateral tube and exiting out to the plant. It is this limited and paced flow that keeps the plant's root zone perpetually wetted.

In the PC emitter there are two features that limit the flow, the orifice between the top and bottom chambers, and the channel that is the flow path from the bottom chamber to the exit. For both the orifice and the channel, the width and height are relatively small compared to the length, and thus the flow through them can be described using the Darcy-Weisbach equation:

$$\Delta P = P_{in} - P_{out} = \frac{1}{2}\rho\frac{Q^2}{A^2}\frac{fL}{D_h} \qquad [1]$$

where ΔP is the change in pressure from entry to exit, ρ is the density of the fluid, Q is the volumetric flow rate, L is the length from entry to exit and A is the cross sectional area. D_h is the wet radius and is given by

$$D_h = \frac{4A}{Perimeter} \qquad [2]$$

and f is the friction factor, which for laminar flow, $Re < 4000$, is given by

$$f = \frac{64}{Re} \qquad [3]$$

For turbulent flow, $Re > 4000$, the Colebrook equation [24] can be solved iteratively to obtain f:

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{\epsilon}{3.7D_h} + \frac{2.51}{Re\sqrt{f}}\right) \qquad [4]$$

where ϵ is the roughness height.

It should be noted that the effective length of the channel changes depending on the deflection of the membrane. The length of channel can vary from just greater than zero, right as the membrane touches the inner edge of the lands, to the length of the lands, when the membrane is deflected to the point it touches from the inner to the outer edge of the lands.

2.3.2. Pressure Compensation

As is evident by the name, pressure-compensating emitters give a steady flow over a range of incoming fluid pressures from the lateral line. Figure 2-7 shows the behavior of the current emitter design in black and the desired behavior in red. The pressure compensating regime of the Jain 8L/hr dripper [25], highlighted in the black box. The activation pressure is the pressure at which the PC behavior begins. Below in Fig 2-7, it is apparent that the current design's activation pressure is around 1.5 bar.

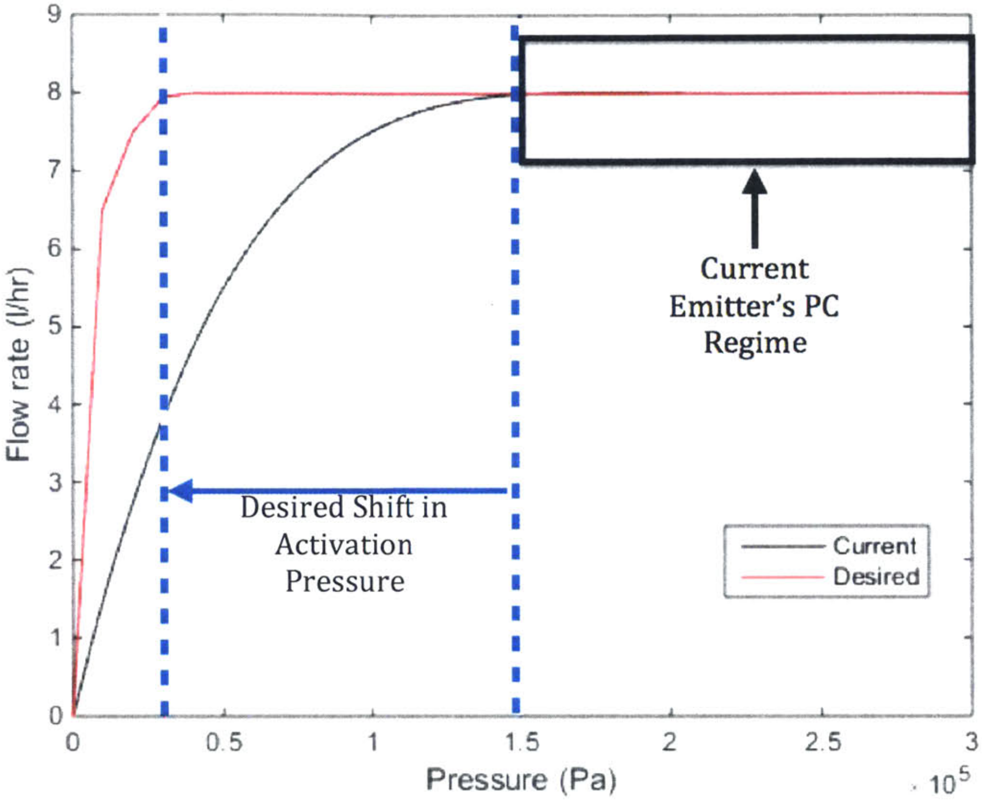


Figure 2-7: PC Behavior of Current and Desired Emitter Design

PC behavior is important in drip systems where drippers at different locations on the field experience different pressures, or when the input pressure to the system is not a constant pressure source, such as a pulsating pump or a direct drive solar pump; If a solar pump does not have a battery buffer or power electronics to stabilize the voltage from the panels to the pump, then water from the pump will flow in an unsteady manner, reflecting the instantaneous irradiance on the panels.

The reason that PC behavior is desirable is that if there is uniform emission from all the drippers in a given field, the yield from that field will be greater because no individual plants will be receiving too much or too little water. There are two factors to uniform emission across a field. The first part is dependent solely on the PC dripper's performance. Karmeli [26] characterizes the flow through an emitter as

$$Q = kh^x \qquad [5]$$

where Q = emitter flow rate, k = constant of proportionality, h = pressure head at the emitter, and x = emitter discharge exponent. The constant of proportionality, k, contains variables including the emitter geometry and the acceleration of gravity. The emitter discharge exponent, x, is what characterizes whether the emitter is PC or not. An emitter with a discharge exponent less than 0.5 is pressure compensating in nature [27]; an ideally pressure-compensating emitter would have a discharge exponent of zero.

The second factor includes not only the PC behavior of each individual emitter, which accounts for factors such as elevation changes throughout the field and lateral line friction, but also for variations in emitter manufacturing and emitter clogging. Wilcox and Swailes [28] first presented the statistical uniformity coefficient in 1947 to describe the uniformity of the emissions of sprinklers in an orchard. They defined the statistical uniformity coefficient, U_s, as a percentage as

$$U_s = 100\left(1 - \frac{S_y}{\bar{y}}\right) \qquad [6]$$

where S_y is the standard deviation of irrigation depth and $\bar{y}$ is the mean depth of water applied. It is generally accepted that a U_s of 90% or higher is deemed excellent; 80-90%, very good; 70-80%, fair; 60-70%, poor and below 60% is unacceptable. Thus, even if there existed an emitter with a discharge exponent of zero, it is still possible that the statistical uniformity coefficient could be less than %100 due to manufacturing variations or clogging.

The mechanism within the emitter that is responsible for the pressure compensating behavior is the deflection of the membrane into the channel. With an increasing pressure differential across the membrane, there is an effective lengthening of the channel as the membrane covers and then dips into the channel from the inner edge of the lands radially outward; this in turn gives an increasing perimeter of the cross-section of the channel as the membrane and a decrease in the area of the cross-section of the channel dips further into the channel. It is the balance between these three parameters - the effective length, cross-sectional perimeter and area - that produce the PC behavior in the emitter.

The membrane deflects in shear into the channel. This analysis was derived by Pulkit Shamsherry and is included to give insight to how PC drippers behave. Assuming that only a small section of the membrane shears, the deflection, w_{shear}, can be approximated by the shearing deformation of a simply supported thick beam, which can be modeled by

$$w_{shear} = \frac{3}{5}\frac{(P_1 - P_L)LW^2}{GA_b}\left(\frac{x}{W} - \frac{x^2}{W^2} - \frac{2}{(\lambda W)^2}\left(1 - \frac{\cosh\left(\lambda x - \lambda\frac{W}{2}\right)}{\cosh\left(\lambda\frac{W}{2}\right)}\right)\right) \qquad [7]$$

where w is the channel width, L is the effective channel length, G is the shear modulus, A_b is the cross-sectional area of the beam, x is the position of interest along the beam in the x-direction, E is the Young modulus, I is the moment of inertia and

[8]

$$\lambda^2 = \frac{\beta}{\alpha}\,;\alpha = \frac{B_0}{A_0} - A_0\,;\beta = \frac{GA_bC_0}{EIA_0}$$

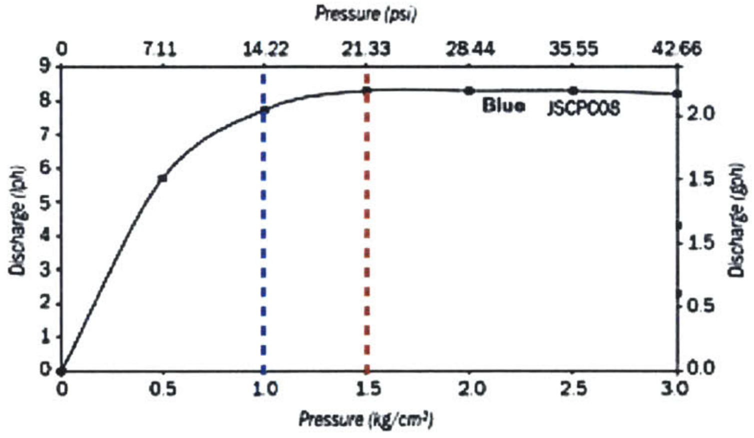
$$A_0 = \cosh\left(\frac{1}{2}\right) - 12\left(\cosh\left(\frac{1}{2}\right) - 2\sinh\left(\frac{1}{2}\right)\right) \qquad [9]$$

$$B_0 = \cosh^2\left(\frac{1}{2}\right) + 6(\sinh(1) + 1) - 24\cosh\left(\frac{1}{2}\right)\left(\cosh\left(\frac{1}{2}\right) - 2\sinh\left(\frac{1}{2}\right)\right) \qquad [10]$$

$$C_0 = \cosh^2\left(\frac{1}{2}\right) + \left(\frac{1}{2}\right)(\sinh(1) + 1) - 4\cosh\left(\frac{1}{2}\right)\sinh\left(\frac{1}{2}\right) \qquad [11]$$

2.3.3. Activation Pressure

For the purpose of modeling the system, activation pressure is defined here as the pressure at which the membrane touches the inner edge of the land, making the only flow path from the bottom chamber to the exit through the channel. Activation pressure is the beginning of the pressure compensating range. It should be noted that companies publish their "activation pressures" as slightly before the actual beginning of the PC range. For instance, Jain irrigation declares that the J-SC-PC Plus Emitter, whose PC behavior is shown below in Fig 2-8, has an activation pressure of 1.0 bar (the blue dashed line), but in reality and for the purposes of this thesis, the activation pressure is at 1.5 bar (the red dashed line), because after that point, the same flow rate is maintained with increasing pressure.



Note: Tested under standard test conditions.

Figure 2-8: PC Behavior of Jain J-SC-PC Plus Emitter with Stated and Real Activation Pressures Highlighted

Image Source: http://www.jains.com/

To parametrically model the activation pressure in an emitter, the membrane is modeled as a simply-supported plate with loading due to the pressure distribution shown below in Fig 2-9.

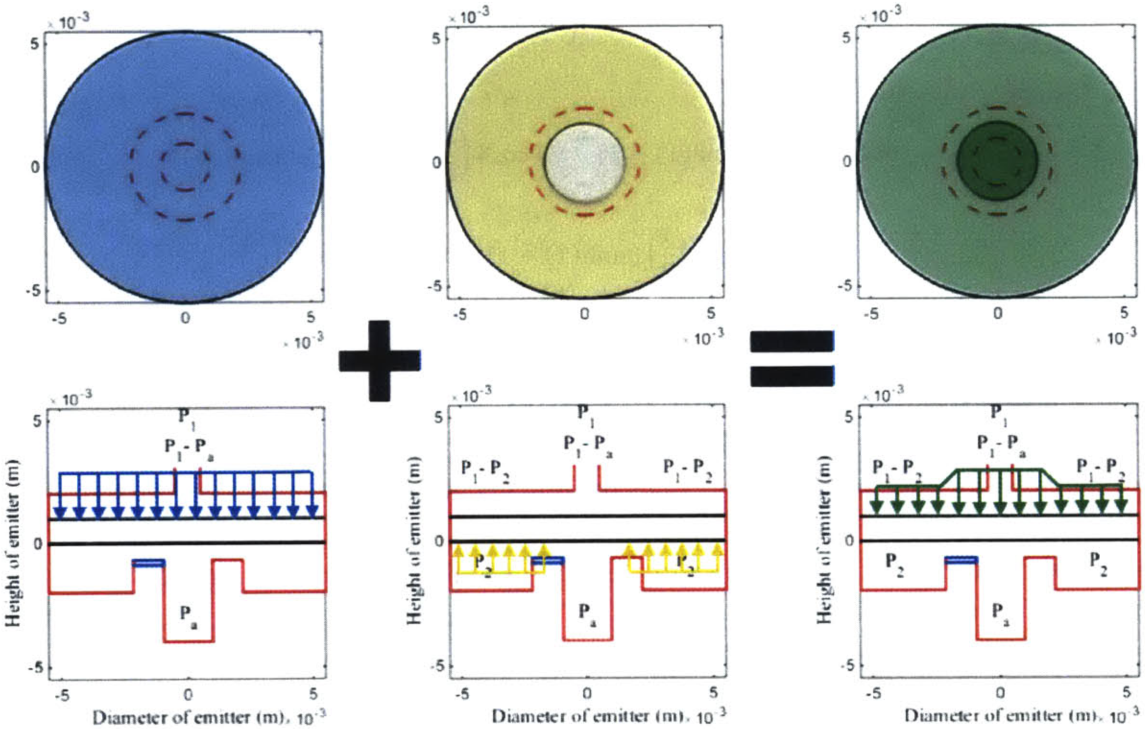


Fig 2-9: Loading of Membrane; [a-Left] Loading from Incoming Pressure; [b-Center] Loading from Chamber below Membrane; [c-Right] Total Loading

The deflection due to the loading shown in Fig 2-9 c) can be calculated by superpositioning the deflection of a circular plate with uniform loading, as shown in Fig 2-9 a), and one with annular loading as shown in Fig 2-9 b). The deflection can be modeled by:

1) Deflection of circular plate with uniform loading, $w_{uniform}$, is given by:

$$w_{uniform} = (P_1 - P_a)\frac{r_m^4}{64D}\left(1 - \left(\frac{r}{r_m}\right)^2\right)\left(\frac{5+\nu}{1+\nu} - \left(\frac{r}{r_m}\right)^2\right) \qquad [12]$$

Where P_1 is the pressure from the top chamber, P_a is atmospheric pressure, r_m is the radius of the membrane, D is the membrane stiffness, r is the radial location of interest on the membrane increasing radially outward, and ν is the Poisson ratio.

2) Deflection of circular plate with annular loading, $w_{annular}$, is given by:

[13]

$$w_{annular} = -(P_2 - P_a)\frac{r_m^4}{2D}\left(\frac{L_{17}}{1+\nu} - 2L_{11}\right) + \left(\frac{(P_2 - P_a)r_m^2 L_{17}\, r^2}{2D(1+\nu)}\right) - \frac{(P_2 - P_a)r^4 G_{11}}{D}$$

Where P_2 is the pressure in the bottom chamber and:

For $r < r_p$, where r_p is the radius of half way between the inner edge and outer edge of the land,

$$G_{11} = 0 \tag{14}$$

For $r > r_p$,

$$G_{11} = \frac{1}{64}\left(1 + 4\left(\frac{r_p}{r}\right)^2 - 5\left(\frac{r_p}{r}\right)^4 - 4\left(\frac{r_p}{r}\right)^2\left(2 + \left(\frac{r_p}{r}\right)^2\right)\log\left(\frac{r}{r_p}\right)\right) \tag{15}$$

For all r,

$$L_{11} = \frac{1}{64}\left(1 + 4\left(\frac{r_p}{r_m}\right)^2 - 5\left(\frac{r_p}{r_m}\right)^4 - 4\left(\frac{r_p}{r_m}\right)^2\left(2 + \left(\frac{r_p}{r_m}\right)^2\right)\log\left(\frac{r_m}{r_p}\right)\right) \tag{16}$$

$$L_{17} = \frac{1}{4}\left(1 - \frac{1-\nu}{4}\left(1 - \left(\frac{r_p}{r_m}\right)^4\right) - \left(\frac{r_p}{r_m}\right)^2\left(1 + (1+\nu)\log\frac{r_m}{r_p}\right)\right) \tag{17}$$

And

$$D = \frac{Et^3}{12(1-\nu^2)} \tag{18}$$

Where t is the thickness of the membrane.

Thus the total deflection from bending, $w_{annular}$, is given by:

$$w_{bending} = w_{annular} + w_{uniform} \tag{19}$$

Equations [12] – [19] are valid for small deflections ($w_{bending,max} < t$). However, once the deflection exceeds the thickness of the plate, it is necessary to use a correction factor to account for the stiffening due to the radial stress. Large deflections are calculated by using small deflection theory and then scaling the deflection to account for the radial stiffening based on the Timoshenko correction factor [29].

2.4. Analysis and Modeling

2.4.1. System Flow Model

The overall goal of developing a parametric model of the dripper is to ultimately lower the power required at the pump. In order to understand how the dripper design and resulting activation pressure affects the overall pumping power requirements, a flow model was developed. The flow model gives the pressure losses throughout the system and takes into account the following variables: the flow rate out of the emitters, the activation pressure, the size of the field, the number of and spacing between lateral lines, the length of lateral lines and spacing of the emitters on the line, the average incline in the field, the radius of the main line and the radius of the lateral line.

The flow model also takes into account the losses across the filter, P_{filter}. For this modeling purpose, the Jain Super-Flow Screen Filter with 100 micron mesh and a rated 7 m^3/hr was chosen [30] and the pressure losses were calculated using an interpolated equation for the pressure loss as a function of flow rate from Fig 2-10.

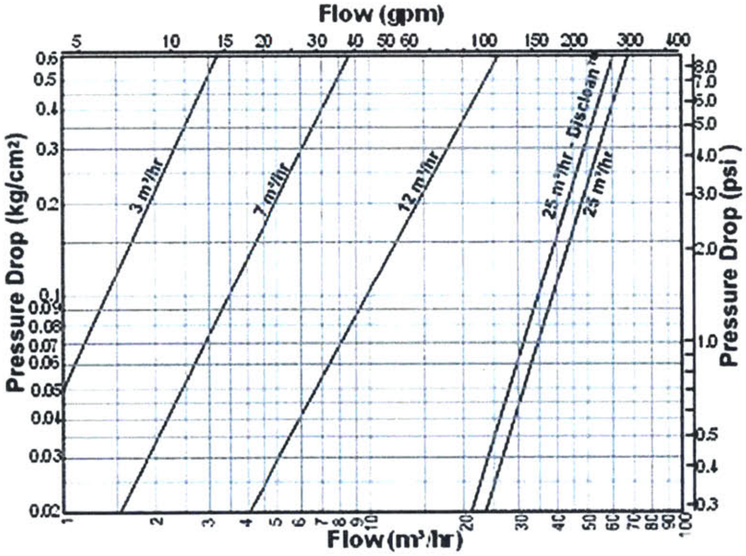


Figure 2-10: Pressure Drop for Jain Super Flow Filter

Image Source: http://www.jains.com/

The losses through an individual lateral line are calculated by iteratively summing the pressure losses from the last dripper on the line (dripper #1), which requires at least the activation pressure to function, up to the first dripper on the line (dripper #n), closest to the main pipe. So for a drip line with n drippers, the loss in the lateral line, $P_{lateral}$, is calculated iteratively using Eq [1], the Darcy-Weissbach equation, like so:

$$P_{2,d} - P_{1,d} = \frac{1}{2}\rho \frac{Q_{1,d}^2}{A_l^2} \frac{f L_{spacing,d}}{D_l} \tag{20}$$

$$P_{3,d} - P_{2,d} = \frac{1}{2}\rho \frac{Q_{2,d}^2}{A_l^2} \frac{f L_{spacing,d}}{D_l} \tag{21}$$

$$P_{n+1,d} - P_{n,d} = \frac{1}{2}\rho \frac{Q_{n,d}^2}{A_l^2} \frac{f L_{spacing,d}}{D_l} \tag{22}$$

$$P_{n+1,d} - P_{1,d} = \sum_{i=1}^{n} \frac{1}{2}\rho \frac{Q_{i,d}^2}{A_l^2} \frac{f L_{spacing,d}}{D_l} = P_{lateral} \tag{23}$$

Where $L_{spacing,d}$ is the spacing between drippers, A_l is the cross-sectional area of the lateral line, D_l is the diameter of the lateral line, $P_{n,d}$ is the pressure at the n^th^ dripper, $Q_{n,d}$ is the flow rate out of the n^th^ dripper and is calculated by

$$Q_{i,d} = i * Q_{1,d}. \tag{24}$$

The losses through the main pipe are similarly calculated by iteratively summing up the losses from the lateral line farthest from the pump (lateral line #1) to the lateral line closest to the pump (lateral line #m). So for a field with m lateral lines, the pressure loss through the main pipe, P_{main}, is found using Darcy-Weisbach, Eq [1], and the total flow per row, Eq [24], like so:

$$P_{m,r} - P_{1,r} = \sum_{i=1}^{m-1} \frac{1}{2}\rho \frac{Q_{i,r}^2}{A_{main}^2} \frac{f L_{spacing,r}}{D_{main}} = P_{main} \tag{25}$$

Where $L_{spacing,r}$ is the spacing between laterals, A_{main} is the cross-sectional area of the main line, D_{main} is the diameter of the main line, $P_{m,r}$ is the pressure at the entrance to the m^th^ row, $Q_{m,r}$ is the flow rate out at the start of the m^th^ row and is calculated by

$$Q_{i,r} = i * Q_{1,r} = i * n * Q_{1,d} \tag{26}$$

The total flow through the system is

$$Q_{total} = m * Q_{1,r} \tag{27}$$

Thus the total losses through the system are

$$P_{total} = P_{filter} + P_{main} + P_{lateral} + P_{act} \quad [28]$$

Where P_{act} is the activation pressure for the emitter. Thus the total power needed to move the water through the system is

$$Power_{total} = P_{total} * Q_{total} \quad [29]$$

When discussing the power needed for a pump, the total pressure needed at the pump is the sum of power to move the water through the system plus the power needed to draw the water from the ground. Considering a situation using surface water next to the pump, the total power of the pump equals the total power for the system.

Consider a square one acre field with a 1° incline in the direction of the lateral tubes, with a flow rate of 20L/hr at each emitter. If each lateral tube has a diameter of 2.5cm, the diameter of the main line is 14 cm, the spacing between each emitter is 50 cm and the spacing between each lateral tube is 1m, then the losses throughout the tubing and spine require a pressure of approximately 0.3 bar of pressure at the pump outlet to achieve a pressure of 0.1 bar at the last dripper, when delivering the peak flow of 20L/hr. Below in Fig 2-11, the pressure losses are shown along a single lateral tube. Figure 2-12 shows the pressure loss along the spine. Note that the diameter of the spine is much larger than the diameter of the tube.

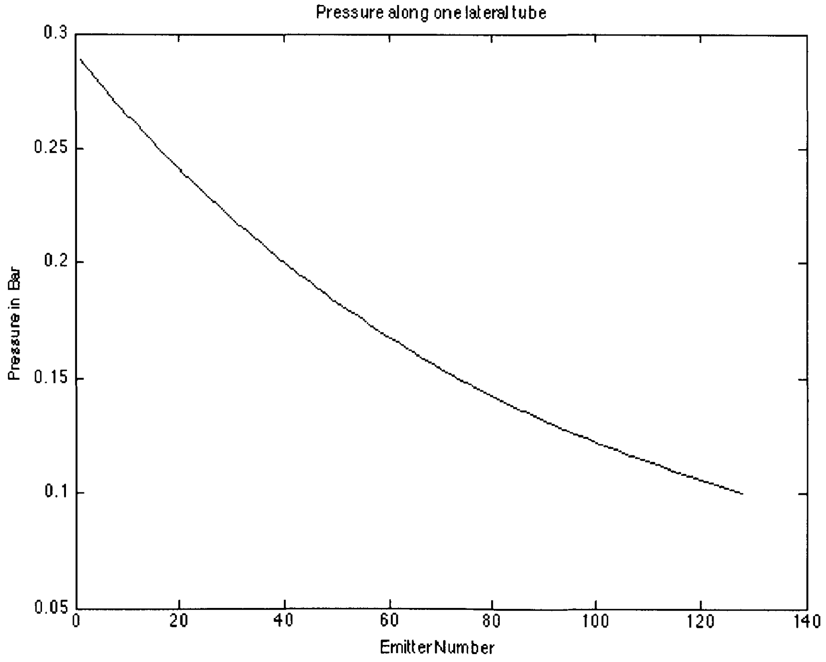


Figure 2-11: Pressure Losses along Lateral Tube

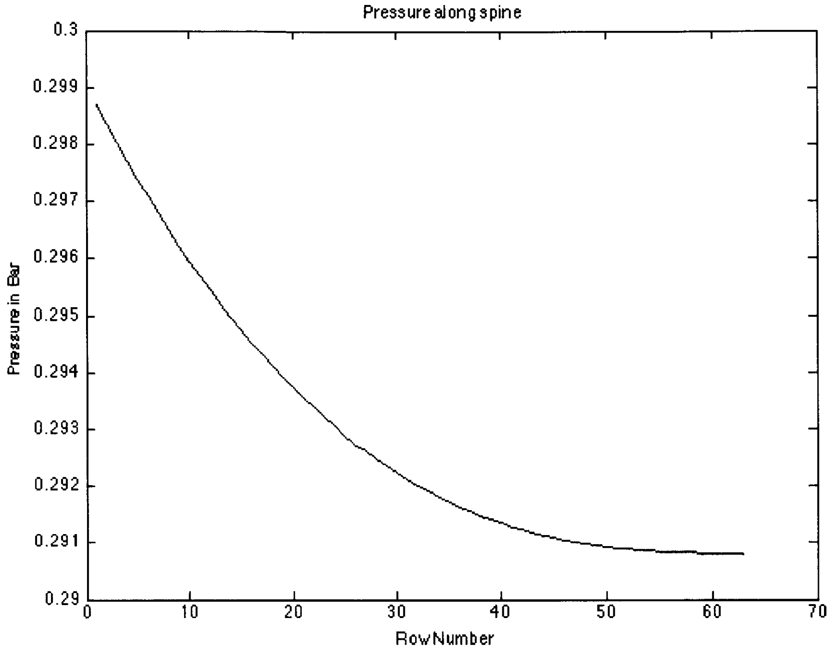


Figure 2-12: Pressure Losses along the Main Tube

2.4.2. Activation Pressure

The activation pressure is defined as the pressure at which the membrane first touches the inner edge of the lands and pressure-compensating behavior commences. Due to the loading on the membrane, described by Eq 19 and shown in Fig 2-9, it is essential to know the pressures in the chamber above the membrane, P_1, and in the chamber below the membrane, P_2. The pressure in the lower chamber, P_2, can be obtained by

$$P_2 = P_1 - \frac{1}{2}\rho V^2 \kappa \qquad [30]$$

Where V is the fluid velocity and κ is the dimensionless resistance factor. This equation is a coupled system: the lower chamber pressure, P_2, is dependent on the flow rate and the flow rate is dependent on the membrane deformation which is in turn dependent on P_2. This leads to a highly coupled problem, which should be solved iteratively until P_2 converges, i.e. the error from the last step P_2 to the next one is within the tolerance of 1%.

In order to determine the coefficient of resistance through the orifice on the Jain 8 L/hr PC emitter, an experiment was conducted. The bottom of the dripper was removed and the membrane was replaced with a solid disk, as shown in Fig 2-13. The orifice remains the same as the original dimensions.

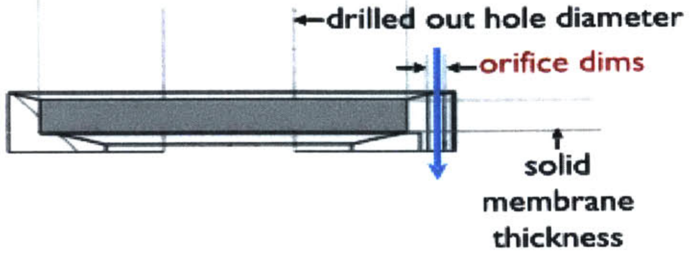


Figure 2-13: Modified Emitter Used to Determine Coefficient of Resistance

The flow through the modified emitter was then measured as a function of varying flow rate. The results are shown in Fig 2-14.

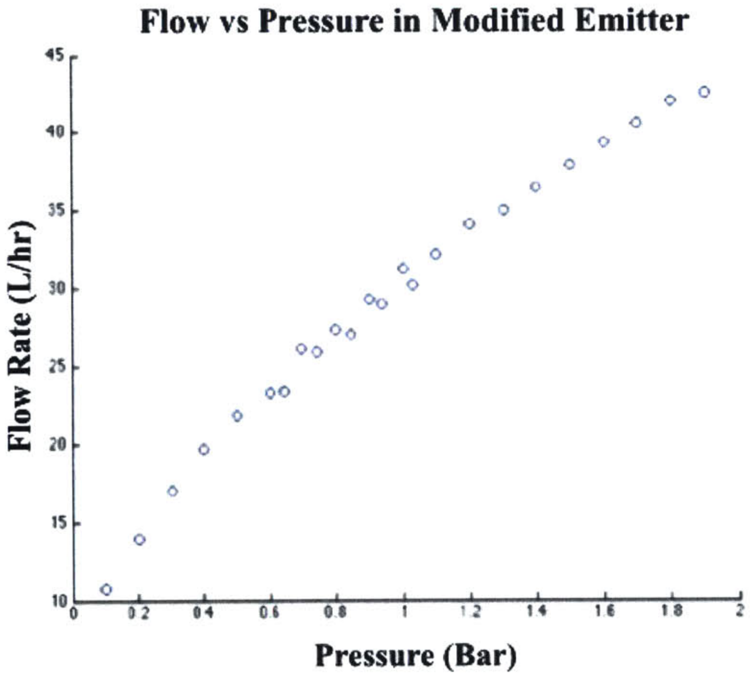


Figure 2-14: Flow vs Pressure of Modified Emitter

From Fig 2-14, the coefficient of resistance was estimated to be 0.94, which is shown in Fig 2-15. Thus, the orifice causes a pressure drop and the pressure of the fluid exiting the orifice was 94% of the pressure when entering the orifice. This coefficient of resistance is used in the following parametric study on the activation pressure.

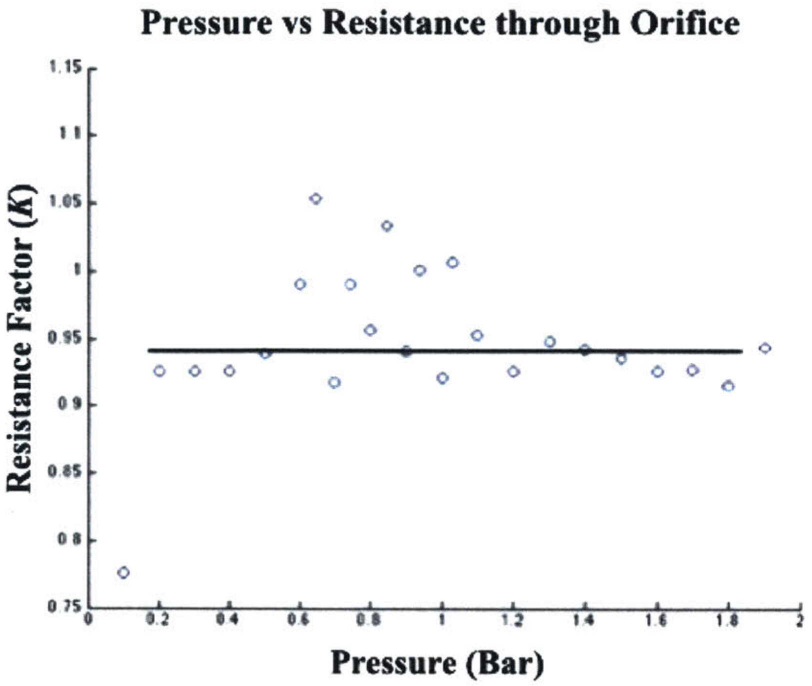


Figure 2-15: Estimation of Coefficient of Resistance through Orifice

The loading and deflection of the membrane are discussed in the theory section, and described by equations [12]-[19], using the Timoshenko correction factor for large deflections.

Each of the following parameters is changed individually to demonstrate the trends in the activation pressure of the 8 L/hr PC emitter: the membrane thickness, the Young's Modulus of the membrane, the radius of the membrane and the radius of the outlet. Note that for each parameter, the model is compared against the current design's measurement to validate this model; the model's activation pressure value at the known (current design's) parameters is shown in the tan box on Fig 2-16 through Fig 2-19, validating the model against the known activation pressure of 1.5 bar.

When the membrane thickness is increased, the activation pressure increases as shown in Fig 2-16. A good comparison between model and experiment has been observed for the thickness of 13 mm.

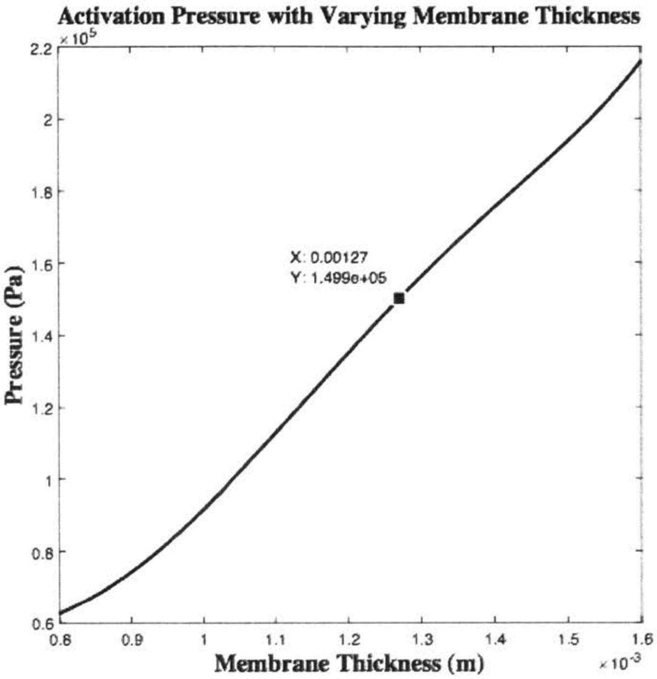


Figure 2-16: Activation Pressure for Varied Membrane Thickness

When the Young's Modulus is increased, the activation pressure increases as shown below in Fig 2-17. Note that only the range of silicone rubber is shown in this figure for comparison purpose. It reveals that the current model can well predict the activation pressure at the Young's Modulus of 3.8 GPa used in the experiment.

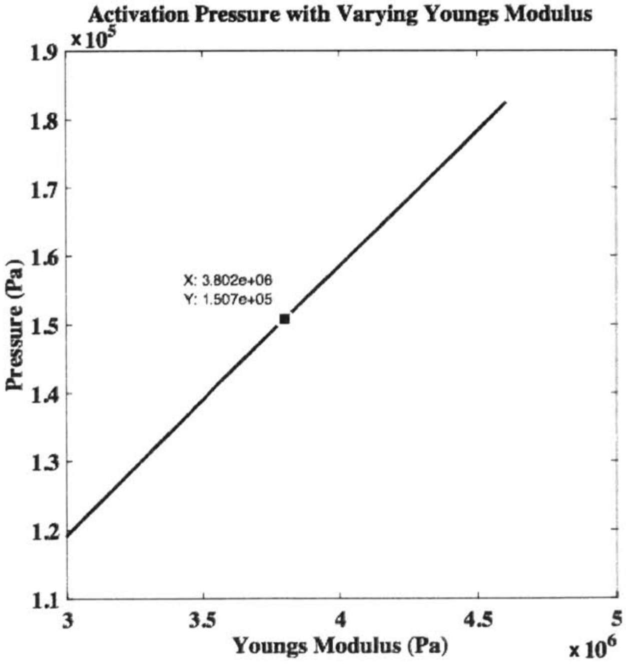


Figure 2-17: Activation Pressure for Varied Young's Modulus

When the membrane radius is increased, the activation pressure decreases as shown below in Fig 2-18. Again, for the membrane radius of 55 mm that is consistent with the experiment, the current model yields the correct activation pressure of 1.5 bar.

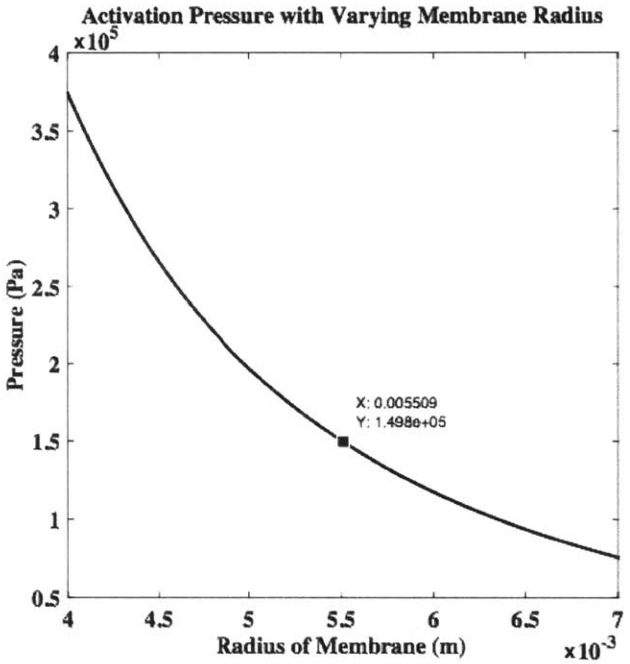


Figure 2-18: Activation Pressure for Varied Membrane Radius

At last, when the outlet radius is increased, the activation pressure decreases as shown below in Fig 2-19. This follows with the logic that the area of the annular loading from the chamber is decreased with increasing outlet radius. The experiment data for the outlet radius of 9.5 mm is marked in the graph, which can be well predicted by the model.

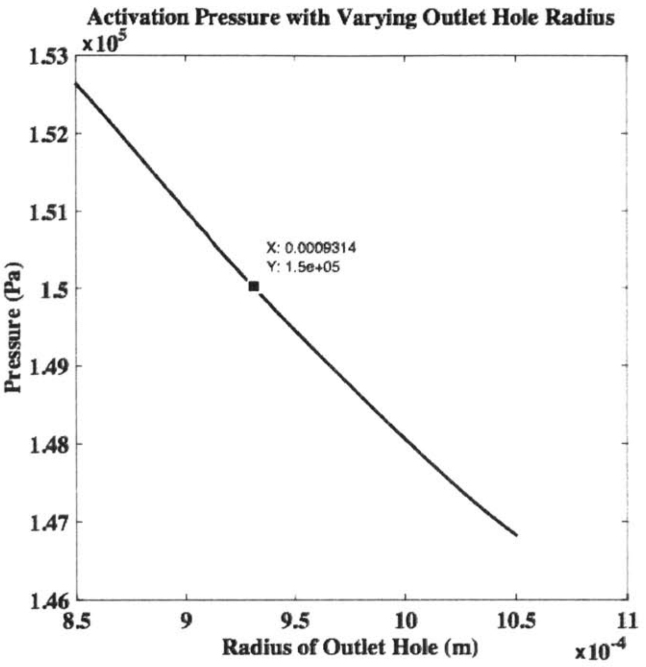
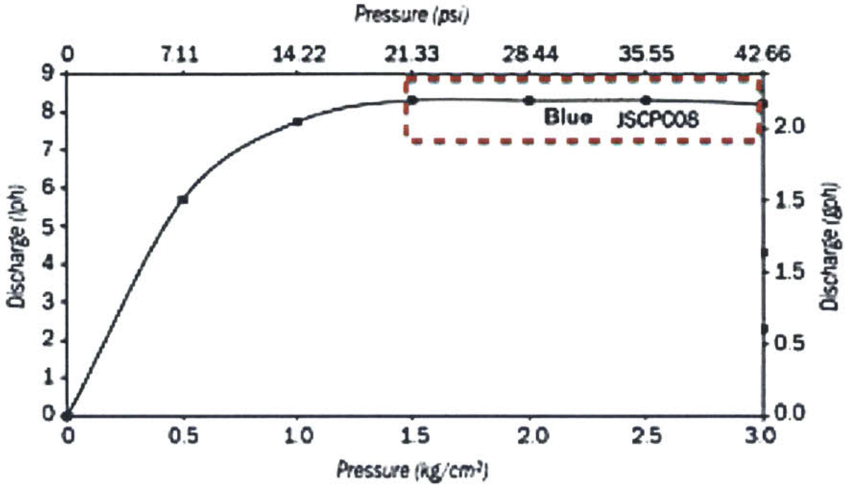


Figure 2-19: Activation Pressure for Varied Outlet Radius

This analysis is an essential design tool that can be used to guide new designs to achieve lower activation pressure based on the existing architecture, or explore new architectures with simpler principles. To summarize, a thinner softer and larger membrane and a larger outer diameter will help reduce the activation pressure.

2.4.3. Flow Limitation/Pressure Compensation

The pressure compensating behavior of the Jain 8L/hr PC emitter, highlighted below in Fig 2-20, is modeled and investigated in detail by Shamsherry, *et al.* [31]



Note: Tested under standard test conditions.

Figure 2-20: PC Region of Jain J-SC-PC Plus Emitter Highlighted

Image Source: http://www.jains.com/

The authors present how the PC behavior in the emitter is governed by the interaction between the section of the membrane over the channel and the dimensions of the channel itself.

There is one important tradeoff to understand with regards to the flow from the bottom chamber through the channel to the outlet. Examine a simple version of the Darcy-Weissbach equation to describe the flow through the channel

$$\Delta P = Q^2 \kappa \qquad [31]$$

Where κ is the general resistance to flow through the channel. It is apparent that for a given ΔP, if the resistance to flow is lowered by, let's say, decreasing the thickness of the membrane which in turn lowers the activation pressure, then the Q^2 term must increase proportionally; this means that when the activation pressure is lowered and it affects the resistance through the channel, then the flow rate through the channel must also change. This requires further exploration.

2.4.4. Summary

The combination of the analysis presented in section 2.4.2 on the activation pressure and the analysis presented by Shamsherry, *et al*. [31] yields a parametric model for the behavior of the emitter. Figure 2-21 shows the comparison in the pressure versus flow rate graphs between the model and Jains experimentally found values. The difference is within 5%.

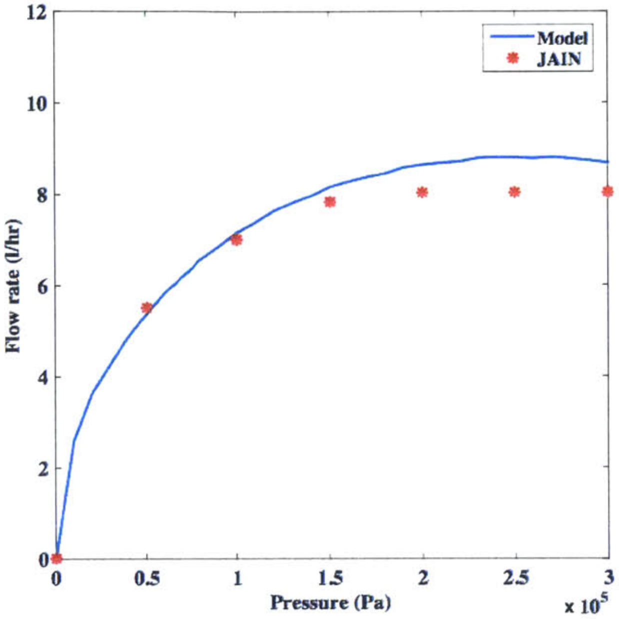


Figure 2-21: Model Validation against Jain 8L/hr PC Emitter

The parametric sensitivity study on activation pressure reveals that the activation pressure can be reduced by decreasing membrane thickness, decreasing membrane Young's Modulus, increasing membrane radius, and decreasing outlet hole diameter, or of course by some combination of the above. The PC behavior is shown [31] be governed by the effective length, perimeter and area of the channel. The model is verified against Jain Irrigation's published data.

The main aim of the development of the mathematical model is to analytically understand the effect individual parameters have on the activation pressure and PC behavior. With this model, it is possible to analytically redesign the dripper by changing parameters individually or in combinations to achieve the lower activation pressure, while maintaining the PC behavior. This model is also essential in gaining a deep understanding into the mechanisms and necessary tradeoffs behind the desired flow-limiting and PC behavior; it is possible with this understanding to apply the principles from these mechanisms into a completely different dripper architecture.

3. Pump

3.1. Introduction

3.1.1. Motivation

Eastern India is made up of four states – Odisha, Bihar, West Bengal and Jharkhand - and one union territory – the Andaman and Nicobar Islands. In Eastern India and eastern Uttar Pradesh, there are over 31 million marginal sized (<1.25 acres) farms [32]. The vast majority of these farms have access to shallow groundwater (<10m) and currently use either a diesel pump to irrigate or don't irrigate at all [33] due to low electrification rates, as shown below in Fig 3-1.

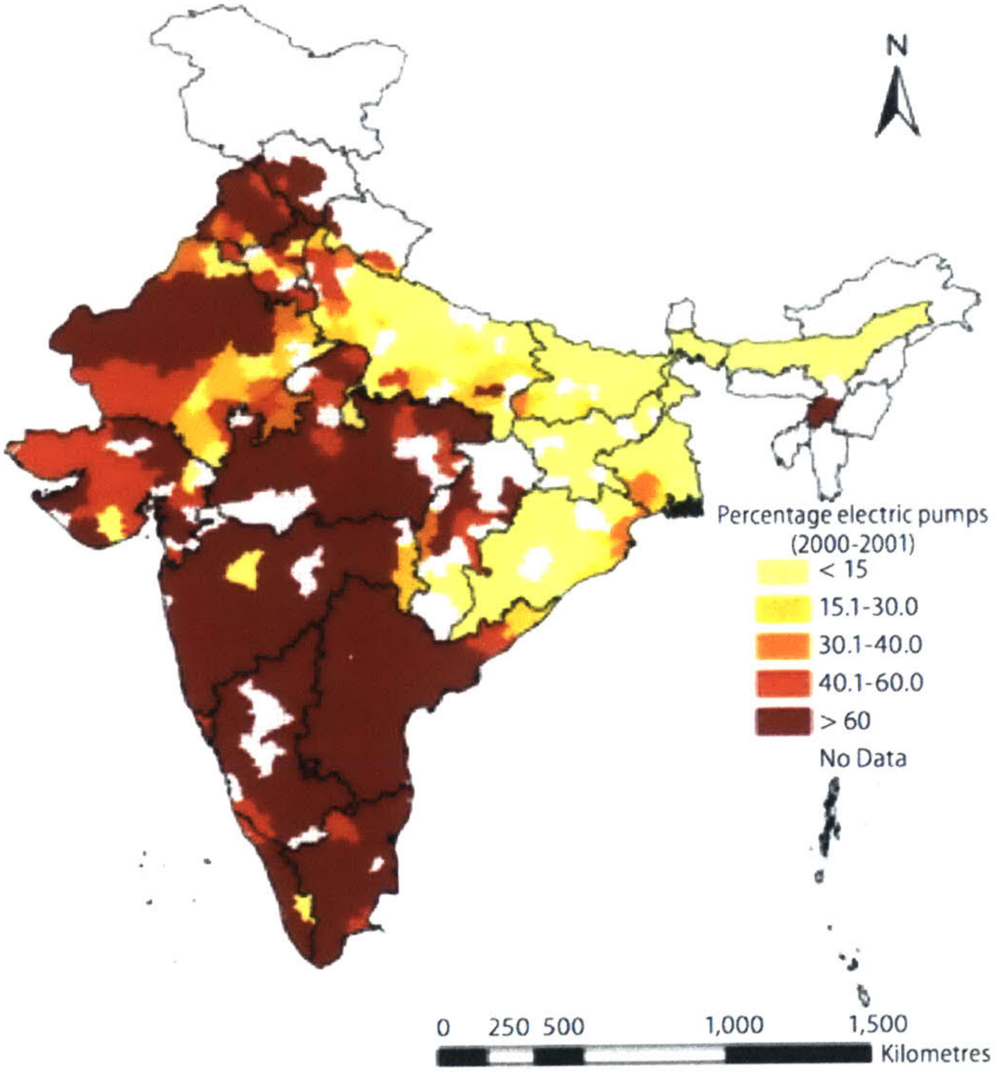


Figure 3-1: Percentage of Electric Pumps in Use [33]

The dependence on diesel pumps for irrigation in eastern India is detrimental both to the environment and to agricultural productivity. Eastern India, with its readily accessible and unstressed shallow groundwater should be the most productive region of India, but due to lack of electrification and prohibitive costs of diesel, farmers often either cultivate only during the monsoon season, or pay for diesel and cultivate during the winter season, but not the dry season. The fact that the price of diesel has risen 10 times faster than the price of agricultural outputs since 1990 [34] is indicative of the increasingly dire energy-irrigation situation farmers in Eastern India have been facing over the past 15 years.

Currently, diesel costs around 55 INR/L and diesel pumps cost anywhere between 6,000 – 90,000 INR, with a lifetime of 3-6 years. It has been estimated that the cost of moving water from a 5 hp, 40% efficient diesel pump at 10m of head is 1.13INR/m3 [35]; however this estimate was made at a time when diesel cost only 32 INR/L, and the 5hp pump is much more efficient than a pump that would be used on a small plot. In this thesis, it is shown that is possible to make a 35% efficient 1/3 hp pump that is the cornerstone of a solar-powered irrigation system tailored to marginal holding farmers in eastern India that can be sold for 30,000 INR. This economically scalable system has the potential to allow some 30 million marginal holding farmers in Eastern India to switch from no or diesel powered irrigation to sustainable, year-round solar-powered irrigation.

There are currently no solar-powered pumps on the market for marginal sized farms drawing from shallow groundwater that individual farmers can own. There are larger solar pumps that could be owned by larger land holding farmers or by collections of farmers, but the fact is that India is a country of small farms. India is home to a quarter of the world's 570 million farms and has an average farm size of 1.3 ha [36]. Luckily, small-scale irrigation can be a boon to national security as it has been shown that small farms can be up to 15 times more efficient in terms of energy inputs for the same crop output than large farms [37].

While the value proposition of switching from no irrigation or diesel-powered to solar-powered irrigation is straightforward (cultivating outside of the monsoon season and no recurring diesel costs, respectively), that of switching from electric pumps attached to the grid to solar is a bit more complicated. In parts of the country with access to the grid, the electricity supply is often poor or unreliable. The poor quality is a problem because frequent tripping and voltage fluctuations lead to increased operation costs, such as the repair or replacement of burnt out pump motors [35]. The unreliability is a problem, because in peak heat, going for days at a time without water (possibly due to blackouts) can destroy an entire crop.

The origin of this overstrained and unreliable grid dates back to the Green Revolution. During this time, in an effort to increase agricultural productivity, the government subsidized discounted and then free (or unmetered) electricity to farmers.

While these power subsidies did lead to increased agricultural output, it also led to India being dependent on groundwater, as shown below in Fig 3-2.

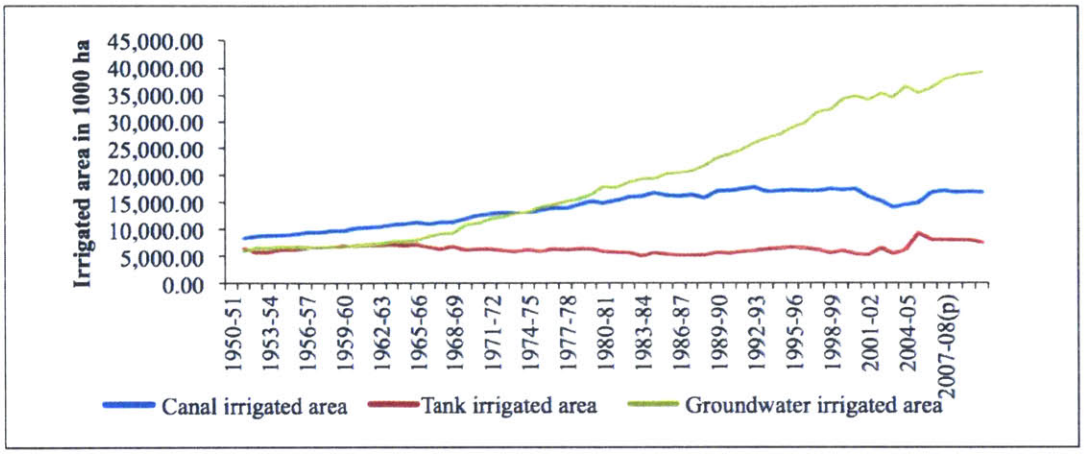


Figure 3-2: Area in India Irrigated by Different Sources from 1950 to 2008 [35]

Over the past few decades, the dependence on electricity for groundwater has increased, partially due to the lowering of the water table from overexploitation. This dependence on subsidized electricity is a topic that political candidates have repeatedly used, promising continued unmetered electricity, to garner the rural vote. However, this comes at great cost to India as a nation. The World Bank estimated in 2001 that the agricultural electricity subsidies in India total to approximately "US $6 billion a year – equivalent to about 25 percent of India's fiscal deficit, twice the annual public spending on health or rural development, and two and a half times the yearly expenditure on irrigation" [38]. The subsidy system also enables major power-theft, to the tune of $160 million USD/year [38], because the utilities hide these losses under the garb of unmetered agricultural power supply.

Bringing affordable, solar-powered irrigation to small acreage farmers in Eastern India will increase agricultural productivity, reduce poverty and even lessen the cycle of yearly flooding [39]. Additionally, irrigation is a perfect application of solar-power, because when there is stronger sunlight, the crops need more water, but the pump also receives more power and is able to move more water by running for a longer period of time; and when there is less sunlight, less water is needed and the pump runs less.

3.1.2. Stakeholder Analysis

The stakeholders discussed below are divided up into primary and secondary stakeholders. Again, primary stakeholders are defined as those who are directly affected by and who directly influence the project, whereas secondary stakeholders are defined as those who are indirectly affected. The primary stakeholders considered are the farmers who would use the solar-powered irrigation system, agencies within the state and federal government, and solar panel manufacturers. The secondary stakeholders considered are NGOs, oil companies, and diesel pump companies.

3.1.2.1. Primary Stakeholders

The farmers who currently use a diesel pump or no pump at all would see clear benefits from switching to a solar-powered irrigation system. Those currently using diesel would no longer have to pay the recurring costs of diesel. Those who do not use a pump at all would be able to irrigate, and thus farm outside of the monsoon season, for the first time. Farmers who currently use electric pumps attached to the grid and pay for the electricity would no longer incur that cost. Those using electric pumps attached to the grid for free would no longer be subject to the odd hours electricity is let through and unpredictable nature of the grid. For instance, the world's largest blackout occurred in India in July 2012 and affected 700 million people [40]; one of the reasons for the blackout was that a delayed monsoon season "increased farmers' demand for irrigation-related electricity while reducing the water available for hydroelectricity" [40].

Since agriculture, and primarily these electric pumps, account for over 20% of the load on the grid, it follows that the Indian power-sector is an interested party in the development and spread of solar powered pumps. When India became independent, the country inherited a relatively young electricity sector that was comprised mostly of small private companies located in a small number of urban areas. In order to close the gap between the urban and rural areas, the Indian government decided to nationalize the energy sector and gave state governments permission to set local electricity prices [41]. Even though the state-owned utilities provided good results, the state governments have implemented policies that have had adverse effects on the sector up until today. Free electricity to the agricultural sector is one of the perverse effects. It has been an effective and common tool for politicians to use to garner support from voters in rural areas. Unfortunately, free electricity to the agricultural sector has put additional pressure on a system that is already weak and vulnerable. For example, the public utility in state of Jharkhand makes a loss of $200 million annually [42].

Another clearly interested party entangled with the utility companies is that of companies that manufacture and sell solar panels. Obviously the more solar-powered pumps sold, the more solar panels sold. India is trying to encourage the adoption of solar power across many sectors; some states offer up to 90% subsidies for residents to purchase solar panels [43]. However, this has had a slightly perverse effect. In recent research funded by the Tata Trust, these subsidies have had the negative effect of increasing the absolute prices of solar panels. The solar industry has attempted to maximize its profits by inflating the prices for their products. Given the rise of prices and the need to compensate for the higher costs, users of the solar pumps have overused the pumps and created a situation of over-extraction of local ground water. Unless over-extraction of groundwater and over-irrigation are not pressing issues in the area where the solar pumps will be installed, it would certainly be interesting to explore the "solar buyback provision" policy that has been implemented in Karantaka. Farmers that generate excess amount of electricity could use it to sell it to the utilities. For example, a farmer with a 10kWp solar power system (10 kilowatts at peak performance or full sun) can earn nearly 50,000 rupees a year (800USD) selling back excess power [43]. Considering that the utilities have struggled with having sufficient resources on the system to provide electricity and limiting losses on the transmission lines, selling a portion of the generated electricity could certainly be interesting to both farmers and utilities. The farmers can indeed use some of the revenues from excess generation to offset the initial cost of the pump.

3.1.2.2. Secondary Stakeholders

Throughout the exploration of this project, the most useful and enthusiastic players have been those at NGOs. The reason is that while they may not directly benefit from solar-powered pumps gaining a strong foothold in India, they can see how it will benefit the farmers, the environment and their country. The NGOs, especially Pradan, who have consulted on the contextual side of this project and made the pilot study possible, are invested in the success of solar-power spreading through India and in farmers being able to access irrigation. They are affected directly only in the way that their mission of helping the poor to lift themselves out of poverty is being furthered.

It would be narrow-minded not to consider the possible adverse effects of the success of solar-powered irrigation. One adverse effect could be overdraw of the aquifers, which is discussed above in section 3.1.2.1. Another possible adverse effect could be the decline in sales by diesel pump manufacturers and oil companies, which could in turn affect the Indian economy or cause layoffs.

3.1.3. Method

The method for approaching this complex problem includes contextual investigation coupled with analytical work to set the desired design specifications, followed by iterative prototyping, testing and optimization. The contextual research includes understanding who the stakeholders are, the market size, the daily life and circumstances of the end users, the prior art and where there is opportunity for disruption. The analytical work is described in sections 3.3 and 3.4. The prototype design and testing is described in sections 3.4 - 3.6. Two prototypes were then deployed as a pilot study in February 2015 in two villages in Jharkhand, India. The pilot study is ongoing.

3.2. Prior Art

Solar-powered pumps for small acreage farmers lies in the middle of two well explored spheres of research. The first is that of pump design. The second is that of agriculture in the developing world. The fact of the matter is that there are many skilled researchers who work within one of these spheres, but very few who work in both. It is necessary to have highly technical resources and skills, and access to contextual understanding through literature research, a network of NGO and interested partners, and visits to the countryside to design a fitting solution for this sector.

The Indian government has been a supporter of solar power and is aiming to become a global leader in solar power. It has launched the Jawaharlal Nehru National Solar Mission as part of its National Action Plan on Climate Change. As part of this initiative, the Ministry of New & Renewable Energy has established the Solar Pumping Program for Irrigation and Drinking Water. This program aims to wean farmers off the use of electric and diesel pumps and replace them with solar pumps. The target is for 100,000 solar water pumps to be installed by the end of 2015 and for one million to be installed by 2021 [44].

This goal is ambitious. The Indian government reports that as of 2014, less than 14,000 pumps had been installed [45]. The government plans to promote the use of solar pumps by subsidizing 30% of the cost. In response to government support, the large potential market, and the low number of solar pumps currently installed, there are a number of established companies that have been developing new solar water pumps and piloting them in India.

Currently, the leaders in solar-powered irrigation in India sell large installations and pumps that range from 1-5 hp. It is a rule of thumb that a solar powered pump costs 1 lakh INR (approximately $1570 USD) per hp [46]. The leaders in the market in India are Jain Irrigation, Rotomag, SunEdison and Claro Energy [47]. Jain Irrigation is the only of these to have a solar-powered pump that is under 1hp – the Jain Nano Pump; however, this pump is fit for deeper groundwater and smaller fields (i.e. lower flow rate) than our pump. At zero head, the Jain Nano delivers 0.2 L/sec, but its best efficiency point is at 30m head). Below in Table 3-1 four pumps currently on the market are compared with the pump described in this thesis. Two of the pumps are solar (both made by Rotomag, due to availability of information) and two are diesel powered. The Honda pump is newer and has a longer lifetime than the Taizhou pump; however the Taizhou pump is similar to the diesel pumps commonly found in eastern India. It is important to note that pumps of different rated hp can irrigate different amounts of land in a given time period. The price per year total is calculated by dividing the total price (including diesel use estimate multiplied by the lifetime for diesel pumps, and the price of electronics and solar panels for the solar pumps) by the expected lifetime.

Company and Model	**Rotomag RS1200 Submersible[48]**	**Rotomag MBP60 Surface[48]**	**Honda WX10K1A[49]**	**Taizhou, Nimbus 50KB[51]**	**Ours**
Type	Solar, Centrifugal, DC	Solar, Centrifugal, DC	Diesel, Centrifugal	Diesel	Solar, Centrifugal, DC
HP	1	2	1 [50]	3.4	1/3
Motor Capacity (W)	800	1500	N/A	N/A	285[53]
Panel/Plate Requirement (W)	1200	1800	N/A	N/A	300
PV voltage	110V	60V	N/A	N/A	24V
Max Total Head (m)	30	15	35	26	18
Max Discharge (L/hr)	12,000 (at 20m head)*	24,000 (at 10m head, 7.5hr day)*	8400	22,000	4680
Material	Stainless steel	Stainless Steel	Aluminum and Ceramic	Metal	Plastic
Size (cm)			33 x 23 x 30	53.5 x 42 x 51	25 x 11 x 11
Weight (kg)			6	27	4
Price (Pump Only) in Rs	75000	43000	29000	5400**[52]	9000
Price Panels (63 INR/W)	76000	114000	N/A	N/A	19000
Price Diesel/Yr/Acre	N/A	N/A	32000	48000	N/A
Lifetime	10	10	7	3	10
Price/yr Total	15100	15700	36000	50000	2800

*= with 3 times tracking on a sunny day with solar radiation on horizontal surface is 5.5 KWh/m^2/day

**=for orders of 100+

Table 3-1: Comparison of Varied Solar and Diesel Pumps

There is a clear opportunity for disruption of the market by designing a highly efficient, small, solar-powered irrigation system that is tailored to marginal holding farmers. The fact is that the lower the flow (and hp) of the pump, the more difficult it is to make a highly efficient pump. This is simply due to the ratio of volume of water being moved to surface area of the impeller and volute and thus frictional losses. This inherent difficulty is why it is essential to use highly technical analysis, as is shown below, to design the most efficient and fitting system possible.

3.3. Concept and Design Specifications

The following describes the design and analysis of a solar-powered irrigation system, primarily that of the DC centrifugal pump, fit for small-acreage farms with access to shallow groundwater; this means that the performance point that has been identified and designed for has daily flow fit for a one-acre farm size, drawing from shallow groundwater.

3.3.1. Flow rate

As previously stated, in Eastern India and eastern Uttar Pradesh, there are over 31 million marginal sized farms [32]. Table 3-2 below shows the percentage of farms under 0.5 ha in the five states according to the 2010-2011 Indian Agricultural Census [32].

State	Percentage of Plots <1.25 acre
Bihar	91.06%
Jharkhand	68.23%
Odisha	72.17%
West Bengal	82.16%
Uttar Pradesh	79.45%

Table 3-2: Percentage of Farms that are Less Than 1.25 Acres (0.5 Hectares)

The high percentage of marginal-sized (less than 0.5 ha or 1.25 acre) in these states makes a compelling case to design a pump with a flow rate at its best efficiency point (BEP) that is fit for a one-acre size plot. Through literature research and informal interviews with farmers and NGOs such as Pradan, it has been found that the water requirements for a one-acre plot in Eastern India vary between 8,000-20,000 L/day. At the chosen flow rate of 1L/sec, this means that the pump would need to run from between 2-5.5 hours on a given day with 5.5 kWh of global horizontal irradiance (GHI). However on days with greater solar irradiance, the batteries receive more energy and thus the pump can run for longer periods of time. A map of the GHI across India during May, the driest month of the year, is shown below in Fig 3-3. Note that the varied water requirements reflect variations amongst farms in the following factors: soil type, solar irradiation, humidity, crop type and stage of the crop's growth.

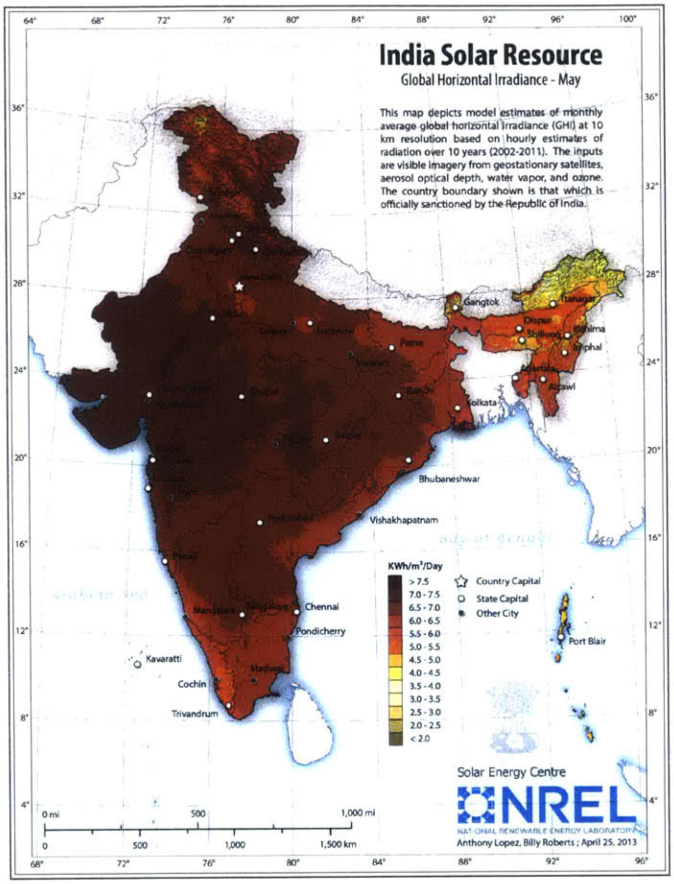


Figure 3-3: Global Horizontal Irradiance (GHI) for India during May, the Driest Month of the Year in East India [54]

3.3.2. Head

In order to determine the required head for the pump, it is essential to know the state of the groundwater in Eastern India Figure 3-4 shows the groundwater depth across India, with Eastern India and Eastern Uttar Pradesh highlighted, in the driest time of the year, right before the monsoon.

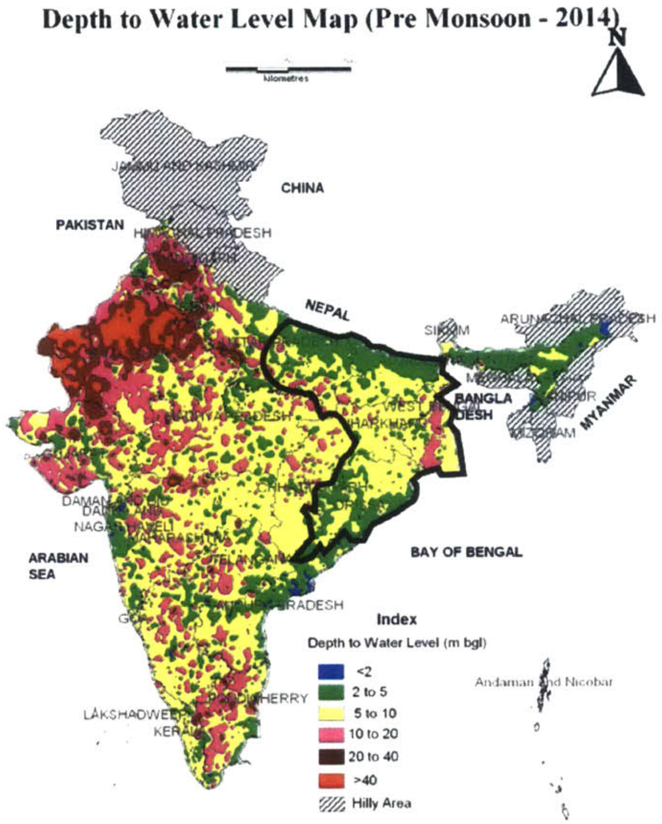


Figure 3-4: Water Table Depth in Driest Time of the year, Eastern India & Eastern UP Highlighted [55]

From Fig 3-4 it is apparent that the majority of the groundwater in Eastern India and Easter Uttar Pradesh is 10 m or shallower even at the driest time of the year. Taking into account the groundwater information from IMWI and discussions with NGOs operating in the area, it was decided that the pump should be able to efficiently move water at 7 to 12m of head.

3.3.3. Panel Requirements

The amount of solar panels is based on the power needed to output the water, and how efficiently the pump can do so. The following analysis was conducted by Kevin Simon and is included to fully understand the design process for the solar pump. Further detail can be found in Simon's thesis [56]. Equation [32] shows the energy balance between the electrical energy from the panels and the mechanical output of the pump

$$E_{panels} = \frac{Q_{daily} P}{\eta_{pump}} \tag{32}$$

Where η_{pump} is the efficiency of the pump. Equation [33] shows the relationship between the irradiance on the panels and the energy the panel sees

$$E_{panels} = GHI_{daily}\frac{w_{panel}}{1000} \qquad [33]$$

Where w_{panel} is the panel wattage. Combining equations [32] and [33], it is possible to find the minimum panel wattage to yield the desired flow and pressure as shown below in equation [34]

$$w_{panels} = \frac{1000 * Q_{daily} * P}{GHI_{daily} * \eta_{pump}} \qquad [33]$$

Given a 35% efficient pump and 5.5 kWh of GHI, Fig 3-5 shows the estimated panel requirements vs the daily flow rate for varied water depths of 7, 10 and 12m.

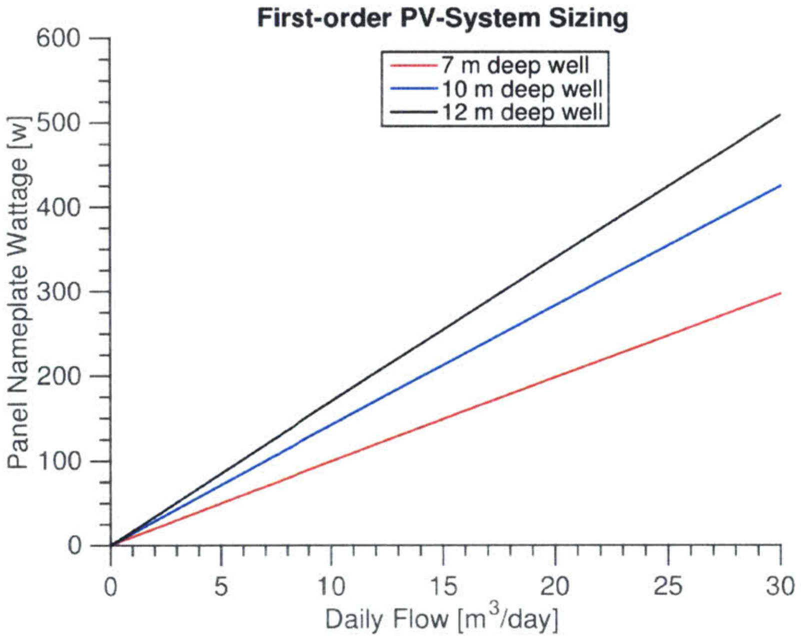


Figure 3-5: Panel Wattage vs Daily Flow for Varied Head

From this analysis, the design point of 10m of head giving 20,000L is shown to be possible with 300 W of solar panels.

3.3.4. Pump type

When selecting which type of pump is best fit for this application, it is important to keep both the functional requirements and practical requirements, such as cost, in mind. There are many types of pumps, but the main two categories are positive displacement pumps and centrifugal pumps. Positive displacement pumps, while inherently very efficient (up to 95%), are much more expensive than centrifugal pumps, because they require precision manufacturing.

Centrifugal pumps move water by converting rotational kinetic energy to the hydrodynamic energy of the water [57]. The part of the pump that is rotating and moves the water is the impeller, which is attached to the motor shaft. There are 3 types of flow through centrifugal pumps: axial, radial and mixed flow. The desired flow, and corresponding impeller geometry, is determined by the specific speed, which takes into account factors such as the desired pressure and head. Figure 3-6 below illustrates the correlation between specific speed and pump type and geometry.

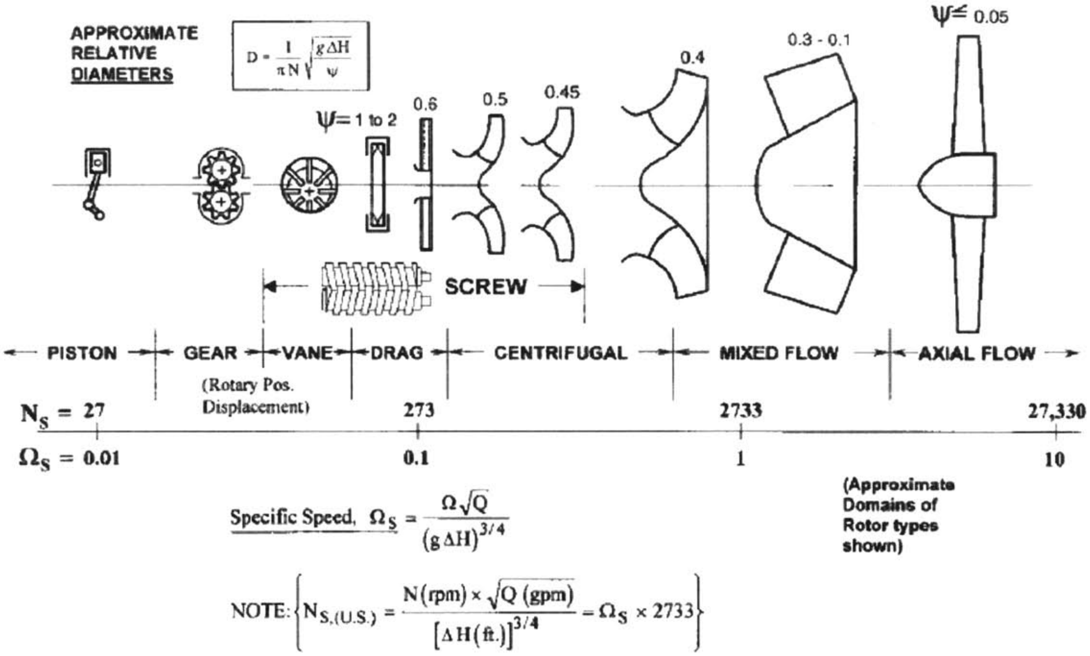


Figure 3-6: Pump Types and Impeller Geometries at Varied Specific Speeds [58]

For the performance point of 1 L/s and 10m head, the most efficient specific speed is determined to be 1300, putting the profile in the mixed flow region [59].

3.4. Analysis

The primary goal of the following analysis is to increase the efficiency of the pump and bring down the overall cost.

3.4.1. Volute

The volute encases the impeller. The main inefficiencies due to the volute design come from recirculation, rubbing and an improperly shaped accumulator. Figures 3-7 and

3-8 depict the important features of the volute from a sectional side and birds eye view, respectively.

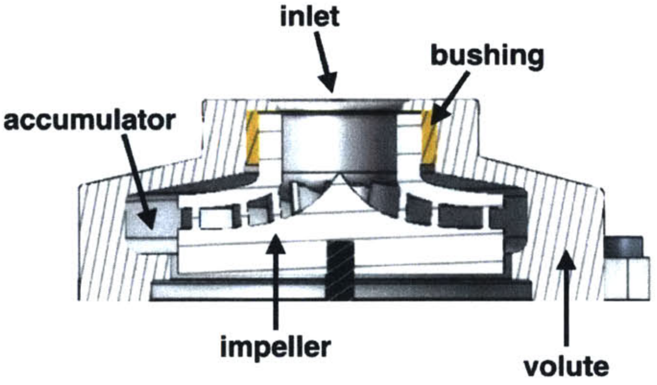


Figure 3-7: Sectional Side View of Volute and Impeller

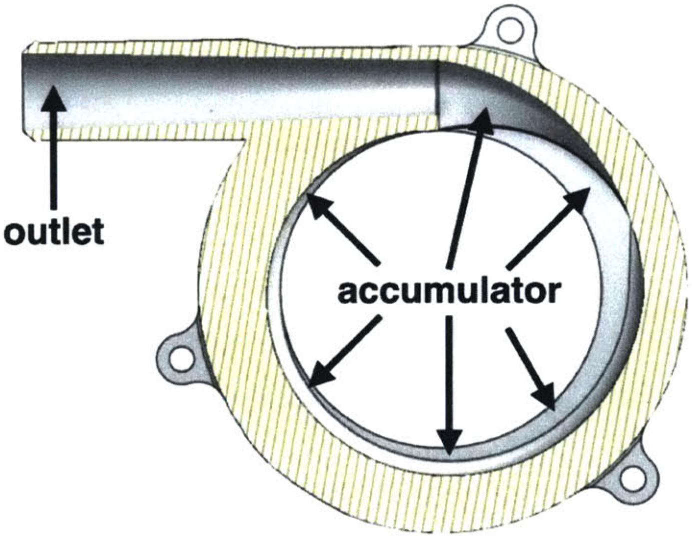


Figure 3-8: Sectional Bird's Eye View of Volute

The main areas in the volute where recirculation is a problem are in the gaps above and below the impeller, between the impeller and the volute. The tradeoff is between making these gaps as small as possible and avoiding the impeller rubbing on the volute due to any misalignment or axial shifts.

The goal of the design of the accumulator is to maintain a constant pressure head throughout the volute. In order to achieve this, the dynamic head of the fluid, $v(\theta)r(\theta)$, should remain constant, i.e.

$$v(\theta)r(\theta) = v(2\pi)r(2\pi) \qquad [34]$$

Where θ is the angular position in the accumulator and $r(\theta)$ is the radial distance from the center of the accumulator to the middle of its cross-section at the given angular position. The flow rate at any angular position can be found by the following equation

$$Q(\theta) = Q(2\pi)\frac{\theta}{2\pi} \qquad [35]$$

Combining equations 34 and 35, we can find the following relationship that yields the optimal design for the cross section of the accumulator, $A_{cs}(\theta)$:

$$A_{cs}(\theta) = \frac{Q(\theta)}{v(\theta)} = \frac{r(\theta)Q(2\pi)\theta}{v(2\pi)r(2\pi)2\pi} \qquad [36]$$

3.4.2. Impeller

The design of the impeller is essential in the overall efficiency of the pump. Important features of the impeller are featured below in Figures 3-9 and 3-10. The analysis that went into this design was conducted by Marcos Esparza and can be found in greater detail in his senior thesis, “Centrifugal Pump Design” [59].

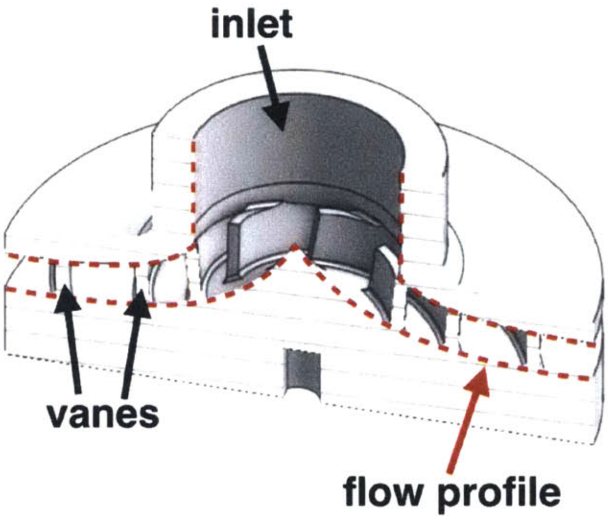


Figure 3-9: Cross-Sectional View of Impeller

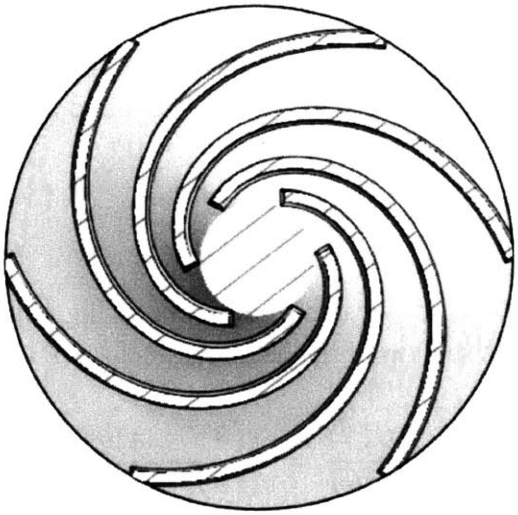


Figure 3-10: Bird's Eye Sectional View of Impeller, Showing Layout of the Vanes

Note that the water exits the impeller at all angular positions around its edge, and that the flow profile corresponds to the specific speed as is shown in Fig 3-6.

3.4.3. Motor

The behavior of a motor is characterized by the internal resistance, R, the voltage constant, K_v, the torque constant, K_t, and the no load current, I_O. Knowing these constants, the following equations can be evaluated as functions of the torque to generate the motor curve:

$$\omega(\tau) = (V - A(\tau))K_v \quad [37]$$

$$I(\tau) = I_O + \frac{\tau}{K_t} \quad [38]$$

$$\eta(\tau) = \frac{\tau\omega}{VA(\tau)} \quad [39]$$

Figure 3-11 below shows the motor curve for the Anaheim Automation brushless DC motor used for the pilot prototype.

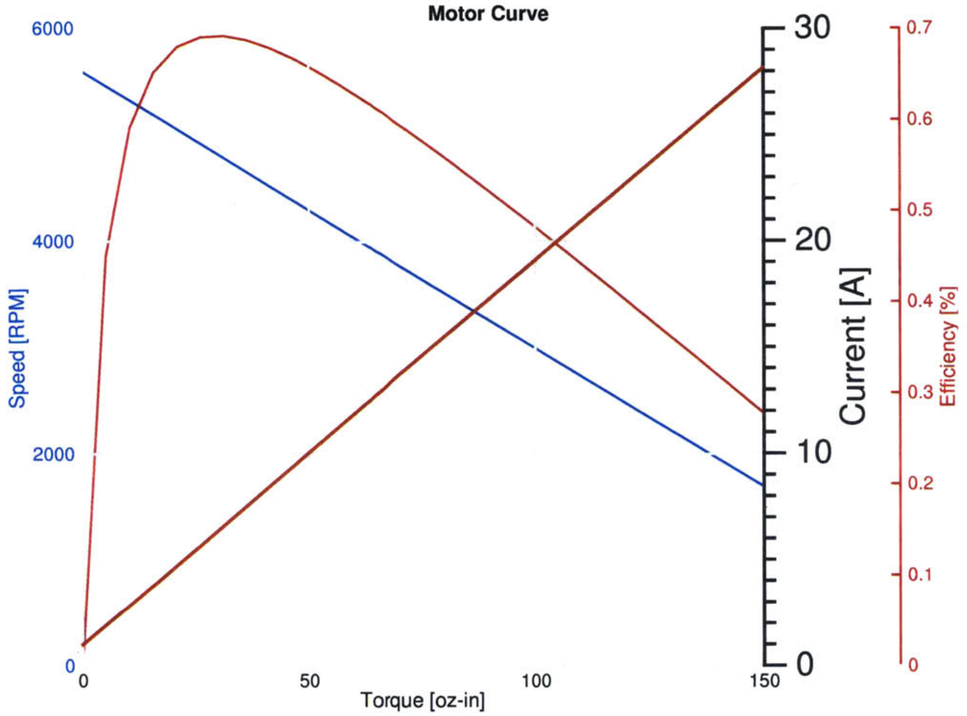


Figure 3-11: Anaheim Automation Motor Curve [60]

The characteristic constants for the BLWS65235S-24V-4000 Anaheim Automation motor are as follows: $R = 0.6$ ohms, $K_v = 2285\frac{rad}{V}$, $K_t = 0.039\frac{N}{A}$, and $I_O = 1.0A$ [60].

The pump's performance is determined by the interaction between the impeller and the motor. As is evident from the above motor curve, the motor's efficiency varies as a function of torque, and corresponds to a given RPM. The trick is that the impeller also has it's own performance curve, with it's own best efficiency point, that is determined by its geometry. This impeller curve maps RPM and torque onto flow and pressure. The motor maps RPM onto torque. The pump's overall efficiency is in part determined by the intersection of the motor and impeller curves [59].

3.4.4 Battery & Panels

The batteries serve two functions in the system. The first is to act as an energy buffer, collecting excess energy during peak irradiation hours of the day and then supplementing the power coming from the solar panels during the lower irradiation hours to extend the running time, and thus daily volumetric output, of the pump. The second is to act as a voltage stabilizer, allowing the system to run when there is insufficient irradiation or the panels are not properly sized.

The majority of the cost of the solar pumping system is in the solar panels; thus it is important to properly size the solar panels for the given system and to investigate how to use fewer or smaller panels. One clear path to decreasing panel size is to increase the efficiency of the pump, through geometric changes to the impeller and through careful matching of the impeller and motor curves. Another path is to use a battery buffer, as has been done here. Without a battery buffer system, and in order to run the same amount of time, there would need to be a greater number of panels to accommodate the lower irradiance hours. Further analysis into the battery and panel module of the design can be found in Kevin Simon's thesis [56].

3.4.5. System Cost-Performance Relationship

The following analysis was on the relationship between the cost and the performance of the system was conducted by Kevin Simon, and can be found in greater detail in his thesis [56]. One of the most significant barriers to the adoption of a technology such as this in emerging markets is the cost. It is essential to understand the relationship between the cost of the overall system and its corresponding performance. Intersecting the pump curve and the pressure curve for the depth of water drawn, a Pareto plot can be made to show the system cost vs the performance [56]. Note that the performance is shown in percentage of undelivered water, as in the percentage of days per year that insufficient water is delivered to the field, and that the "sufficiency" of the daily volumetric output takes into account solar irradiation measurements taken throughout the year in the pilot site's geographic area. Figure 3-12 shows the Pareto plot of the total system cost (pump, panels, batteries and all accompanying electronics) for the experimentally determined pump curve (see section 3.6.1.) drawing from a depth of 9.5m.

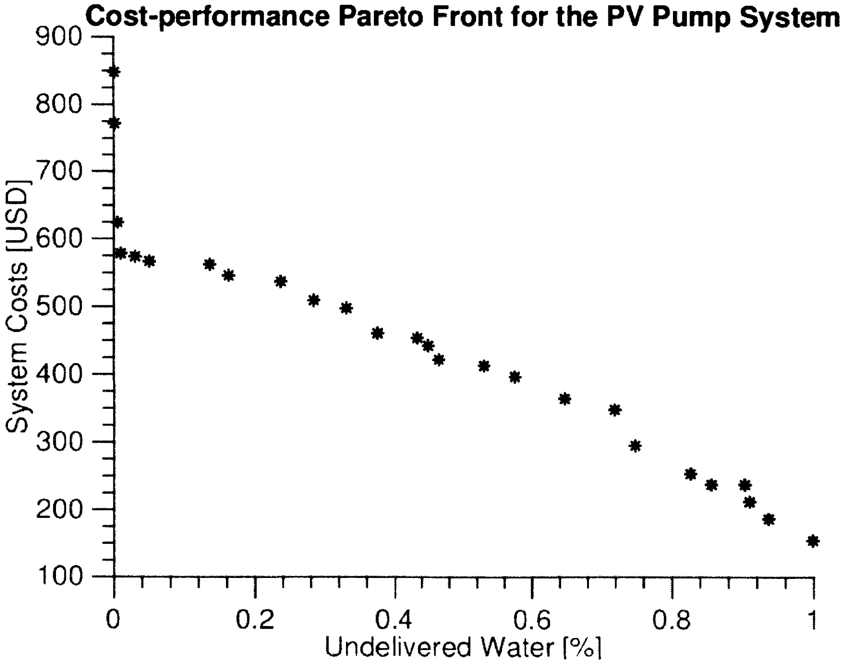


Figure 3-12: Relationship between Cost and Performance of System Used in Pilot Study[56]

As was mentioned in section 3.4.4., one way to increase the overall efficiency of the pump, and thus bring down the number of solar panels needed, is to better match the impeller and motor curves for their respective BEPs. Since the geometry of the impeller is determined by the desired flow and pressure output of the pump and is thus fixed, it is possible to change the pump's performance curve by getting a custom wound motor. Without changing anything else about the pump, if a specifically designed motor was substituted for the current Anaheim Automation motor, then the pump's efficiency would jump from 29% to 35% [56]. This jump in efficiency would yield the following Pareto curve, shown below in Fig 3-13.

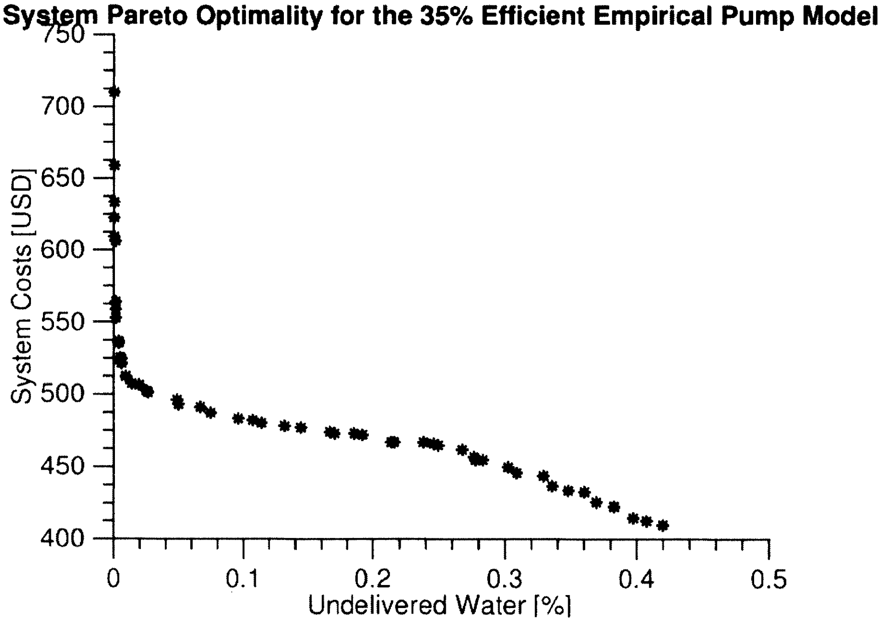


Figure 3-13: Relationship between Cost and Performance of System Using Custom Wound Motor[56]

This shows that the full system, with a 35% pump, that meets 99% of yearly water demands for a 1-acre holding farmer in Jharkhand would cost around 500 USD.

3.5. Design Goals & Salient Features

The design of the pump used in the pilot study in Jharkhand is shown below in Fig 3-14 and 3-15. The goal of the design is to best translate the analysis into a physical system, keeping in mind qualitative requirements for a pump used for irrigation in the field in Eastern India.

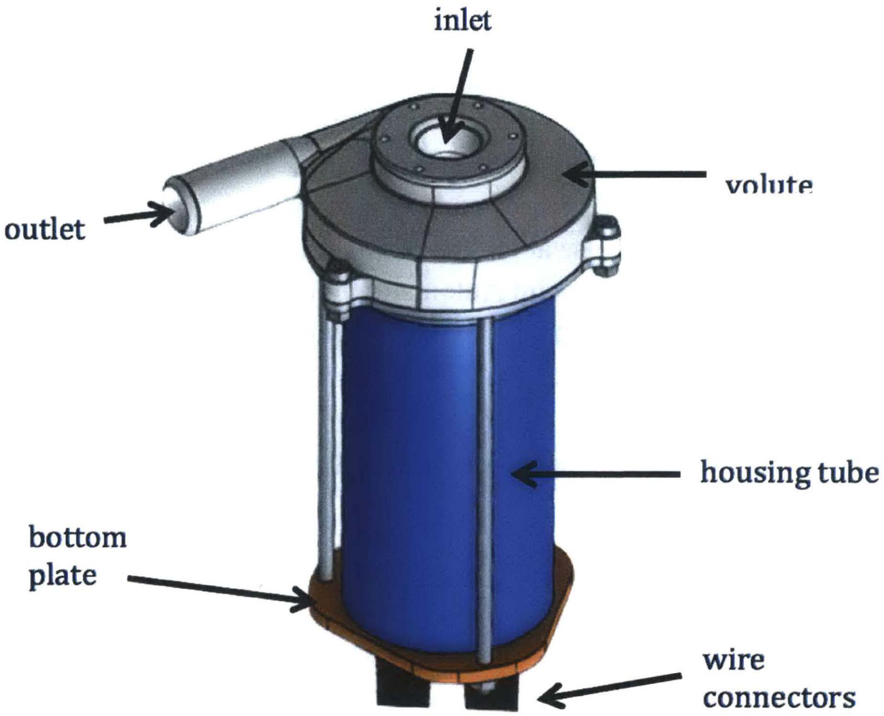


Figure 3-14: CAD of Final Pump Prototype

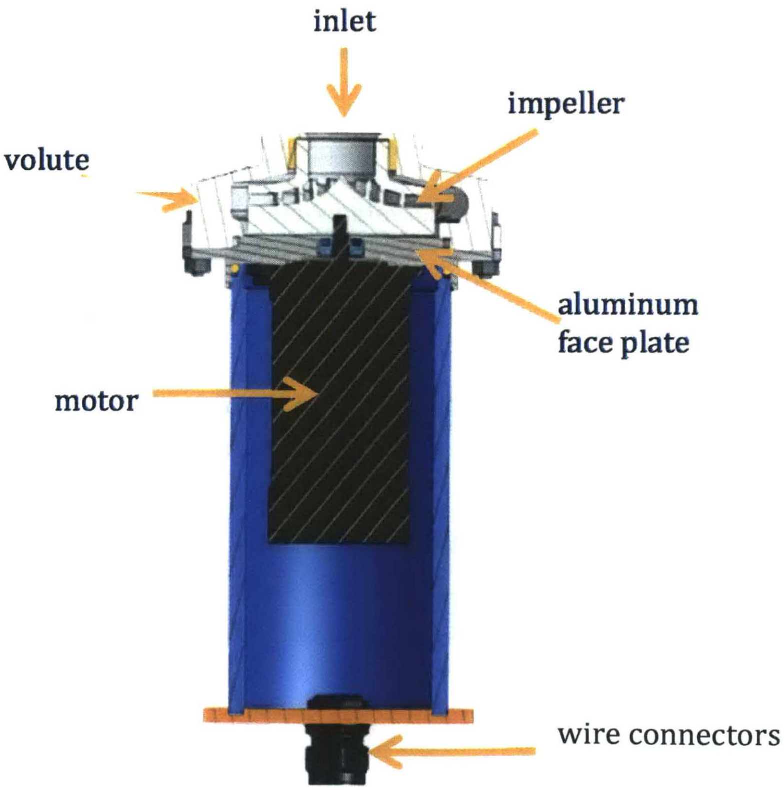


Figure 3-15: Cross-Sectional View of CAD of Final Pump Prototype

3.5.1. Robustness

The pump system should be robust in its intended environment. It should be durable against the elements as well as against reasonable wear and tear.

The housing of the pump is made of a PVC tube glued to a PVC bottom plate. The tube sits in a groove in the bottom plate and the two were welded together using PVC glue. The cylindrical shape of the tube makes it resilient to crushing by being stepped on by a cow or person, since the foot could just slide off.

The housing encases the motor in a watertight fashion, since the motor used is splash-proof, not waterproof. There three components to the sealing of the housing, other than the end glued to the PVC bottom plate: the wire connectors, the O-ring between the aluminum face plate and housing tube, and the dynamic seal around the shaft.

The waterproofing of the wire connectors is based of off St Venant's principle: in order to securely couple two components, stabilizing forces must be applied 3-5 characteristic diameters apart [61]. This means that there needs to be 3-5 diameters of wire between the sealing structure and the connector for the bending moment of the cable not to affect the seal. Thus relatively long waterproof connectors were chosen for the prototypes, as shown below in Fig 3-16.

Figure 3-16: Waterproof Connectors

In order to access the motor, the housing tube must be able to disconnect from the face plate, but remain watertight when closed, thus an O-ring seal was chosen. The max pressure that the seal may need to withstand comes from how deeply it may be submerged. Given a submersion of 10m, the seal must be watertight up to 0.1 MPa, which allows for the use of a Buna-N O-ring. The groove the O-ring sits in was sized with to allow for 15% compression and 70% cross-sectional fill. The O-ring sits between overlapping lips of the housing tube and the aluminum face plate as shown below in Fig 3-17.

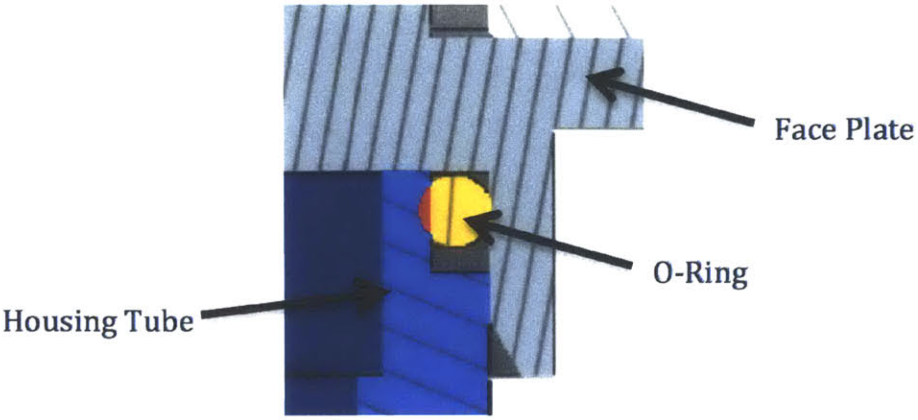


Figure 3-17: Cross-Section of O-ring Junction Between Face Plate and Housing Tube

The last junction that must be watertight is the dynamic seal around the motor shaft. Taking the same submersion of 10m, and factoring in the pump's stall pressure, this seal needs to be watertight up to 0.3 MPa. A U-cup seal was chosen due to its low-friction, pre-load on the seal, the low-pressure requirements, and the fact that it retains grease for lubrication and sealing. To maintain alignment, the U-cup sits in a pocket in the aluminum face plate and is held in place by a retaining ring that rests against the motor's face, as shown below in Fig 3-18.

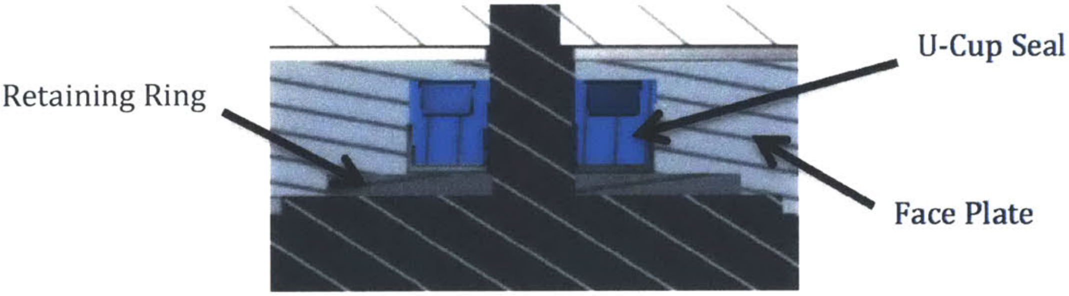


Figure 3-18: Cross-Section of Dynamic Seal

Originally solar batteries, which are flooded, deep-cycle batteries, were investigated for this application, however they were found to be lacking in terms of durability. As with other flooded batteries, there are skilled use and maintenance guidelines that must be followed, especially when moving the batteries. They are also large and heavy. Thus, sealed lead acid (SLA) batteries are used. SLA batteries are smaller and very durable with regards to use and exposure to the elements.

The other consideration taken with regards to the elements is that of thermal management. In the area of Jharkhand where the pilot is conducted, temperatures can reach up to 45 degrees Celsius. Thus, it is important to keep the electrical components cool. As for the external electronics (charge and motor controller) and the batteries, they can simply be kept in the shade under the panels to avoid overheating. The motor within the housing requires a different solution for thermal dissipation. This takes the form of aluminum fins fixed to the motor and the aluminum face plate with thermal putty, to dissipate heat from the motor, through the fins, and into the plate, which is in contact with the water the pump is submerged in.

The final consideration for robustness in the field has to do with the varied water quality to be encountered in wells or streams. The worry is that in highly particulate water, there would be damage done to the impeller, which would result in increasing inefficiencies. However, the material of the impeller, UHMW polyethylene was chosen both due to its relatively low cost, and due to its self-lubricating and abrasion resistant qualities [62].

3.5.2. Modularity

The design of the pump was intentionally made to be modular. There are two reasons for this. The first is the ease of switching out parts during testing; for instance when testing different impellers of different geometries, all that is needed is to undo the screws that hole the volute to the aluminum face plate, remove the volute, pop the impeller off of the shaft and press the new one on. The second reason for the modular design is that should the pump be commercialized, it would be simplest to have distinct replacement parts that could easily be hot-swapped onto the pump in the field and sent to a central repair center.

3.5.3. Portability

The design requirement of the portability of the entire system is important to the farmer. Intuitively, it makes the pump and system less cumbersome and able to be used by men, women and children, which is important in rural India where often the entire family participates in farming. However, more importantly, it is an anti-theft prevention. The pump, accompanying electronics and, primarily, the solar panels are valuable items. If the system were not portable, which is often the case in solar-powered pumping systems in use in India which tend to have greater hp pumps and require a larger solar panel array that is fixed to the ground, a guard is needed to ensure they systems safety, particularly at night. However with a portable system, such as the one detailed here, the entire system can be brought into the home at night. Currently, the most cumbersome part of the system is the solar panels. While it was observed that an adult could carry both panels on top of his head from home without trouble, work is underway to design a carrying satchel for the panels that could be affixed to a bike, which is a very common possession amongst the rural farmers. It is also important to note that with efficiency gains in the pump, the required panel size decreases and the system becomes more easily portable.

3.5.4. Ease of Use & Familiarity

The system was intentionally designed to be easy to use & maintain. The pump itself is only made of 4 parts, not counting the hardware and O-rings. The electronics are designed such that to run the pump, the farmer simply puts the system out in the morning and connects two color-coded, non-reversible plugs. The timing of whether the pump is running or shut off to allow the batteries to charge is fully automated. At the end of the day, the farmer simply disconnects the plugs and carries the system back into his house.

All of the tools needed to take apart the pump, as well as the SLA batteries themselves, were locally sourced. The SLA batteries are two 7Ah 12V motorcycle batteries, with which the farmers are familiar. The batteries also can be used at night with a simple LED light in the farmers home (something that the farmers requested!).

3.5.5. Quantitative Requirements

The pump should meet the specifications determined in section 3.3: a BEP flow rate and head of 1L/s and 10m, requiring under 300 watts of panels.

3.5.6. Prototype Manufacturing

Five prototypes of the final pump design were made using a wide range of machines in the shop. The volute was 3D printed using a Fortus 360 FDM printer and then coated with epoxy to ensure water could not escape through the walls. The impeller was milled in two pieces with mating/alignment features, and was then glued using B-40 glue, which is works with UHMW polyethylene, a typically difficult-to-glue material. The retaining ring for the dynamic seals was laser cut out of acrylic. The PVC bottom plate was milled on the Shopbot desktop CNC. The PVC housing tube was turned on the lathe. Lastly, the aluminum face plate was milled on the CNC mill.

3.6. Testing

3.6.1. Lab

3.6.1.1 Experimental Setup

The five prototypes were tested on a lab-scale experimental setup, depicted below in Fig 3-19.

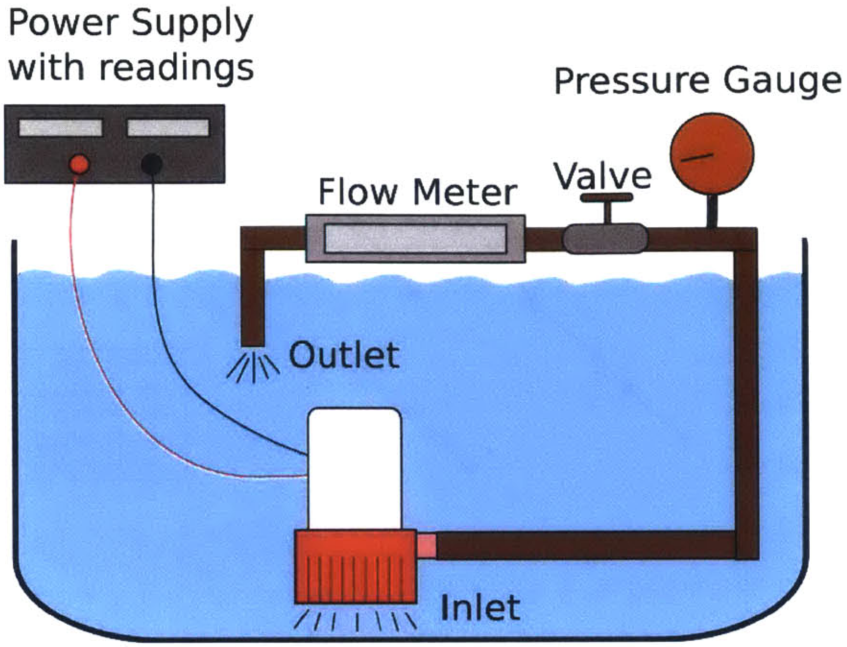


Figure 3-19: Lab-Scale Experimental Setup

The pump is submerged in the tank and outputs water into a flow loop that runs through a pressure gauge, a ball valve, a flow meter and then back out into the same tank. The ball valve is used as a variable flow restrictor to simulate different pressure heads and generate a pump curve. Not well depicted, the pressure gauge is held at roughly the same height as the outlet of the pump and thus can be read as the outlet pressure of the pump.

Current measurements were taken with a Fluke 373 True-RMS Clamp-On meter, which has a rated error of +/- 1%. Pressure measurements were taken with a high accuracy test gauge (PN 4007K2) purchased from Mcmaster-Carr, which has an error of +/- 0.5%. Flow measurements were taken with an Omega FTB792 flow meter that is rated for 2-20 gallons per minute and an error of +/- 1.5%. Other error in the pump curve can come from pressure losses along the flow-loop.

3.6.1.2 Results

The five prototypes were tested using the experimental setup described in Section 3.6.1.1.. The pump was turned on using a power supply that fed 24V at all times. The pressure and flow measurements were then taken at varied positions of the ball gauge, simulating different heads. The results are shown below in Fig 3-20 through 3-22.

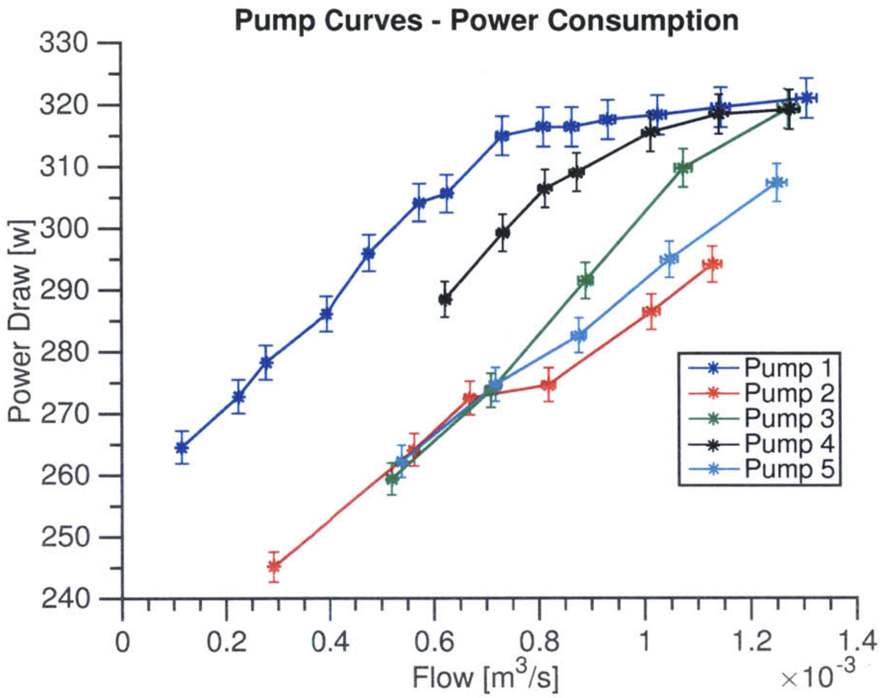


Figure 3-20: Power Consumption vs Flow Rate of Prototype Pumps

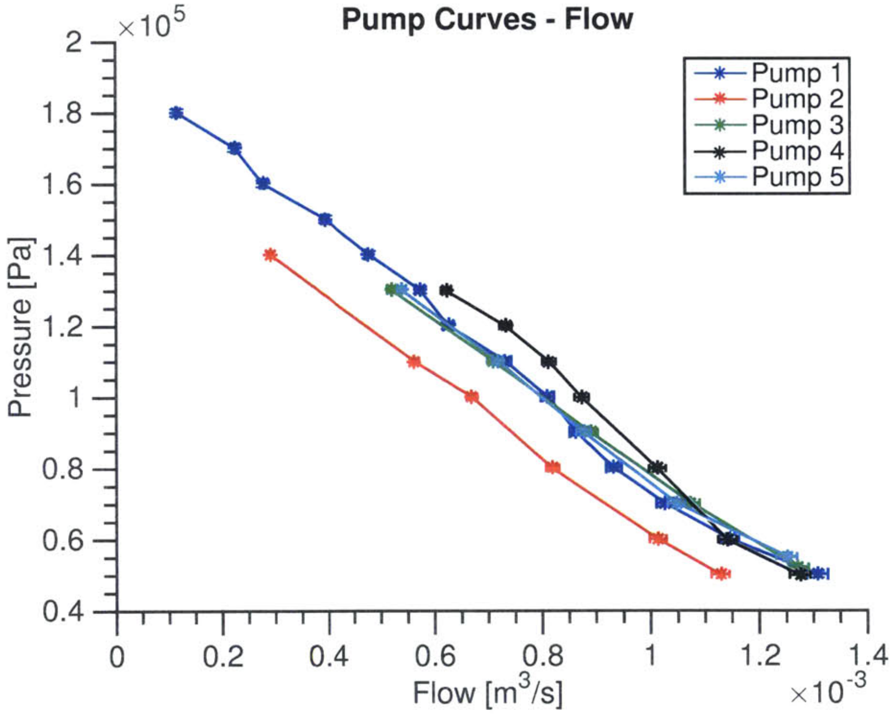


Figure 3-21: Pump Curve Showing Flow vs Pressure of Prototype Pumps

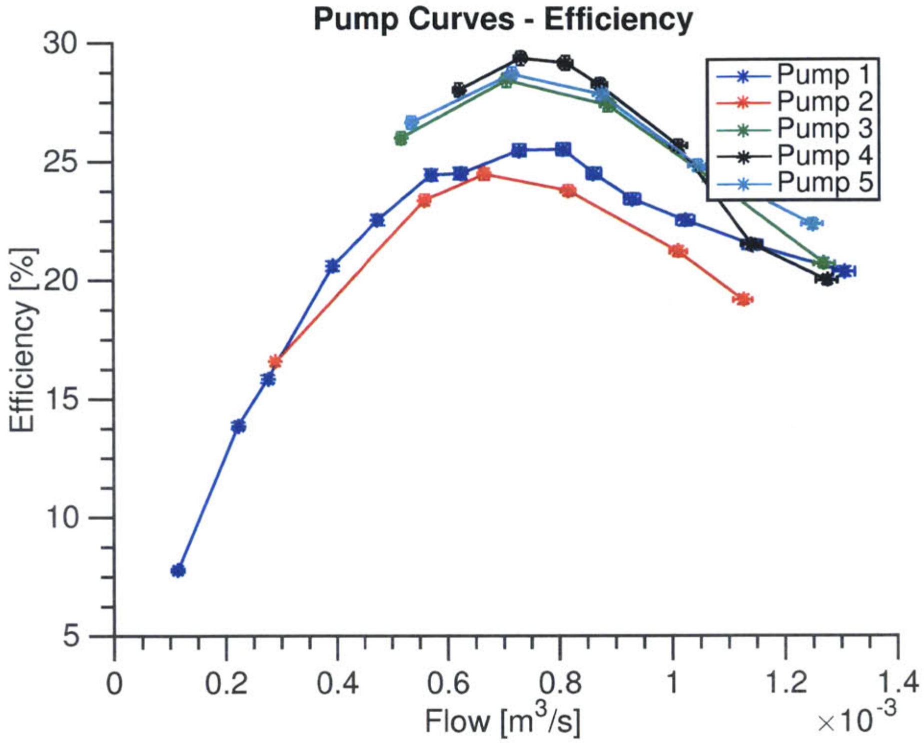


Figure 3-22: Efficiency vs Flow of Prototype Pumps

From the above figures, the maximum efficiencies, ranging from 24-29%, are occurring at 0.8 L/s, which correlates to a head of 8-11m and power draw of 275-315 watts. The maximum efficiency point reached was by Pump #4 and was just over 29% efficient. It is important to note the variation between the prototypes. The most obvious explanation is that since all of the pieces were made by hand that there were geometric imprecisions.

3.6.2. Pilot Study

The pilot study for the solar-powered irrigation system was deployed in mid-February 2015 in two villages in Jharkhand, India and is ongoing.

3.6.2.1. Community Engagement

The pilot would not have been possible without the help of Pradan, an NGO operating in seven of the poorest states in India, including Jharkhand. Pradan's mission is to conquer "economic poverty… through enhancing the livelihood capabilities of the poor and giving them access to sustainable income earning opportunities". The key takeaway from this mission statement, and something that they actively pursue, is that Pradan is not the type of NGO that drops off aid and then walks away; Pradan works actively and regularly with the community to teach skills and do projects that the community wants to take ownership of and commit to long term.

In the months preceding the deployment of the pilot, the researchers communicated with Pradan first by email, then phone calls, and then had two separate visits to the villages with Pradan employees. In these visits, elders from the village, farmers and their families, and women from the village's self-help group (SHG) came and sat with the researchers to discuss whether or not they'd be interested in participating in the pilot, what the expectations on both sides would be, the duration of the study, who would be responsible for what, and even wrote out a contract on the spot and signed. Below in Fig 3-23 is a photo from one of the sit-down meetings, where the farmers and villagers were examining the pump and asking questions. The notebook in the bottom left is where the contract was written out by one of the farmers and signed by all who would be using the system.

Figure 3-23: Farmers and Their Families Examining Pump During Preliminary Meeting

The two pilot sites were chosen with great help from Pradan. The criteria for selection included a site where there are farmers who are interested in new technologies, who Pradan is familiar with and working on other projects with (so that continued check-ins by Pradan employees would be less of a burden since they would be visiting anyways), and who are familiar with irrigation. It turns out that at both sites, the farmers irrigated using their diesel pumps in the winter season, but not in the dry season when significantly more diesel is required due to higher temperatures. Pradan was also very excited about these two sites and felt that they were representative of this type of farmer in Jharkhand, because of the number of men who were migratory workers. Many of the farmers used to migrate during the winter and dry seasons to Mumbai or Kolkata or other cities to work in construction, mining or in factories before they got access to irrigation, and could cultivate in the winter season, making enough money to sustain their families.

3.6.2.2. Pilot Sites

There are two pilot sites: Sombra and Jenasai. At both sites, multiple families have organized, with the help of Pradan, to cultivate a combined plot. This means that each family has their own plot that they are in charge of cultivating, but that the plots are all next to each other making up a multi-acre plot that is fenced in along the border. The main reason for this has to do with the livestock in the area. First off, fencing is very expensive. Metal fencing isn't used because metal wire is too valuable and may be stolen. Wood fences cost too much – approximately 1 lakh INR per hectare. Natural fences, i.e. weaving branches together, are most common, but require know-how to make and upkeep. Thus, it is common practice in places that cultivate only in the monsoons to split the work-load between taking care of the crops, and taking care that the livestock do not graze on the land being cultivated. Since everyone farms during the monsoon, because the water is obviously free, it is easy to organize this way. However, if certain farmers purchase a pump to irrigate in the winter or dry season, they will still need to ward off the livestock, which would mean someone in the family being on watch 24/7. But, if plots are combined, then the perimeter to area ratio decreases and the watching duties can be split between families.

Sombra has a plot shared by 9 families and is 11 acres total. The site is located on a hill next to a small perennial river. The total head at the site is 9.5m. The site has 5 "jalcunds", or water tanks, built into the ground. Each jalcund holds approximately 4000L. Jenasai has a plot shared by 12 families and is 7 acres total. It is located next to a well that is fed by a perennial stream. There are 4 jalcunds on the plot. There is a makeshift greenhouse for the seedlings. Both villages have been taught by Pradan to use these jalcunds and the technique of spot watering as an efficient irrigation practice. Below in Fig 3-24 is a photo of a farmer at Sombra spot watering in front of a jalcund.

Figure 3-24: Farmer at Sombra Spot Watering in Front of a Jalcund

3.6.2.3. Interviews

During the two visits in December and January leading up to the deployment of the pilot in February, as well as during that visit, informal interviews were conducted with Pradan employees and with the farmers, with translation help from the Pradan employees. Then, during the follow-up visit in March, formal interviews were conducted with the help of a hired translator. The full results of the formal interviews can be found in Appendix num. The knowledge gained in the informal interviews is worked into the following section 3.6.2.4. on lessons learned.

Four farmers were interviewed formally, three at Sombra and one at Jenasai. Up to this point, all four farmers had cultivated during monsoon and the winter season, but not the dry season due to high diesel costs. They all purchase their diesel fuel from the nearest town, Chakradharpur (CKP) which is 12 km from Sombra and 9 from Jenasai. Note that due to the poor infrastructure, it takes between 45 minutes to an hour to get from either village to CKP on a motorcycle. They also sell their harvest at small markets in CKP. Both villages currently own one diesel pump that Pradan secured for them through a NABARD scheme. The farmer at Jenasai estimated that the diesel pump cost 85,000 INR, or $1335 USD. During the winter season, the farmers use about 20L of diesel a month to irrigate, which totals to around 3500 INR for the entire 3 month season. However, there are also the diesel costs of the weekly round-trip to CKP to purchase diesel. All four farmers pointed out that the solar pump was desirable for two reasons:

first that there are no recurring diesel costs, and secondly that it is much easier to use than the diesel pump. Three of the four said that 30,000 INR would be a reasonable price for the solar pumping system, and the fourth said he would pay between 25,000 to 30,000 INR. They expressed concerns over the complexity of the process of securing a loan. All four farmers said that if they accrued additional savings from using the solar pump year-round that they would spend it on education for their children. They also mentioned spending it on a larger home, more land or learning more farming techniques.

3.6.2.4. Lessons

Many lessons were learned in the time leading up to and during the pilot study, both from the farmers and NGO employees as well as from the experience of deploying a pilot. Below are a few of the more significant lessons learned.

In informal interviews, the farmers communicated that life in the rural village is preferable to migratory work, because they get to see their family and are in control of their own lives. In many of the migratory work positions, such as in a clothing factory or a diamond mine the farmers felt that the conditions were unsafe or unhealthy, and that they were always at the mercy of their supervisors. Living in their village and farming to make a living is considered preferable. While farming is certainly not easy work, these farmers felt that especially with their collective plot situation, that they could choose their own hours and that they were more in control of their lives. They also felt that growing pulses and vegetables to feed their families and sell at market is an honorable and honest way to make a living.

One employee at Pradan, Subhajit Gosh, emphasized that if there is irrigation, then the men will come back from migratory work to the farms. At both of the pilot sites, Jenasai and Sombra, this was proven true when they acquired a diesel pump through a NABARD scheme 4 years back. Again, it is important to note that with their diesel pump, they still have only been irrigating during the winter season, not during the dry season, due to prohibitively high amounts of diesel required.

Pradan has seen through their years of work with these and other similar villages that they are willing to work hard. The state of Jharkhand has a very high population of scheduled tribal farmers; 60.86% of the marginal (<1.25 acres) size farms in the state are owned by scheduled tribal farmers [32]. Both of the pilot site villages are made up of mostly scheduled tribes, a sector of indigenous people who have historically and systematically been discriminated against in India. In conversations with Pradan employees, it has become clear what a multi-faceted struggle these scheduled tribal people face. The state government is incredibly unstable. The literacy rate is one of the lowest in the nation. There are problems with rampant alcoholism from young ages; However Pradan has faith that through collaborative projects such as our pilot, these villagers can learn the skills and gain the tools to lift themselves out of poverty.

Some of the lessons learned from deploying a pilot are purely logistical, others are more emotional or abstract. In terms of logistics, some important take-aways are: build in a significant amount of buffer time to your schedule leading up to the pilot (at least 20% of the total time you think you need); bring extras of everything including tools and hardware; design so that parts or tools can be locally sourced; pack up carefully so that everything is well cushioned and well organized; make a formal training and maintenance manual/script that you can adjust in the field; make sure to leave time for a full system integration and aesthetic polishing of the prototype, because it is difficult to get feedback on the most critical module of the system when users are distracted by poor aesthetics or other parts of the system not functioning smoothly. In terms of maintaining reasonably good mental health, the most important lesson is to pick reliable partners, meaning both teammates and partners in India for executing the pilot. While choosing reliable and trustworthy teammates may sound obvious, it is worth mentioning that in deploying a pilot, there will be high highs and low lows, and having someone you can trust not only to show up, but to be supportive, positive thinking, creative, hard-working and a good friend, is essential. Choosing a partner on the ground to work with is also important – especially if there is a desire to collect data while you are not there. Lastly, it is recommended that you show up multiple times – you don't want to just show up and drop off a system and then leave. By visiting multiple times in as many months, it is much easier to grow trust, which will in time lead to being able to learn more from the pilot.

4. Conclusion

4.1. Summary of Challenge, Approach and Results

The global community, and India in particular, is facing an increasingly serious crisis with regards to the food-energy-agriculture nexus. In order to feed a growing population, shifts will have to be made to more water- and energy-efficient methods of agriculture that also give higher yields per unit of land. Drip irrigation is one such method that boasts high yield with low water usage; however drip traditionally is fairly expensive. In order to be effective on a global scale, these efficient and high yield methods will need to be readily adoptable by all scales of farmers, including those at the bottom of the pyramid with the smallest landholdings. This thesis presented one way to decrease the capital and ongoing cost associated with drip by designing an emitter with a lower activation pressure. In order to design this emitter, a thorough investigation into the mechanisms behind the behavior of the emitter was conducted. From this investigation, a parametric model exploring the geometric and material sensitivities was developed. It is with this parametric model and the understanding that comes with it, that an emitter with a lower activation pressure may be developed.

While energy-efficiency of irrigation is important, the fact is that it will be increasingly necessary in coming decades to switch from fossil-fuel based energy to renewables, such as solar. Due to the scarcity of commercially available solar pumps for small-acreage farmers, millions of these farmers who lack access to the grid face the choice between not irrigating at all, and using expensive and environmentally degrading diesel to power their pumps. Those who do have access to the grid often find it unreliable or are responsible for putting a massive detrimental strain on it, increasing its unreliability. This thesis presented the analysis behind and design of an affordable solar powered irrigation system that is tailored for small-acreage farmers drawing from shallow groundwater. The pump is 29% efficient, delivering 0.8L/s from 10m head at its BEP, and uses 300W of solar panels with two 7Ah 12V SLA batteries. The estimated total price of the system is $500 USD.

4.2. Future Work

4.2.1. Dripper

The next step in the dripper research involves validating the model by prototyping different dripper designs, varying the important parameters discussed in section 2.3, and then comparing the model with the experimental data. Then, an optimization study will be conducted to achieve an activation pressure of 0.1 bar and maintain PC behavior, while taking into account factors such as cost of material, lifetime of the dripper and clogging resistance. Lastly, drippers meeting the aforementioned design requirements will be prototyped, tested against the model and then redesigned with manufacturing considerations kept in mind.

4.2.2. Pump

The future work associated with the pump will include incorporating results and lessons from the conclusion of the pilot study in July 2015 into the design of the irrigation system with regards to its usability and durability in the field; it will also include technical changes aimed at increasing the efficiency of the pump, which will bring down the driving cost of the solar panels.

4.2.2.1. Technical

The upcoming technical work on the pump includes using computational fluid dynamics to model the fluid-structure interaction around the impeller and volute to isolate areas of inefficiency. There is also more analysis that needs to be done into the type and size of battery buffer to be used. Lastly, it will be essential to rework the design of the pump with manufacturing considerations kept in mind, especially if commercialization of the technology is a viable option

4.2.2.2. Commercialization

Due to the high efficiency of the pump, the large total accessible market and the low cost of the entire system, that this solar-powered irrigation system may be commercially viable. The reason to pursue commercialization would be to bridge the gap between academia and actual farmers using the pump to improve their livelihoods.

4.2.2.2.1. Challenges to commercialization and adoption

There are many challenges to the commercialization and adoption of this irrigation system. The challenges to commercialization in the rural Indian market span topics such as the design and logistics of the distribution network, available financing or loan schemes, the potential lack of brand trust, the design and execution of maintenance and repair services and the marketing channels.

The challenges to the adoption of this agricultural technology in the rural Indian market could include the farmer's lack of information or understanding of the problem, the farmers' intensely risk adverse mindset, land ownership or labor problems and/or a lack of appropriateness of the technology.

If this technology is to be commercially successful and adopted on a large scale, these challenges must be addressed in a comprehensive business plan, which is currently in progress.

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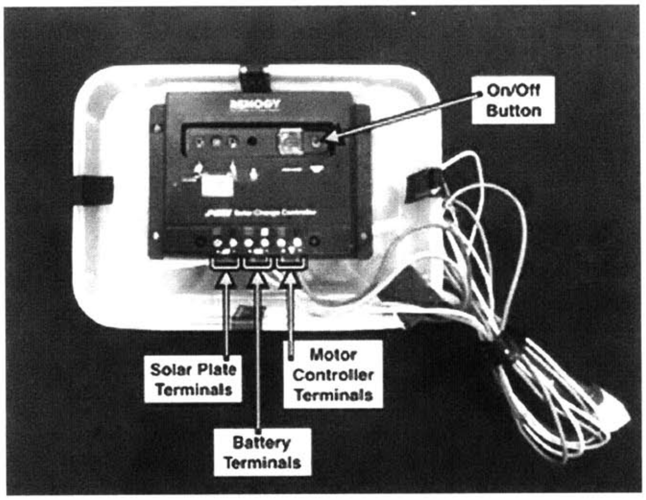
6. Appendices

6.1. Training Manual

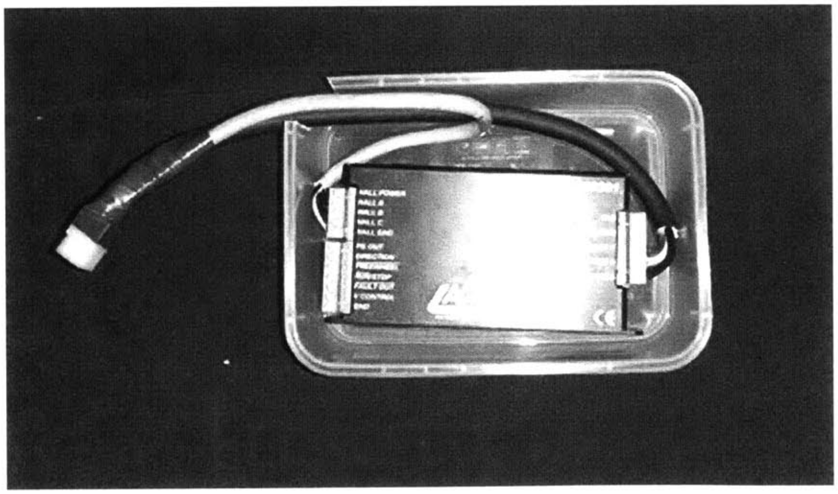
Solar Pump 1: Operating and Setup Instructions

The pump system is made of 5 different components:

1. DC Pump
2. 2x 150watt solar panels
3. 2x 7Ah battery
4. Renogy 30A charge controller (inside the control box)



5. Anaheim Automation motor controller (inside the control box)



To turn the system **on**:

1. Connect the solar panel connectors from the control box to the solar panels.

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2. Connect the + terminal from one solar panel to the - terminal on the other solar panel.

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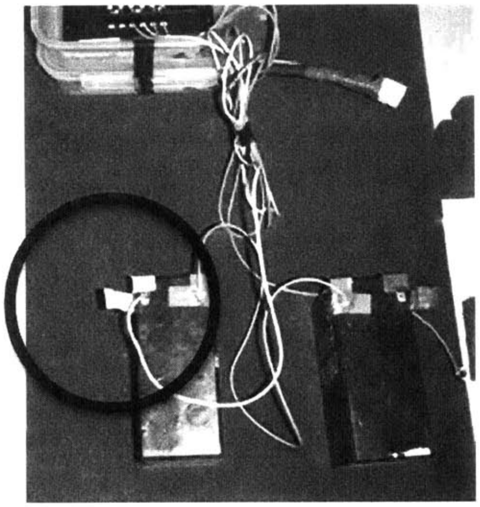
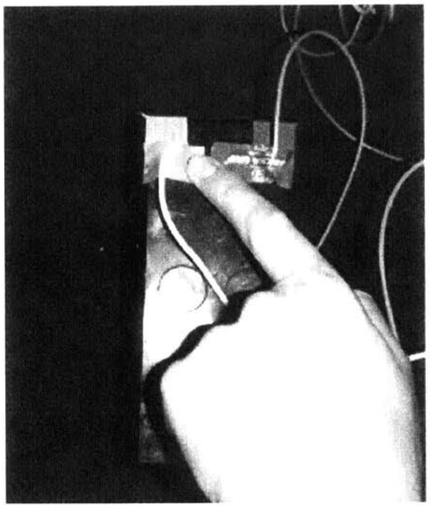
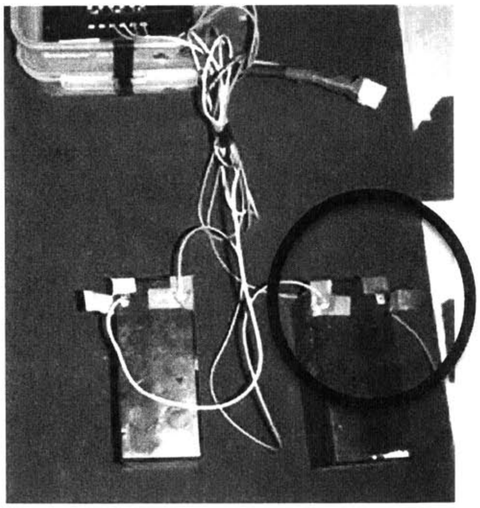
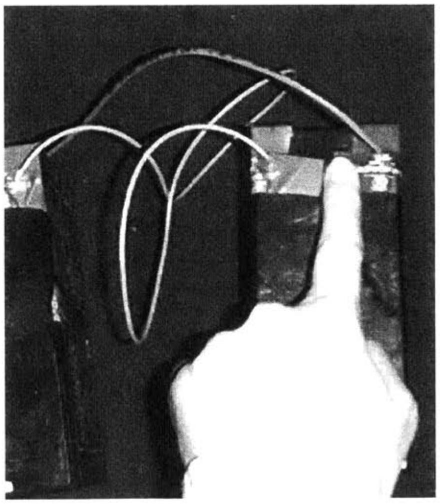
3. Connect the long yellow wire from the control box to the yellow terminal on the battery. Tape it down.





4. Connect the long red wire from the control box to the red terminal on the battery.





Tape it down.

The last connection will turn the pump on, and SHOULD ONLY BE DONE AFTER THE PUMP IS PLACED IN THE WATER SUPPLY. THE PUMP SHOULD NOT BE OPERATED DRY!

4. Before placing the pump in the well, feed the discharge hose through the hole in the filter bag and attach the irrigation pipes to the pump outlet with a hose clamp. Then place the pump (with flotation bottles attached) in the filter bag and tie up the filter bag with the rope and wire cables sticking out of the top.

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5. Lower the pump into the water with the rope.

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6. Check that the wires coming out of the pump are not under the water and that the pump is floating straight.

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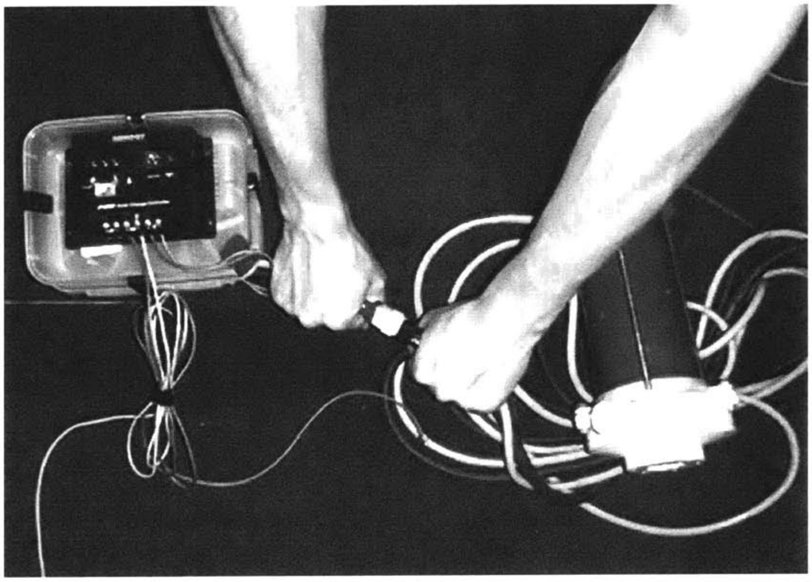
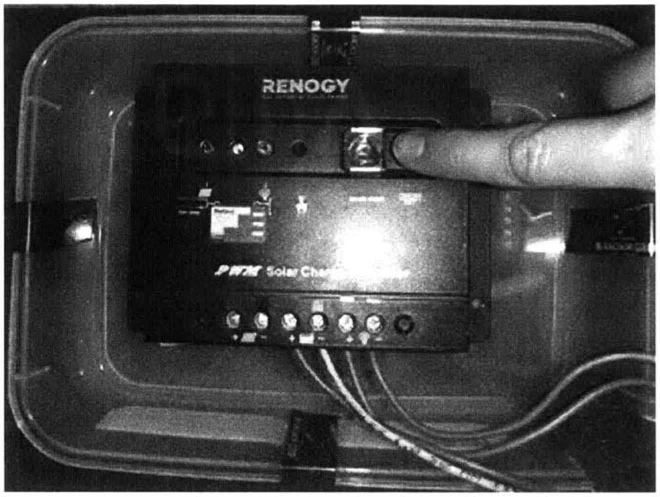
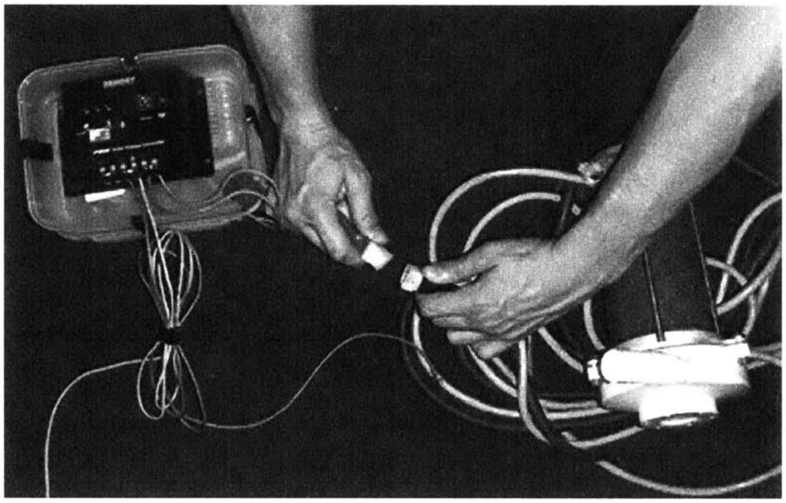


7. Connect the motor wire to the control box connector.



8. To turn the pump **on**, push the ON/OFF button on the charge controller.
9. To turn the pump **off**, disconnect the connector between the control box and the pump.



Additional Important Information

Batteries

Both the batteries and panels are necessary to give enough current to run the pump. This means that while the pump is running, the batteries will be drained. On a typical day, the pump will run off of the panel and batteries until the batteries are too low.

When the batteries are too low, the pump will cycle off and on. Then the pump should be turned off so the batteries can be charged.

The batteries will be full when the middle light is blinking green. Then the pump can be turned on until it cycles on and off. It should take 30 min to 1 hour for the batteries to fully charge.

Panels

The panels should be placed in a good position to get the most energy from the sun. Tilting them towards the south will yield the most sunlight on the panels over the day. Alternatively, they can be repositioned as the sun moves across the sky to get more power out of the panels. See 'Maintenance and Repair' for more information on positioning.

DO NOT place them in the shade, or shade them by standing over them. The pump will shut off if the panels are shaded.

The panels should be weighed or tied down to prevent them from blowing away and breaking.

The panels should be wiped down with a dry rag every day that they are used and stored in cardboard to keep dust from accumulating and sticking to the panel.

Control Boxes

The control boxes should be kept in the shade of the panel. They can easily overheat and break. Additionally, on hot days, the controllers can become too hot. If this happens, they will need to be kept outside of their containers to provide good airflow.

LED

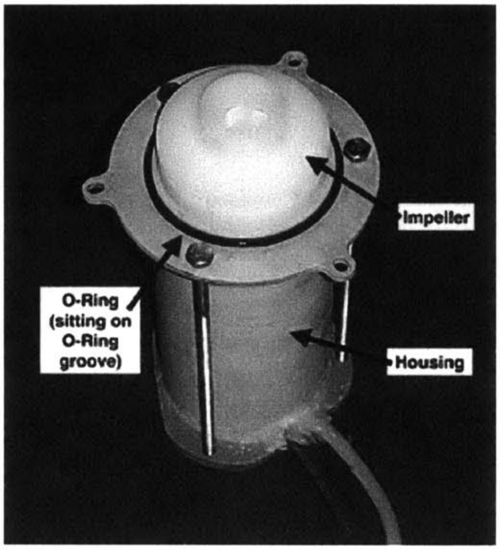
At night, it is possible to use the LED lights by wiring them directly to the battery. The switch can be used to operate the LED light. If the light is left on, the pump will have less energy the next morning.

Safety

Keep your hands away from the pump inlet. It can easily suck your hand in and damage it.

6.2. Repair Manual

Solar Pump 1: Maintenance and Repair

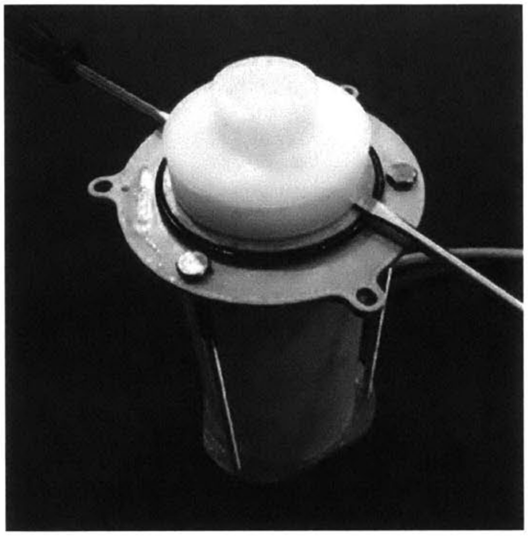


Pump

Impeller

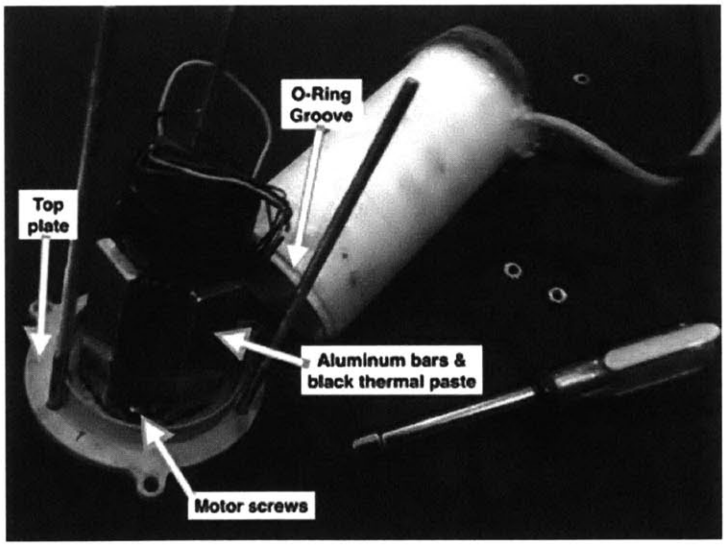
Check the impeller for damage or clogging. If the clogging can be removed, then remove it.

If the impeller cannot be repaired, replace it. The impeller can be removed by gently prying it with 2 or more screwdrivers.



To attach an impeller to the shaft, *carefully* align the flat side of the motor shaft with the flat side of the hole on the bottom of the impeller. Then press the impeller onto the shaft on a flat surface. This may need to be done with a drill press or some other form of leverage.

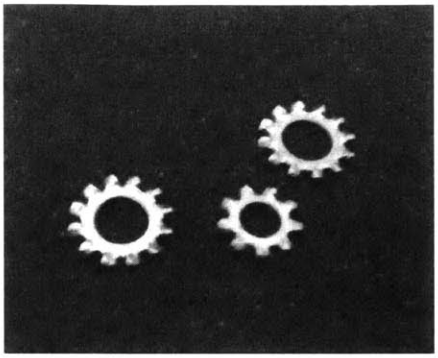
Leaks



Check the housing for leaks by opening it up.

Washer-rings

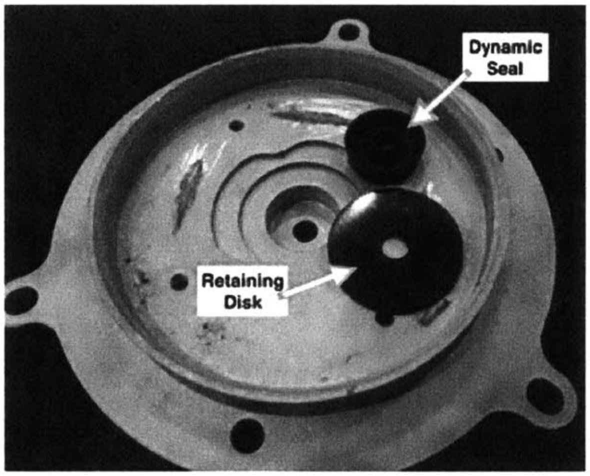
Be sure to keep the anti-vibration washer rings underneath the nuts. Those prevent the housing and volute from slipping apart.

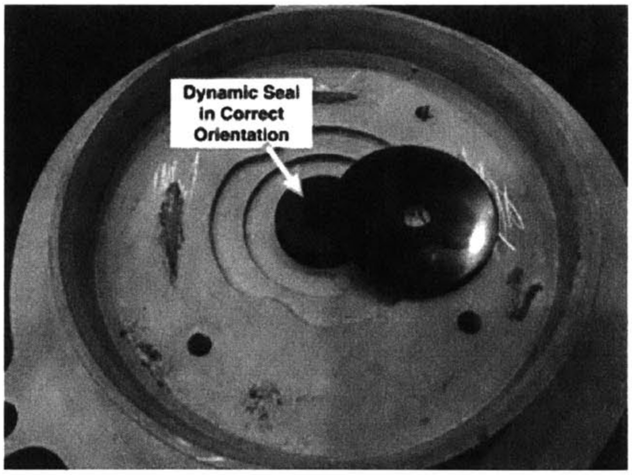


O-rings and Seals

When the pump is disassembled, the O-ring and O-ring groove needs to be cleaned or replaced if it is dirty. The O-ring needs to be lubricated if it is cleaned or replaced.

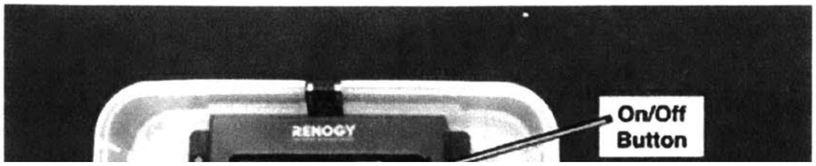
Check the dynamic seal around the motor shaft for damage. This seal can only be accessed by removing the motor from the aluminum housing plate, and removing the retaining disc.





Control box

Renogy

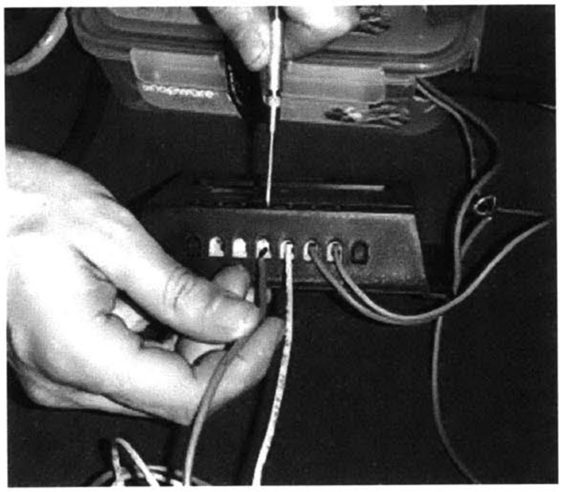


Everything must be wired up correctly for the system to work. A wiring schematic will come soon. The following list of connections is every connection required.

There will be multiple wires coming out of each Renogy terminal. Here are the connections from the Renogy charge controller:

6. Renogy ‘battery’ +/- (middle two) terminals go to the battery’s +/- terminals
    a. +/- is red/yellow
7. Renogy ‘panel’ +/- (left two) terminals go to the solar panel’s +/- leads
    a. +/- is red tape/black tape
8. Renogy ‘light’ +/- (right two) terminals go to the Anaheim Automation motor controller in the bottom control box ‘Vin’ and ‘GND’
    a. +/- is red/blue

To connect a terminal, put the exposed part of the wire in the opening and tighten the screw on top of it. To release the wire, unscrew the terminal and pull the wire out.



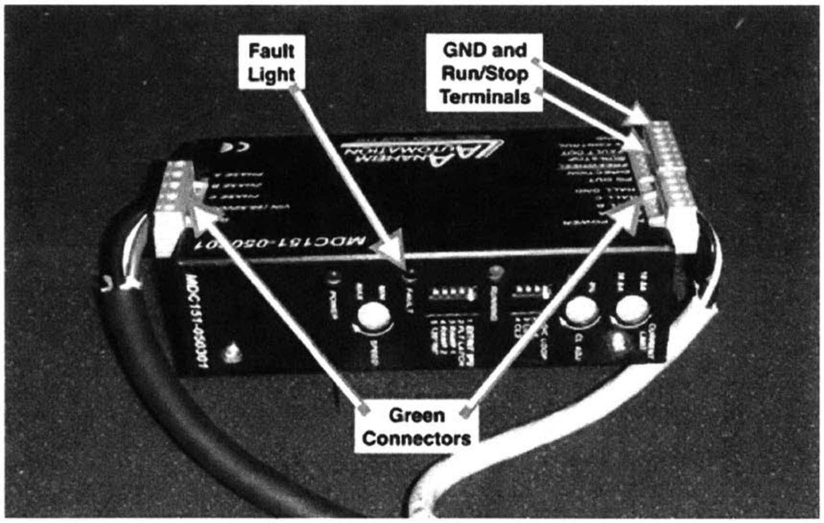
Check that the units are not overheating in the control box. On hot days they may need to be used outside of the control box to prevent over-heating. This will especially be likely for the Anaheim Automation controller in the bottom control box.

Renogy indicator lights:

Symbol	Light Indicator	Meaning
Panel	Green <u>ON</u>:	Solar power is connected
	Green <u>BLINKING</u>:	The system is over voltage
Battery	Green <u>ON</u>:	Battery level is right
	Green <u>SLOWLY FLASHING</u>:	Battery is full
	Orange <u>ON</u>:	Battery is low
	Red <u>ON</u>:	Battery is too low
Light/Output	Orange <u>ON</u>:	The output is on
	Red <u>SLOWLY FLASHING</u>:	Overload
	Red <u>BLINKING</u>:	Load is short circuit

The output indicator number can be changed by holding the 'on/off' button down until the number flashes. Then, you can change the number by pressing the 'on/off button.' To set the mode, hold the 'on/off' button until the number stops flashing.

The output indicator number should be 6. In mode 6, the system output can be turned on and off by pushing the 'on/off' button.



Anaheim Automation

If an Anaheim Automation controller is broken, remove the green connectors from the broken box, and attach them to a new box. This is easier and more reliable than using the screw terminals.

If red fault light in the bottom control box is on:

5. Check that the motor is connected inside the housing
6. Check that all connections on the Anaheim Automation controller in the bottom control box are connected
7. Check that the pump housing does not have water in it.
    a. If it has leaked:
        i. Disconnect the motor
        ii. Leave the motor and housing top to dry for at least 2 days
        iii. Disconnect the 'RUN/STOP' and 'GND' terminals, and plug the motor in with the Anaheim Automation box powered.
    b. If there is still a fault light:
        i. Gently remove the impeller from the motor shaft with 2 or more flat screwdrivers or something similar.
        ii. Unscrew the motor from the housing, clean off the black thermal paste that is still on the aluminum housing plate.
        iii. Leave it to dry for 2 more days
        iv. Repeat step 3.a.
    c. If the motor is still not working, replace it.
        i. When replacing it, screw the motor onto the top housing.
        ii. Then use the black paste to attach the aluminum bars to the sides of the motor so they touch the aluminum top plate and the housing tube still slides over the motor and aluminum bars.

Batteries

The green wire on the batteries should connect to the green taped terminals on each battery.

Do not over-charge the batteries. If they fill up at a low-voltage *determine what that voltage is for these batteries* or discharge too quickly, they likely need to be replaced. It may be the case that both batteries need to be replaced at the same time.

Solar Panel

Cleaning

Make sure that the panels are cleaned regularly. This can easily be done with a dry cloth and should be done every time the panels are brought outside to prevent a buildup of dust.

Position and Angle

1. In the summer (March 30 – September 12), the panels should be tilted at 2.3 degrees, which is practically flat
2. In the winter (September 12 – March 30), the panels should be tilted to 41.4 degrees, or a little bit more flat than halfway
3. The panels should point to 'True South.' In India, true south is very close to magnetic south so magnetic south should be used to orient the panels.

4. The solar panels must not be shaded. If they are shaded (by a person, tree, or bush) the pump will shut off.

6.3. Interview Notes

Written by Katherine Przystup

Date of Interview	3/25/2015	3/25/2015	3/26/2015
Village	Sombra	Sombra	Jenasai
Name	Salukar Sombre	Salm Sumed (This is the uncle of Salukar Sombre. This interview morphed into combined interview with his nephew and so many of the questions had already been answered).	Singh
When is the harvest season?	The end of September until June.		Summer: March, April, May (Vegetables) Winter: Oct-Feb
Do you have other sources of income?	No, fully dependent on agriculture.		Sell milk from cows
What do you do outside the harvest season?		Stays in the village, leisure.	
Which crops do you grow and how much do you earn from each crop?	70,000-80,000 rupees for vegetables 70,000-80,000 rupees for rice		Cabbage, cauliflower, tomatoes, green chili, rice 40 rupees/kg for tomatoes. However, this depreciates in value depending on the time of year it is sold.
Where do you sell your harvest?		Small markets	Small village market, CKP
What are the costs of growing crops?		475 rupees for 1 month	Pesticides, diesel
Where did you purchase your diesel pump?	Pradan		Pradan
How much did it cost?	It was free		It was free
How much diesel do you use?	During the dry season, 1 liter of diesel is needed each day.		
Where do you purchase diesel?	Travel by bicycle to CKP and purchase 5-10 liters each trip.		
What are the benefits of using the solar pump v. the diesel pump?	The solar pump isn't working properly. However, if it was working the benefits would be that he doesn't have to pay for diesel, the trip to CKP to	The solar pump is easier to use. The diesel pump is difficult to understand. The solar pump requires only 1-2 days of training.	Don't have to pay for diesel, can save money, it's easier to use. Only takes 15-20 minutes to learn how to use it.

	buy diesel wouldn't be necessary, and it's easier to use.		
Would you prefer to rent or own a pump?			Own
Is 30,000 rupees too high of price for the solar pump?	No, because a diesel pump costs 40,000 rupees		
Are there any financial institutions nearby?	No, there no institutions nearby. There are no loans available to them.		There are banks in CKP. Getting a loan is not an easy process. If they wanted a loan, someone from Pradan would take them there.
Would you be open to taking out a loan?			Yes, because 30,000 rupees is too high to pay up front. He would expect the down payment to be 5000 rupees and to pay the loan over 3 years.
How much are you able to save each year?	15,000-20,000 rupees		
What is the size of your family?	10 people: wife, 2 children, 4 brothers, and his brother's family		
Who makes financial decisions in your family?	His father makes decisions about savings and expenditures. He makes the decisions about agriculture.		There is small union of farmers and there is a community leader. The decision to participate in the pilot project for the solar pump was first made in a small group and then approved by the community leader.
If you had additional savings from using the solar pump, what would you spend it on?	Education for children	Save money for the future, bigger home, education	Purchase more land from neighbors, educate children, learn more farming techniques
What are your goals for the next 5 years for you and your family?	Educate children, grow mangos,	Other crops, bigger farm	Good experience for children, learn better farming techniques. *Farming techniques are passed down generation to generation. They don't usually learn new techniques from non-relatives.