THE POTENTIAL APPLICATION OF DUCKBILL CHECK VALVES IN LOW-COST HANDPUMPS USED IN THE DEVELOPING WORLD

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by

Christie Lauren Hutchison

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ABSTRACT

CHRISTIE LAUREN HUTCHISON
The Potential Application of Duckbill Check Valves in Low-Cost Handpumps Used in the Developing World
Under the direction of DR. MICHAEL F. MACCARTHY

The purpose of this study was to determine the potential for application of duckbill check valves in low-cost handpumps used in the developing world. In pumping scenarios where the fluid being pumped contains sediment, the check valves currently used in handpumps can experience technical performance issues. Handpumps can lose performance ability and, in some cases, all functionality in the presence of such issues.

In this study, duckbill valves were explored as an alternative check valve option for use in low-cost handpumps. Literature was reviewed on the duckbill valve's design and fluid mechanics, history, and uses across various professional fields. The technical performance of duckbill valves was also tested with two different manufactured valves whose intended uses were for small-scale pumping applications. Manometers were constructed to test the two manufactured duckbill valves for differences in positive and negative pressure heads required for valve breakthrough. Finally, a duckbill valve was constructed with materials that can commonly be found in developing world contexts. The homemade valve was tested with the same methods used to test the manufactured valves.

A review of the literature confirmed the potential applicability of duckbill check valves in handpumps. The results of both positive breakthrough pressure tests run on the manufactured duckbill valves indicated that any measurable positive pressure applied to the back of the duckbill caused valve breakthrough. Results of the negative pressure test similarly indicated that the valves required minimal application of suction pressure to achieve breakthrough. Fabrication techniques used to construct the homemade duckbill valve proved to be unsuccessful, as the homemade valve failed to prevent backflow. Future work should investigate alternative techniques for fabricating duckbill valves in a developing context that will allow for the production of duckbill valves with more detailed design specifications and, in turn, better functionality.

CHAPTER 1

INTRODUCTION

Motivations

Handpumps, or mechanical devices that are operated by hand to transfer fluids, are commonly used in the developing world for a number of applications. Most handpump designs incorporate check valve components which permit flow through a system in only one direction while preventing backflow (i.e. flow in the opposite direction). In scenarios where the fluid being pumped contains sediment (e.g. sand, clay, etc.), the check valves in these handpumps are prone to clogging and mechanical failures. As an alternative to the three types of check valves that are most often incorporated in handpump designs, this research assesses the potential applicability of a fourth type of check valve, known as the duckbill valve, for use in handpumps. The duckbill valve's characteristics and uses suggest that it has potential for alleviating technical performance issues currently seen when pumping water with sediment through handpumps.

Goal and Objectives

The goal of this research is to assess the potential of duckbill valves to pump water with sediment in handpump systems. The potential of duckbill valves for use in this context is assessed through literature review and technical performance testing. The research objectives were thus determined to be:

(1) To perform a literature review of duckbill valves and their common applications;

(2) To assess the technical performance of two models of manufactured duckbill valves;

(3) To construct and test a duckbill valve from materials that can commonly be found in developing world contexts.

CHAPTER 2

BACKGROUND

In the developing world, where water treatment and distribution infrastructure are commonly lacking or nonexistent, many individuals and communities are tasked with the responsibility of providing their own suitable sources of water for consumption and hygiene purposes. The two sources that are drawn from in these contexts are groundwater and surface water bodies. However, uncovered surface water sources are most often contaminated with an array of pathogenic life forms. Thus, as a solution to the global crisis surrounding the inaccessibility of safe drinking water for those in developing community contexts, non-government organizations (NGOs) often subsidize the drilling of boreholes and construction of wells for those in need. As a more sanitary alternative to the "rope and bucket" well water extraction technique, handpumps are frequently installed at these well sites [1]. Check valves often serve as components of these handpumps.

Check valves, also known as one-way valves or non-return valves, exist to permit flow through a system in only one direction while preventing backflow. Many are manufactured in developed regions to complement unique design specifications in water treatment facilities that serve large populations. However, in the developing community context, check valves may often be produced locally to ensure that costs remain low and repair and maintenance of the valves is possible for use in small-scale water projects. Because of their purpose and necessary function, it is essential that these valves are properly chosen for the applications they are to serve. It is also important that they be well constructed to ensure the longstanding operation and sustainability of handpumps.

Swing/Flap Valve

The swing valve, also referred to as a flap valve, is perhaps the most commonly used among check valves. A swing valve is comprised primarily of a disk or flap, a seat, and a hinge (*Figure 1*).

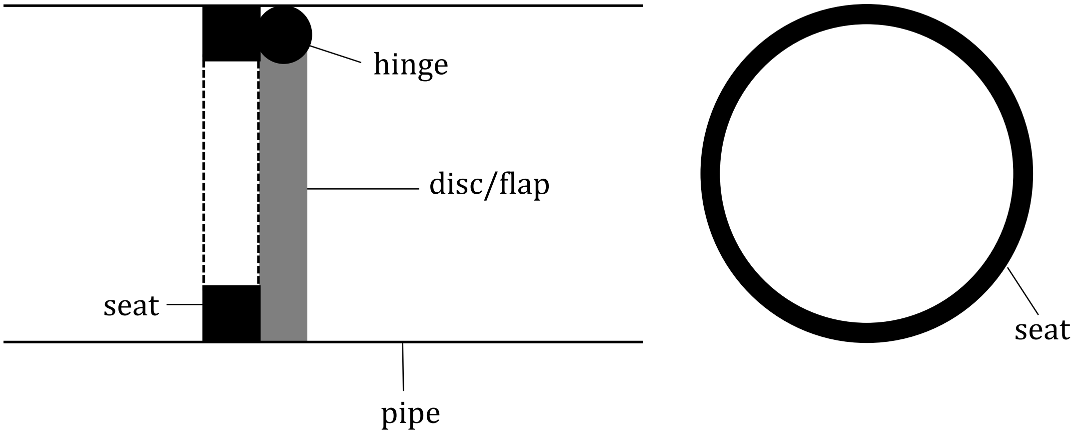

Figure 1. Swing/flap valve configuration and cross-sectional view of seat, respectively
Image drawn by Christie Hutchison

The disk or flap is slightly smaller than the inner diameter of the pipe that the check valve is installed in. The hinge connects the swing or flap to the inside of the pipe through which water travels. The seat is located directly opposite the hinge inside the pipe, just behind the swing or flap in the direction of flow. The swing or flap opens to permit flow in the desired direction. However, when the flow ceases or when water attempts to flow backward through the pipe, the valve closes and seals the pipe off (*Figure 2*) [2].

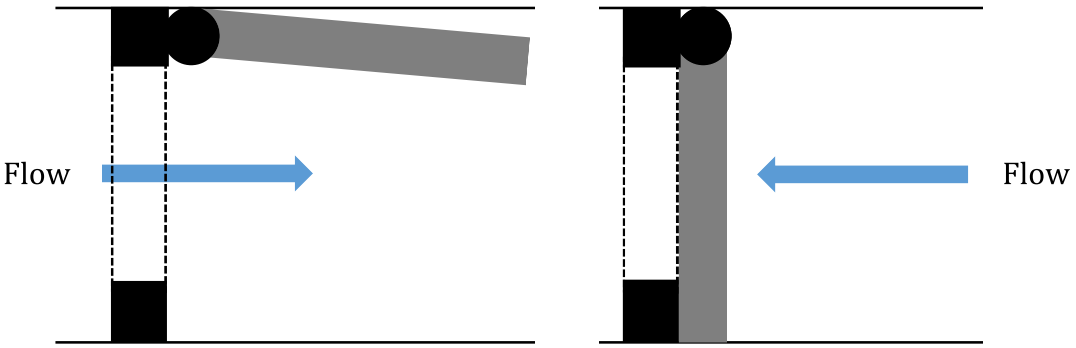

Figure 2. Swing/flap valve function in different directions of flow
Image drawn by Christie Hutchison

In a developing context, the materials used to construct a swing valve may include sheet metal or a weighted piece of leather that is attached to the hinge for the swing component. Hinges can be found at local hardware stores and any material from metal to plastic, rubber, or leather may be used to construct a seat for the valve. The seat may be attached to the inside of the pipe using PVC primer and cement. Swing/flap valves are commonly constructed at the bottom of bailers used for digging boreholes or retrieving water from boreholes. They are also used in a variety of handpumps including the pitcher pump and Tara handpump [1].

Ball Valve

A ball valve is made up of a ball or sphere, a seat, and a component that limits or restricts the movement of the ball in the direction of flow (*Figure 3*). The seat houses the ball in its rested position. The component that limits the movement of the ball is constructed on the side of the ball that is opposite the seat. This component is strategically placed such that the ball may only travel approximately an inch and a half from the seat.

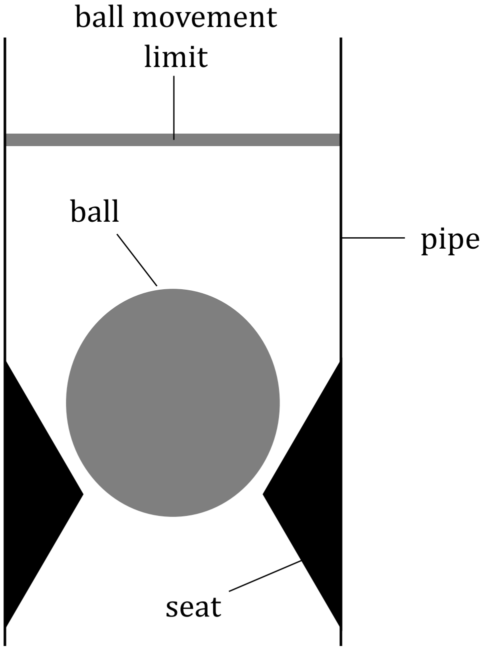

Figure 3. Ball valve configuration
Image drawn by Christie Hutchison

In the forward flow direction, the ball comes off the seat and presses against the movement limiting bar. When flow attempts to pass in the opposite direction, the ball returns to the seat, sealing off the flow area (*Figure 4*) [2].

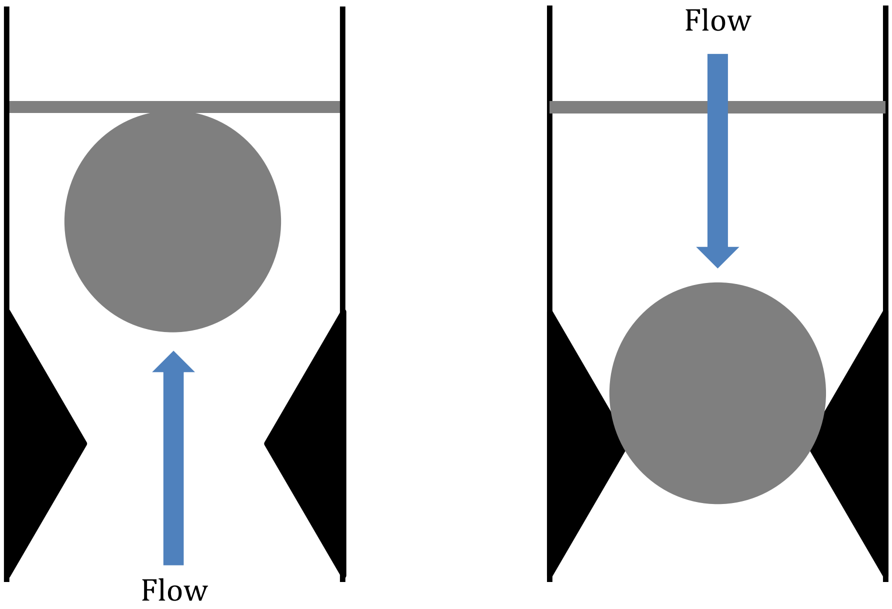

Figure 4. Ball valve function in different directions of flow
Image drawn by Christie Hutchison

In certain developing contexts, it is common for a glass marble to be used as the ball component in this particular type of valve [3]. A reducer bushing is often used as the seat of the valve and can be attached via PVC primer and cement to the pipe. The component that restricts the movement of the flow can be constructed with a plastic or metal rod that is pierced through pipe and cut flush with its sides. Ball valves are often chosen as foot valves and are used in handpumps such as the EMAS pumps and the India MK II handpump [1].

Lift Valve

A lift valve's three main components are a lift or disc, a perforated disc, and a guide (*Figure 5*). The diameter of the perforated disc is the same as the inner diameter of the pipe through which water is being moved. It has a central hole, through which the guide is secured, as well as a series of holes around its body. The latter holes are drilled in consideration of the turbidity and viscosity of the fluid that will pass through the valve. The solid disc has a central hole that allows it to slide freely along the length of the guide. While the diameter of the solid disc is smaller than the inner diameter of the pipe, it is also large enough that it covers all of the holes in the perforated disc when in the resting position [4].

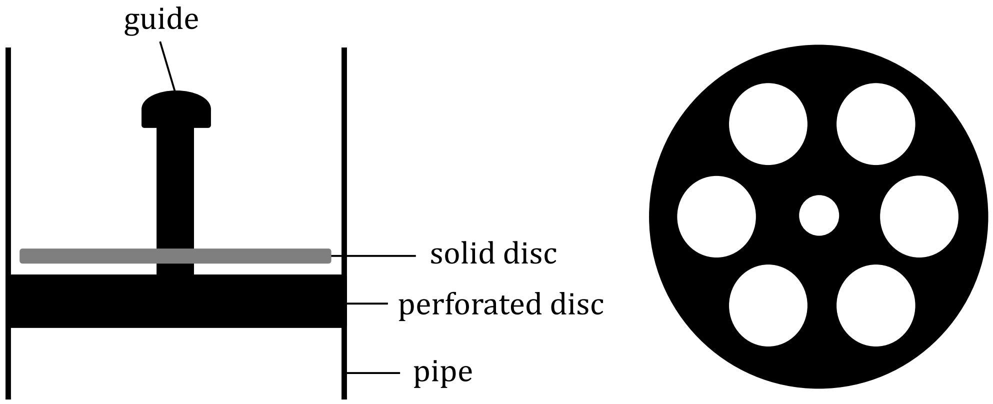

Figure 5. Disc/washer valve configuration and cross-sectional view of perforated disc, respectively
Image drawn by Christie Hutchison

In the forward flow direction, the solid disc lifts off the perforated disc and slides up the length of the guide. Water is allowed to pass through the holes of the perforated disc and around the sides of the solid disc. When pressurized flow in the forward direction is removed, or when it is applied in the opposite direction, the solid disc returns to its resting position on top of the perforated disc. Water is restricted from flowing backward through the valve (*Figure 6*) [2].

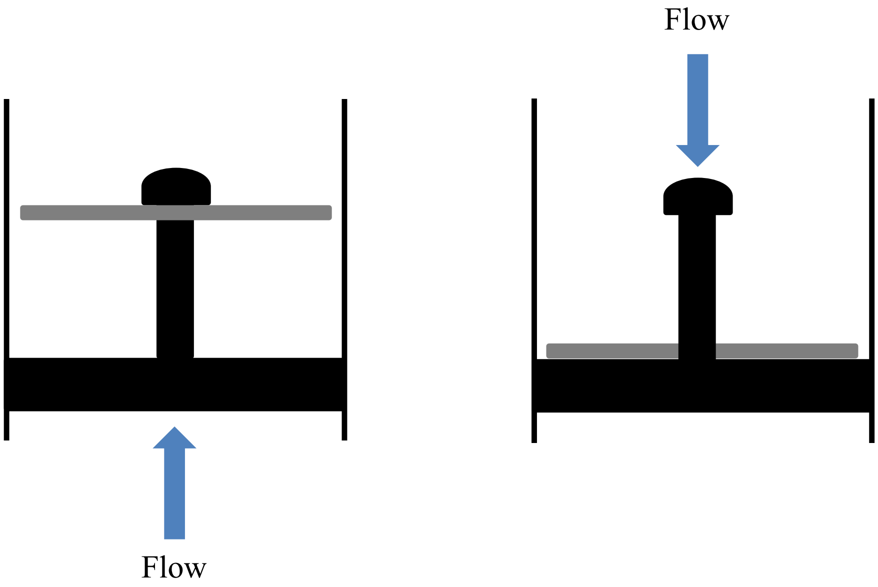

Figure 6. Disc/washer valve function in different directions of flow
Image drawn by Christie Hutchison

In a developing context, the perforated disc is often constructed by drilling holes in a piece of PVC and gluing the disc to the pipe using PVC primer and cement. Washer and bolt combinations are commonly used as the solid disc or lift and guide components, respectively; thus, the lift valve may also be referred to as a washer valve. The solid disc may also be constructed from rubber and attached securely to the perforated disc by a screw. In this scenerio, the disc does not slide up a guide, but rather, its rubber sides lift off the holes in the perforated disc to allow passage of water. Lift valves are used in handpumps such as the rower pump and hand pressure pump [4].

Problems Currently Experienced with Check Valves

The swing, ball, and lift check valves all have applications in handpumps that are used in developing contexts. Each of these types of check valves can feasibly be constructed using materials accessible in developing communities. However, in heavy sediment pumping contexts, the three valves discussed can experience mechanical failures. Sediment can become lodged between parts of the valves such that they cannot fully close to prevent backflow. In such a scenerio, the valves become significantly less efficient. Alternatively, sediment can cause the valves to become stuck in the closed position and prevent flow. Specifically in the swing valve, abrupt changes in flow may cause the flap to slam against its seat, creating water hammer and causing wear of the system [5]. In the ball valve, the glass marble often becomes weathered and smaller in size. Each of the these valves, when constructed using low-cost materials found in developing communities, have significantly shorter lifespans than those manufactured in developed regions. Thus, all three types of valves must also be replaced frequently in addition to their inherent mechanical failures.

CHAPTER 3

LITERATURE REVIEW

Duckbill Valve Design and Fluid Mechanics

The duckbill valve is characterized by its three different components, manufactured as a single, continuous material: the cuff, bill, and saddle (*Figure 7*). The cuff is located on one end of the valve and takes on the cylindrical shape by which the valve is fitted to a pipe or hose. Manufacturers denote the different duckbill valve sizes by the diameters of their cuffs. The bill is located at the valve end that is opposite the cuff. In the relaxed (i.e. natural) position, the bill forms a slit shape comprised of two "lips" or "gates". The saddle is the valve material between the cuff and the bill. It progressively narrows from the cylindrical shape of the cuff at one end of the valve into the slitted shape of the bill at the other end of the valve.

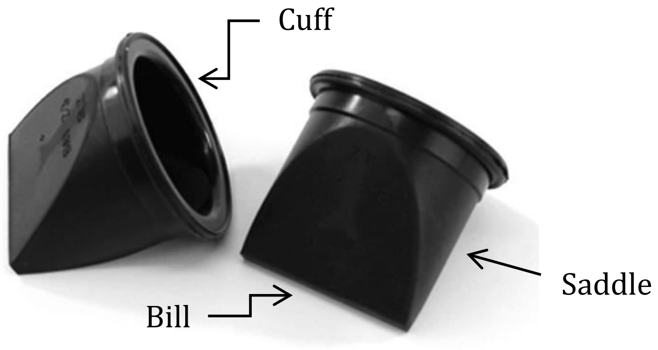

Figure 7. Components of a duckbill valve [6]

When pressurized flow is applied through the cuff of the duckbill, the assembly functions as a check valve. In response to the pressure, the bill opens, allowing the flow to pass through the saddle and out the other end of the valve. However, when the pressurized flow is removed from the cuff, the bill assumes its relaxed, slitted shape. Any pressure that is applied to the bill end of the valve causes the bill to seal even tighter than is naturally characteristic of its relaxed position (*Figure 8*). This sealing action prevents backflow, giving the duckbill its check valve designation [7].

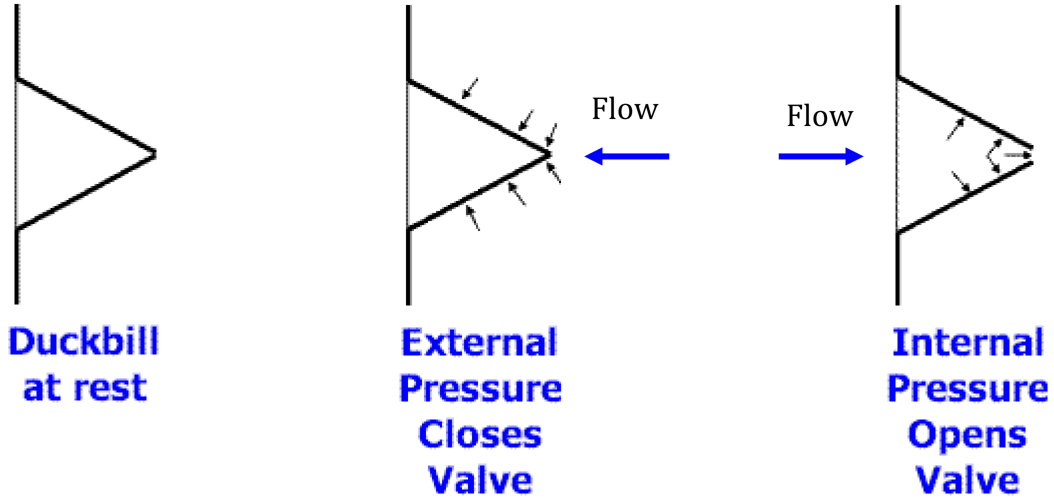

Figure 8. Function of duckbill valve under pressure from either direction [8]

While the exit velocity from fixed, or rigid body, diameter ports varies linearly with flow, the same cannot be said for the duckbill check valve [9]. The effective open area at the effluent end of the valve varies non-linearly with flow [10].

However, the effective effluent area of the duckbill valve has been found to maintain a linear relationship with the driving pressure head of the flow [9]. In other words, the greater the pressure head applied to the upstream flow, the larger the opening of the “bill” component of the valve. Energy loss across the body of the valve is considered to be negligible due to the smoothness of material that is used to manufacture duckbill valves: a “neoprene flexible material reinforced with synthetic fabric, much like a rubber automobile tire” [11].

The geometric design of a check valve may vary drastically depending on its application. In Tideflex® check valve technologies, the bill of the valve is characteristically designed so that its slitted length is 1.57 times the inner diameter of the pipe or cuff. It should be noted, though, that there are more than 50 different geometric and relative material stiffness designs of duckbill check valves within each nominal pipe or cuff diameter size [12].

Duckbill Valve History

Check valves, also referred to as non-return or one-way valves, open to permit flow in one direction and seal to prevent backflow [13]. Prior to the 1960’s, check valves were widely constructed of metals for use in the water industry. However, constant contact with fluids caused check valves used in water treatment processes to corrode. Specifically in the wastewater context, these valves also posed major mechanical problems to treatment facilities by repeatedly becoming clogged with influent debris.

The Red Valve Company addressed the aforementioned issues in 1961 by developing the pinch valve. Though the outer, supporting structure of the pinch valve is constructed of metal, the back flow prevention component of the valve is made of a tubular rubber sleeve contained within the metal body (*Figure 9*). Flow passes freely through the rubber sleeve inside the valve until the external actuator is tightened, at which point, the sides of the rubber tube are pressed together to discontinue passage of water through the valve. Use of this rubber sleeve eliminated the issue of corrosion and increased the efficiency of the check valve function in the presence of heavy sediment. A series of specialized rubber sleeve configurations were developed to further improve this efficiency. A cone-shaped sleeve, also patented by the Red Valve Company, was released to the market to allow passage of larger solids through pinch valves [14].

Figure 9. Cut-away view of pinch valve [15]

After experiencing the success of the pinch valve, and in consideration of its design components, the Red Valve Company produced another new technology that was of particular importance to the wastewater industry. In 1981, the company was commissioned by the Environmental Protection Agency (EPA) to develop the first all-rubber "duckbill" check valve [14]. The valve (*Figure 10*) was designed as a fully-functional, standalone piece of equipment; it resembled half of the rubber sleeve in a pinch valve when in the closed position, but required no external actuation for its use. Elimination of all metal parts for this particular check valve's design inherently resolved the issues that mechanical check valves had sealing off against backflow containing heavy sediment; the elastomer material used for the duckbill valve gates successfully sealed whenever pressure was removed, even in the presence of large solids. In 1984, after three years of testing, Red Valve installed its first duckbill valve on the Wards Island Outfall in New York City to prevent inflow of tidal water. The valve was fifty-four inches in diameter and is still in use to this day. The duckbill valve was so successful that over 600,000 of similar size and millions in smaller sizes currently service a number of gravity-fed and pumping applications in the United States [12].

Figure 10. Duckbill valve serves as tide gate for outfall [16]

Existing Applications of the Duckbill Valve

Duckbill valves have a large number and variety of applications in water treatment and transportation contexts. They were first introduced to the industry through use on wastewater effluent pipes. In many cases when a plant location is coastal, these outflow pipes introduce treated water into the ocean. Duckbill valves prevent sea water, as well as salt water plants and creatures, from flowing into the outflow pipes during times of tidal rise. When utilized in this way, duckbill valves are referred to as “rubber tidal gates” [14]. These valves are also scaled down and used in wastewater transportation infrastructure prior to treatment; it is common for duckbill valves to be used in place of tilted, tilted weight and lever, and tilted spring and lever check valves within wastewater lift station configurations [12]. Preliminary research conducted at the University of South Florida has also identified similarities between the circulation of slurry in EMAS manual percussion-jetting-rotation drilling and the biological circulatory system, suggesting that duckbill valves be used in this drilling process and comparing its function to a heart valve in the circulatory system [17].

Despite the fact that duckbill valves are used in water contexts for the purpose of this research, they have applications in many other fields. After their proven success in outflows, the valve design was adapted for use as a diffuser under other circumstances [14]. Specifically in the biomedical field, duckbill valves have found a number of uses. For many laryngeal cancer patients, the duckbill valve allows for communication through speech long after the erosion of the larynx. Prosthetics often include the use of a duckbill valve that is inserted in the tracheoesophageal puncture. The valve's low resistance to flow, even in small pressure applications, makes the duckbill valve a particularly desirable piece of equipment for this job [18].

Another biomedical application of the duckbill valve again involves its use for the transportation of fluids. Hydrocephalus, or "water on the brain", caused by birth defects, brain abnormalities, tumors, inflammations, infections, encephalitis, intracranial hemorrhaging, or trauma may be relieved by the use of this rubber valve. Research has recently been conducted to investigate the duckbill valve's use for draining cerebrospinal fluid in place of the commercial one-way membrane valve. Data suggests that the application of duckbill valves in this context may well reduce the rate of shunt failures in patients [19].

CHAPTER 4

METHODOLOGY

Duckbill Valves

Several models of duckbill check valves were considered for this study. Two pre-manufactured duckbill valves intended for use in small pumping applications were selected for testing. The ⅜-inch Maymom® breast pump duckbill valve (BPDV) manufactured as a replacement part for the Ameda Purely Yours® breast pump series and the 1 ¼-inch Sealand® vacuum pump duckbill valve (VPDV) manufactured as a replacement part for vacuum and discharge pumps were chosen for testing. Both duckbill check valves fell within a size range that was comparable to that of check valves used in small-scale manual pumping technologies commonly used in developing communities. The BPDV allowed for testing of a thinner elastomer material while the VPDV was made of a thicker elastomer material and provided a contrast for experimentation purposes. Because of its intended application in a portable sewage pumping configuration, the VPDV was particularly chosen to represent a valve that was well suited to moving liquids high in sediment. *Figure 11* shows the BPDV and VPDV respectively.

Figure 11. Maymom® breast pump duckbill valve and Sealand® vacuum pump duckbill valve, respectively

In addition to the two pre-manufactured duckbill valves, a homemade duckbill valve was constructed and tested. The duckbill was constructed from a 26-inch universal bicycle inner tube. A 3 ½-inch section of the tube was cut out and stretched over a 3-inch long piece of 1-inch PVC. The inner tube was secured to the piece of PVC with a ¾-inch to 1 ½-inch stainless steel adjustable clamp such that the tire and PVC overlapped ¾ of an inch. Starting at the far end of the inner tube, the sides were pressed together and 3 staples were punched along each of the two edges such that it resembled a duck bill. Heavy polyester thread was used to sew up the sides of the tire, just inside the staples. Silicone adhesive sealant was painted over the holes around the thread and staples on either side of the valve and allowed to cure for twenty-four hours to prevent leaking. *Figure 12* shows the homemade duckbill valve after construction.

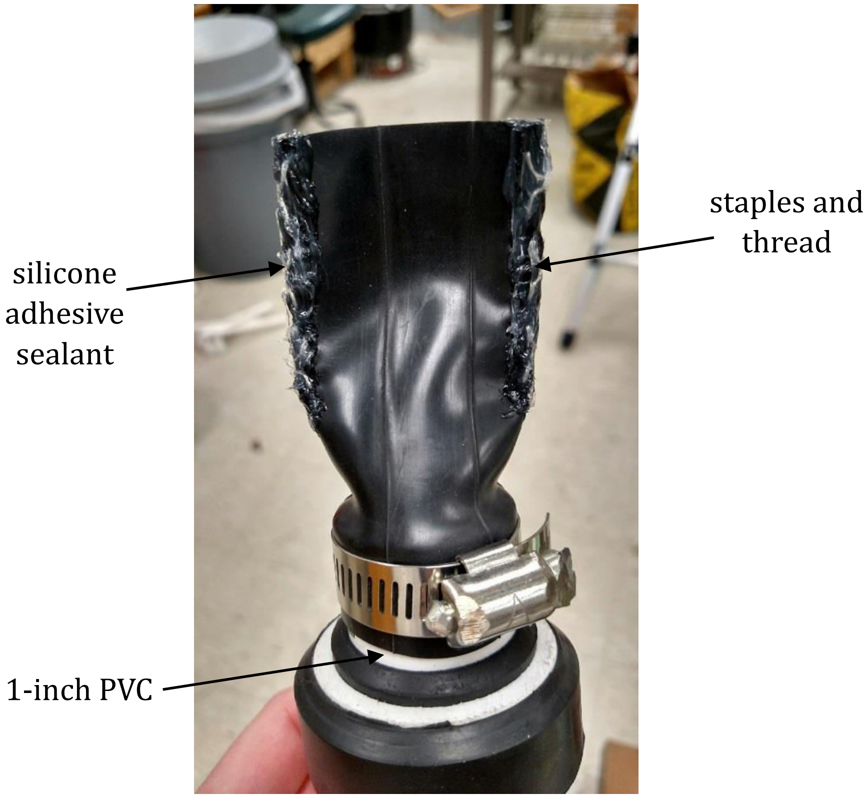

Figure 12. Homemade duckbill valve

Manometer Construction

Three different manometer configurations were constructed. Transparent 8-foot pieces of 1-inch PVC pipe were used as the vertical tubes on either side of the manometers. An 8-foot tape measure was taped along the length of each vertical pipe. The check valves were positioned such that flow was allowed to pass through the manometers from left to right. A 1-inch by ¾-inch slip to thread reducer bushing was cemented to the outflow vertical pipe on the right side of each manometer. A Mityvac® vacuum pump was attached to the reducer bushing to allow for negative pressure testing.

Maymom® breast pump duckbill manometer

The BPDV was secured inside a ¾-inch PVC union socket. A 4-inch long piece of ¾-inch PVC pipe was cemented to each side of the union. The 4-inch PVC pipe lengths on either side of the union socket were cemented to 1-inch by ¾-inch slip reducer bushings. These bushings were cemented to 1-inch slip PVC tees. Two 1-inch by ¾-inch slip to thread PVC reducer bushings were cemented to the far ends of the two PVC tees. Thread sealant tape was used to join ¾-inch by ½-inch threaded male adapters and two ½-inch brass drain valves to the 1-inch by ¾-inch slip to thread reducer bushings on the PVC tees. *Figure 13* shows the BPDV manometer configuration described. The 8-foot transparent PVC pipes were connected to the PVC tees using silicone grease.

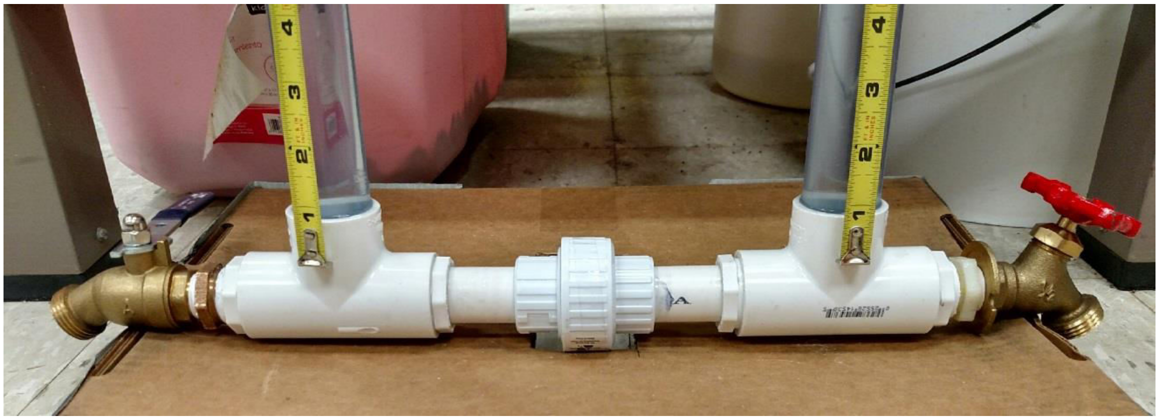

Figure 13. Maymom® breast pump duckbill manometer configuration

Sealand® vacuum pump duckbill manometer

The VPDV was secured inside a 1 ½-inch PVC slip union socket. A 4-inch long piece of 1 ½-inch PVC pipe was cemented to each side of the union. The 4-inch PVC pipe lengths on either side of the union socket were cemented to 1 ½-inch by 1-inch by 1 ½-inch slip PVC tees. Two 1 ½-inch by 1-inch slip PVC reducer bushings were cemented to the opposite ends of the tees. These reducer bushings were cemented to 1-inch by ¾-inch slip to thread reducer bushings. Thread sealant tape was used to join ¾-inch by ½-inch threaded male adapters and two ½-inch brass drain valves to the 1-inch by ¾-inch slip to thread reducer bushings on the PVC tees. *Figure 14* shows the VPDV manometer configuration described. The 8-foot transparent PVC pipes were connected to the PVC tees using silicone grease.

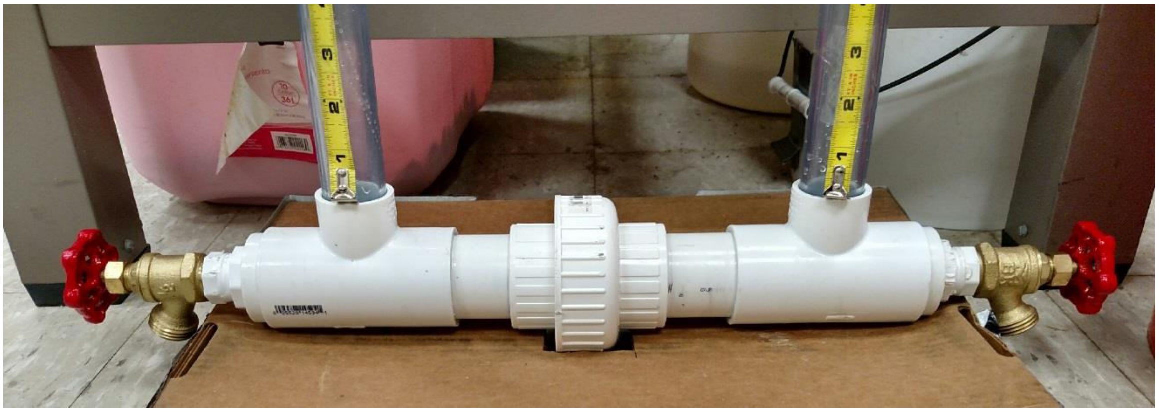

Figure 14. Sealand® vacuum pump duckbill valve manometer configuration

Homemade duckbill manometer

A rubber compression ring was placed just behind the homemade duckbill valve on the piece of 1-inch PVC. The 1-inch piece of PVC was then inserted inside a 4-inch long piece of 1 ½-inch PVC such that the rubber compression ring secured the 1-inch PVC inside the 1 ½-inch PVC. A second rubber compression ring was placed on the edge of the 1 ½-inch PVC just behind the protruding 1-inch PVC and duckbill valve (*Figure 15*).

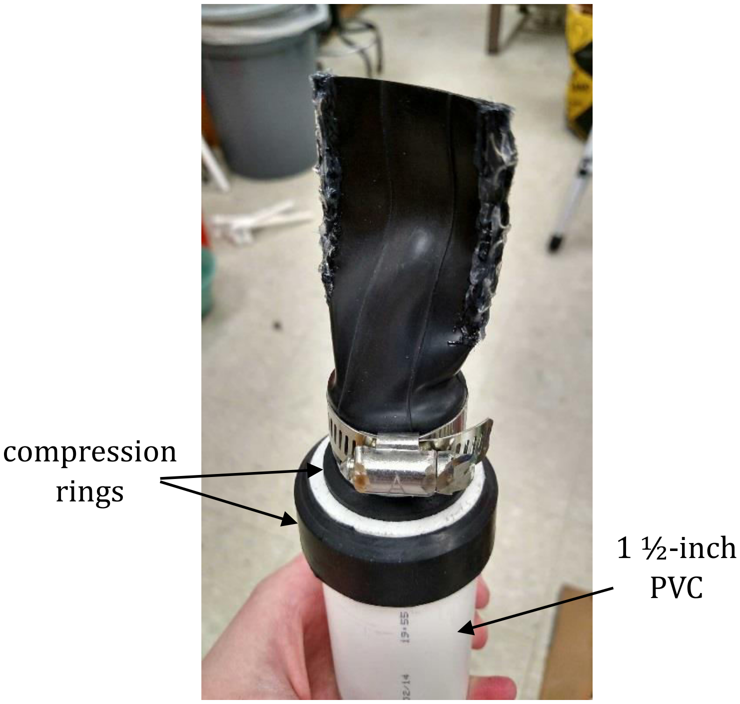

Figure 15. Homemade duckbill valves with compression rings

The 1 ½-inch PVC was then inserted inside a 1 ½-inch diameter coupling such that the duckbill valve was completely enclosed inside the coupling. The nut was slid over the back side of the 1 ½-inch PVC and secured to the coupling. Another 4-inch piece of 1 ½-inch PVC was attached to the other side of the coupling with a compression ring and nut. The two pieces of 1 ½-inch PVC on either side of the compression fitting were cemented to 1 ½-inch by 1-inch by 1 ½-inch slip PVC tees. Two 1 ½-inch by ¾-inch slip to thread PVC reducer bushings were cemented to the opposite ends of the tees. Thread sealant tape was used to join ¾-inch by ½-inch threaded male adapters and two ½-inch brass drain valves to the 1-inch by ¾-inch slip to thread reducer bushings on the PVC tees. *Figure 16* shows the homemade duckbill valve manometer configuration described. The 8-foot transparent PVC pipes were connected to the PVC tees using silicone grease.

Figure 16. Homemade duckbill valve manometer configuration

Vacuum Pump Connection

A ¾-inch thread to slip female adapter was cemented to a 3-inch long piece of ¾-inch PVC pipe. The opposite end of the piece of ¾-inch PVC pipe was cemented to a ¾-inch by ½-inch slip to thread female adapter. Thread sealant tape was used to join a ¼-inch poly barb adapter to the ¾-inch by ½-inch slip to thread female adapter. A Mityvac® vacuum pump was connected to the ½-inch x ¼-inch poly barb by 25-feet of ⅜-inch outer diameter by ¼-inch inner diameter polyethylene tubing. This attachment was secured to the right sided vertical PVC pipes on the manometers by the 1-inch by ¾-inch thread to slip bushing for negative breakthrough pressure testing. *Figure 17* shows the fully assembled vacuum pump connection. Thread sealant tape was wrapped around the threaded end of the bushing before connection to each manometer.

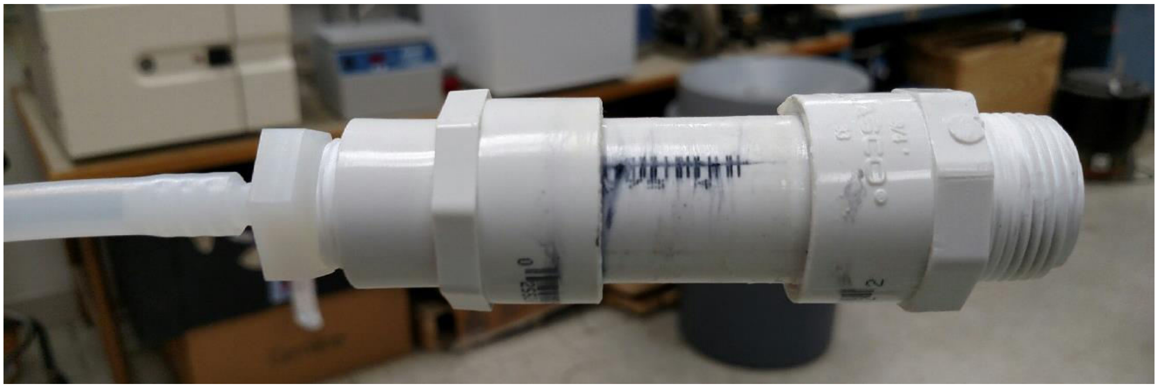

Figure 17. Vacuum pump connection

Breakthrough Pressure Testing

It was assumed that the positive pressure needed for valve breakthrough would differ from the negative pressure needed for breakthrough. Thus, two types of tests were conducted for determining the breakthrough pressures of the check valves. It was also determined that due to the duckbill valve design, orientation of the valves in the manometer would have no effect on the breakthrough pressure testing results. The duckbill valves were oriented horizontally in their respective manometer configurations for the duration of the testing period to accommodate for the height of the room in which the tests were run.

Positive Pressure Testing

Both the vertical pipes on the left and right sides of the manometer configurations were filled with water to a height of 12-inches. Water was added to the vertical pipe on the left side of the manometers until movement in the water columns was observed. The height of water in the left column at which breakthrough of the check valve was accomplished was noted. The same experiment was repeated for initial heights of water at 2, 3, 4, 5, 6, and 7-feet in both columns.

Negative pressure testing

Both the vertical pipes on the left and right sides of the manometer configurations were filled with water to a height of approximately 46 inches. The suction pump attachment was connected to the right sided vertical pipe of the manometer being tested by the 1-inch by ¾-inch thread to slip reducer bushing and thread sealant tape. The Mityvac® vacuum pump was squeezed until its gauge read a pressure of 2-inches of mercury. Water heights in both columns were recorded. The pump was squeezed and the water heights were repeatedly recorded for pressures at 3, 4, 5, and 6-inches of mercury.

CHAPTER 5

RESULTS AND DISCUSSION

Literature Review – Duckbill Valve Design and Applications

A review of the literature confirmed the potential applicability of the duckbill check valve in handpump technologies. The duckbill valve's uses for controlling wastewater transport prior to treatment suggested that the valve was designed to handle flow high in sediment. The elastomer material commonly used to manufacture duckbill valves was also noted in the literature as being comparable to that of a rubber automobile tire, a material widely available in developing contexts.

Manufactured Duckbill Valve Assessment

Analysis and interpretation of the data was driven by Equation 1, Bernoulli's theorem, which states that the sum of pressure, kinetic, and potential energies are constant at any point for non-viscous, incompressible, steady state fluids.

$$\frac{P_1}{\gamma} + \frac{{v_1}^2}{2g} + z_1 + \Delta h_{pump} = \frac{P_2}{\gamma} + \frac{{v_2}^2}{2g} + z_2 \qquad (1)$$

$$[pressure\ energy + kinetic\ energy + potential\ energy \ldots]$$

All experiments were conducted from a state of zero velocity such that the kinetic energy terms on either side of Bernoulli's equation were eliminated. The position of the datum was designated at the midpoint of each valve's bill.

The results of the positive pressure tests indicated that both valves achieved breakthrough when a pressure head of less than $^1/_{16}$–inch of water was applied to the backs of the valves. When as little as a few drops of water were added to the left-sided vertical pipe of a manometer, movement was observed of the water level in the right-sided vertical pipe until the water in both columns reached an equal height. This result was true for both valves at all initial testing heights. Since measurements of pressure head were limited by the tape measure taped along the length of each vertical pipe, accurate data could not be collected for the exact height of added water at which breakthrough was achieved.

Negative pressure testing results for the two valves are given in *Tables 1* and *2*. Additionally, the Maymom® pump duckbill valve was removed from its respective manometer and the negative pressure test was run so that anomalies in the pump could be identified. The results of the negative pressure test run without a duckbill valve are presented in *Table 3.*

Table 1. Maymom® Pump Duckbill Data

$z_2 - z_1$ (in H_2O)	Δh_{pump} (in Hg)	Δh_{pump} (in H_2O)	$z_1 + \Delta h_{pump} - z_2$ (in H_2O)
0	0	0	0
26.375	2	27.14	0.765
39.75	3	40.71	0.96
53.25	4	54.28	1.03
67	5	67.85	0.85
80.5	6	81.42	0.92

Table 2. Sealand® Duckbill Data

$z_2 - z_1$ (in H_2O)	Δh_{pump} (in Hg)	Δh_{pump} (in H_2O)	$z_1 + \Delta h_{pump} - z_2$ (in H_2O)
0	0	0	0
26.65625	2	27.14	0.48375
40.5625	3	40.71	0.1475
53.59375	4	54.28	0.68625
67.75	5	67.85	0.1
80.5	6	81.42	0.92

Table 3. No Duckbill Data

$z_2 - z_1$ (in H_2O)	Δh_{pump} (in Hg)	Δh_{pump} (in H_2O)	$z_1 + \Delta h_{pump} - z_2$ (in H_2O)
0	0	0	0
27	2	27.14	0.14
41.0625	3	40.71	-0.3525
54.3125	4	54.28	-0.0325
68.09375	5	67.85	-0.24375
81.0625	6	81.42	0.3575

Negative values represented in the fourth column of the *Table 3* are indicative of the suction pump's imprecision in gage units. Because the pump gauge measured in units of inches mercury and the data was converted to and interpreted in inches water, discrepancies are assumed to be present in the pump head data. The values presented in the final column of each table are representative of the additional pressure head required to achieve breakthrough of the duckbill valves by suction alone. *Figure 18* shows the relationship between the movement of water through the columns and the pressure head read on the suction pump. *Figure 19* depicts the relationship between the negative pressure head required to achieve valve breakthrough and the pressure head read on the suction pump.

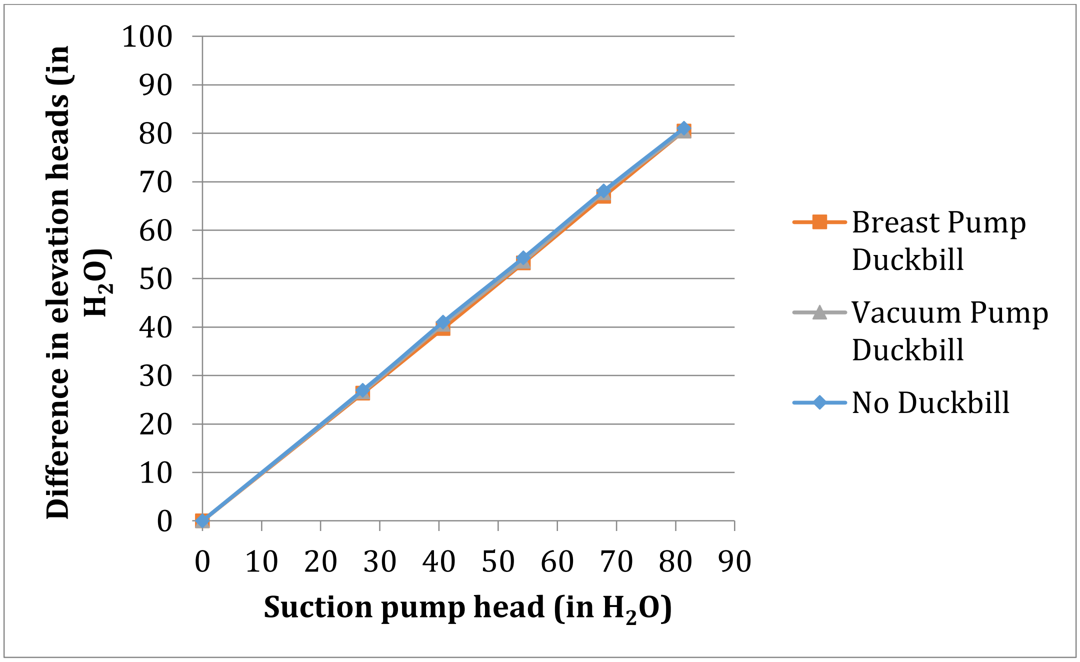

Figure 18. Performance comparison of manufactured duckbill valves

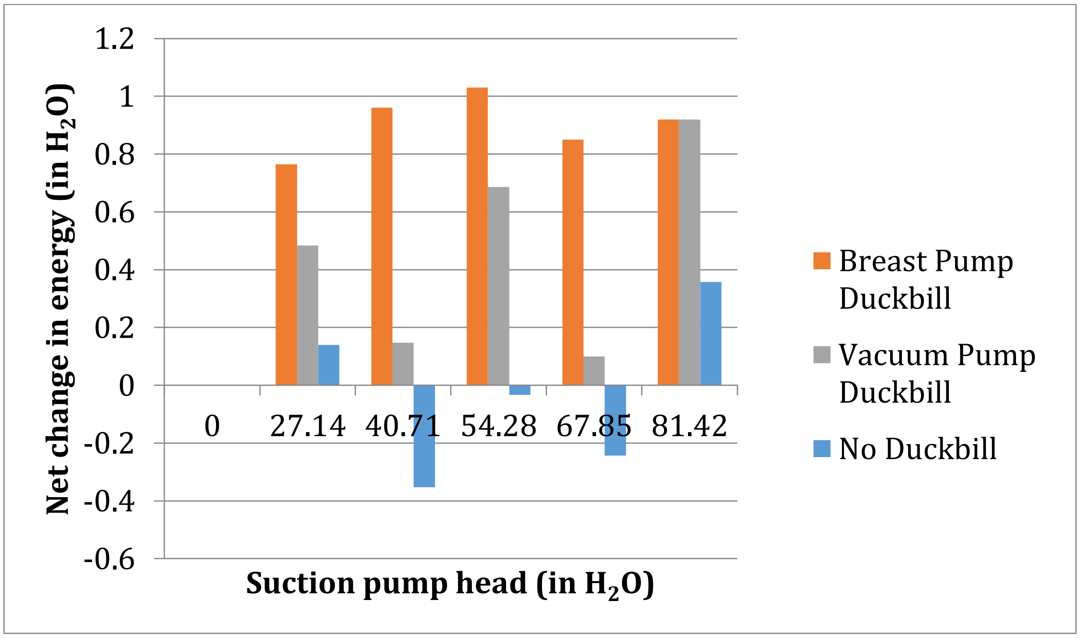

Figure 19. Departure from ideal theoretical performance

The data provides proof of the concept that different duckbill valves do require different amounts of pressure head to achieve breakthrough. However, the two manufactured duckbills tested for the purpose of this research were very similar; as can be seen in *Figure 18*, both valves required the application of very small amounts of negative pressure head to achieve breakthrough. The similarities between the "No Duckbill" data and the "Vacuum Pump Duckbill" data graphed in *Figure 19* highlight the anomalies of the suction pump used to conduct the negative pressure tests.

Construction and Testing of Low-Cost Duckbill Valve

Tests run on the homemade duckbill valve after the first stages of construction revealed that the valve was not successfully sealing against backflow. The valve was removed from the coupling and ¾-inch was cut from its bill, just behind the frontmost staple (*Figure 20*).

Figure 20. Material cut from bill of homemade valve

Reinsertion into the coupling and a second round of testing revealed that the valve was still allowing backflow. The valve was removed a second time. A quarter of the length of the bill was sewn together on either side of the valve using the same heavy polyester thread. Silicone adhesive sealant was again painted over the holes around the thread and allowed to cure for twenty-four hours (Figure 21). After being reinserted into the coupling, a third round of testing revealed that the valve was still allowing backflow, but at a much slower rate.

Figure 21. Duckbill sewn in and glued along outer length of bill

When comparing the designs of the two manufactured duckbills with that of the homemade duckbill valve, one major difference was noted and is thought to have attributed to their variations in performance; the manufactured duckbill valves both featured walls that parabolically tapered to the slit at the bill of the valve while the homemade duckbill did not. Geometrically speaking, the flat, parabolic taper incorporated into the designs of the manufactured duckbill valves allowed the backpressure created by water in a pumping scenario to act against each of the two walls in a single direction. The pressure distributed from the outside of the two opposing, flat walls of the duckbill, in corporation with the ovular sides of its saddle, encourage the bill of the valve to seal shut. The homemade duckbill valve that was fabricated from bicycle inner tube tire did not taper parabolically such that its two walls maintained a flat shape. Rather, the sides of the bicycle inner tube tended to maintain the cylindrical shape that it was manufactured to uphold. The cylindrical shape of the sides would have allowed water to act on the duckbill in a number of different directions rather than the desired two, opposing directions along its two main walls (*Figure 22*).

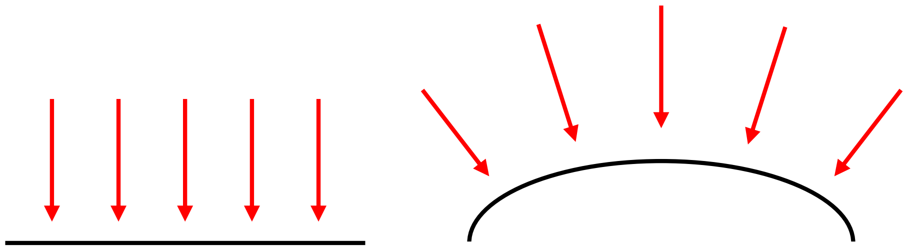

Figure 22. Difference in fluid forces acting against one side of saddle body

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The duckbill valve's historical uses in wastewater transportation contexts, as indicated by the literature, suggest that the valve is well-equipped to handle fluid flow that is high in sedimentary content. The elastomer material commonly used to manufacture duckbill valves is also widely available in developing contexts in car and bicycle tire inner tubes, making the duckbill valve a seemingly suitable alternative to the check valves currently used in handpump technologies. Testing results confirm that very little applied positive and negative pressure head is required to achieve valve breakthrough for two different models of manufactured duckbill valves that are similar in size to a check valve that would be used in a developing world handpump. Though the homemade duckbill valve constructed for the purposes of this research was not successful in sealing against backflow, the duckbill valve technology does have potential for use in the developing world context. Further research should be conducted as to the optimal methods for construction of the duckbill valve in such contexts.

Recommendations

The two manufactured duckbill valve models both shared the common characteristic of flat sides that tapered parabolically along the lengths of their saddles down to their respective bills. Because the homemade duckbill valve was constructed using a bicycle tire inner tube, the elastomer material tended to maintain the natural cylindrical shape that it was manufactured to uphold. Thus, after construction was complete, the homemade duckbill did not maintain a flat taper to its bill as the manufactured duckbills had. This notable design difference would promote fluid forces acting backwards against the bill to act in several different directions along one side of the valve's saddle, rather than the one desired direction.

The design limitations inherent in the fabrication techniques used to construct the homemade valve suggest that future research should focus on alternative fabrication methods that would allow researchers to implement a design better equipped to successfully seal against backflow. Alternative fabrication techniques may also be explored to ensure that there is minimal variation between replicates. The first step in developing an alternative manufacturing technique should be to design a mold and determine the material best suited for creating it in a developing context. Since duckbill valves are made from an elastomer material comparable to that of a tire inner tube, it will also be helpful to research whether tire inner tubes available in the developing context are heat reformable and can be used to manufacture duckbill valves on site.

For future duckbill valve testing, it is recommended that transparent PVC unions be used for securing duckbill valves in the manometers. This would allow the researcher to observe any backflow leaks that were present either around the flanges of the valves or through the bills of the valves. It may also be beneficial to incorporate a way to inject dye behind the valves in the manometers so that leaks are easier to visually detect.

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[26] Go Reef, "PVC pipe tube." Photo.

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[32] A&B Supply, Inc., "PVC compression coupling." Photo.

[33] Sea Tech, “Poly tubing.” Photo.

[34] Sprinkler.com, “Male thread adapter with barb insert.” Photo.

[35] Sprinkler.com, “PVC female adapter.” Photo.

[36] Sprinkler Warehouse, “Slip PVC pipe adapter.” Photo.

APPENDIX A

Figure A1. Detailed Maymom® breast pump duckbill valve manometer configuration (half of full manometer)

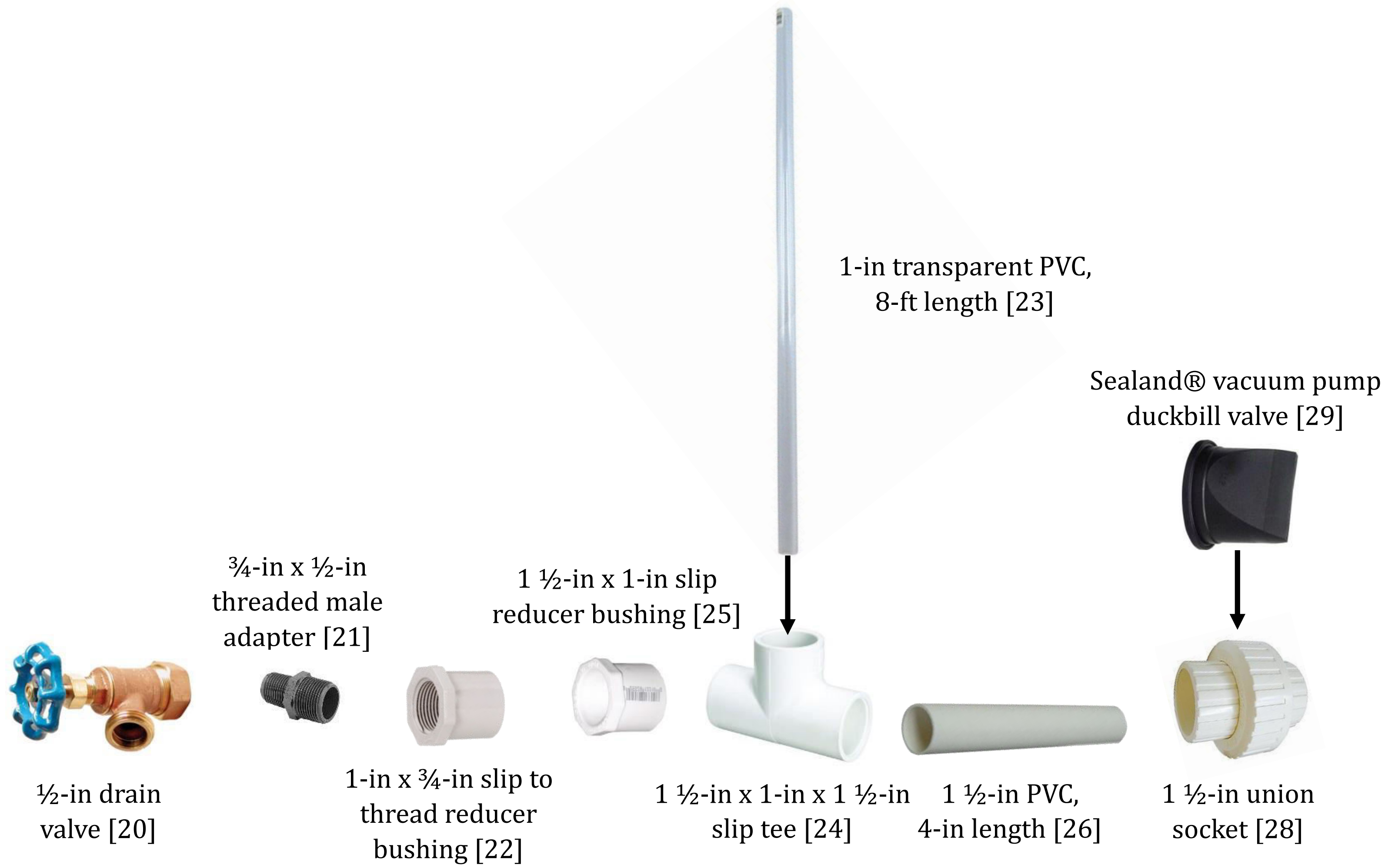

Figure A2. Detailed Sealand® vacuum pump duckbill valve manometer configuration (half of full manometer)

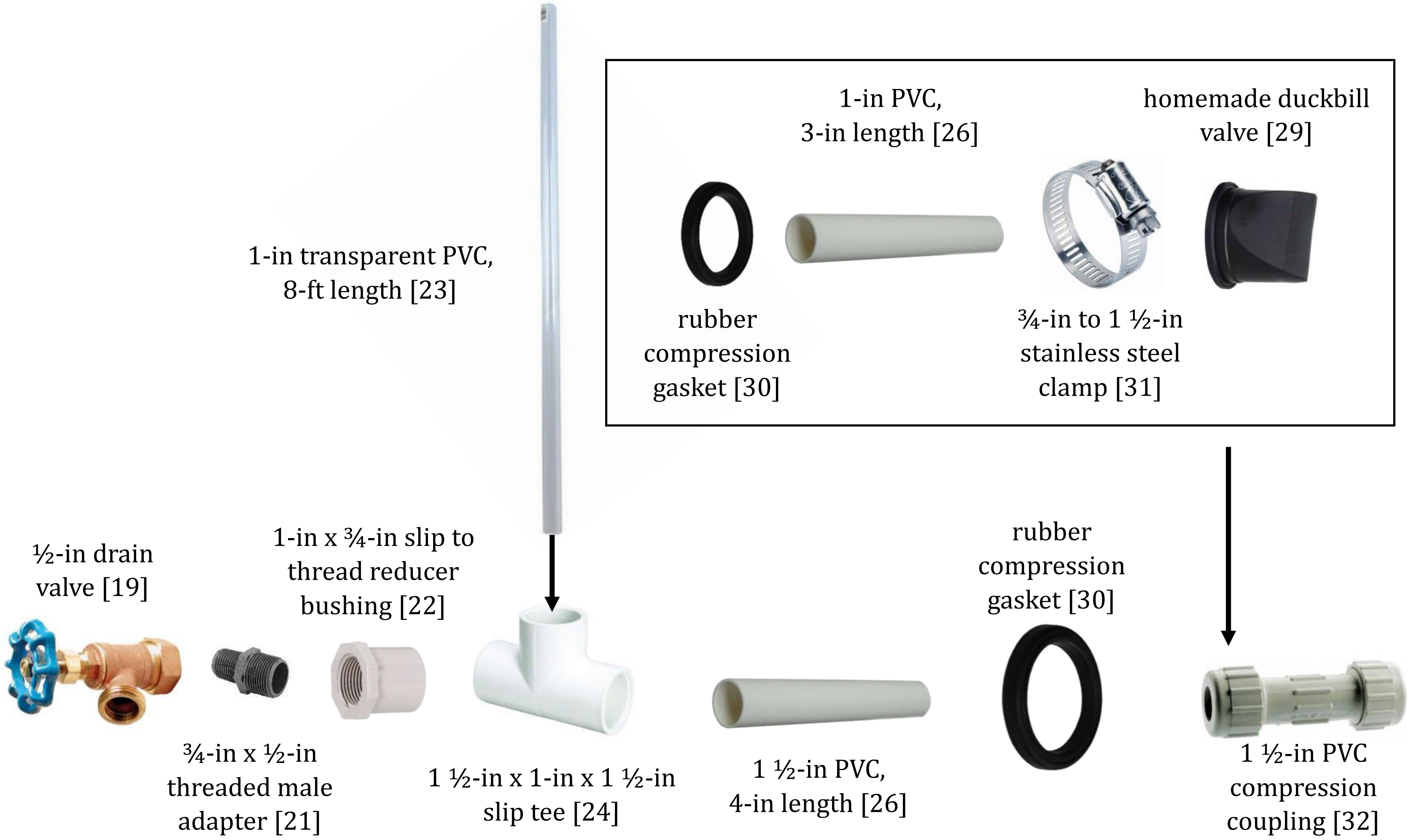

Figure A3. Detailed homemade duckbill valve manometer configuration (half of full manometer)

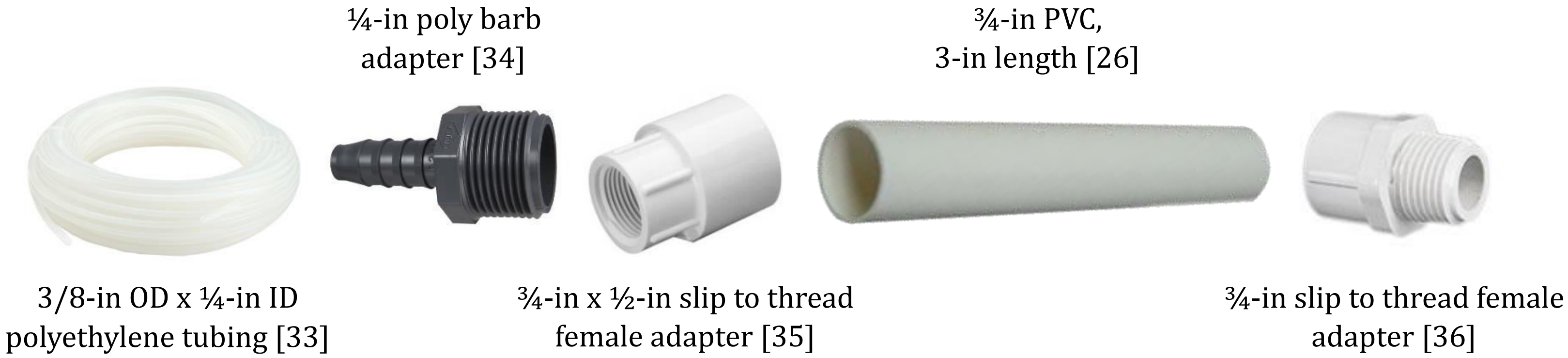

Figure A4. Detailed vacuum pump connection configuration

APPENDIX B

Table B1. No Duckbill Valve Negative Pressure Test Calculations

z_1 (in H2O)	z_2 (in H2O)	Corrected z_2 (in H_2O)	z_2-z_1 (in H_2O)	Δh_{pump} (in Hg)	Δh_{pump} (in H_2O)	$z_1 + \Delta h_{pump} - z_2$ (in H_2O)
46.5625	46.5625	46.5625	0	0	0	0
32.9375	59.9375	59.9375	27	2	27.14	0.14
26.1875	67.25	67.25	41.0625	3	40.71	-0.3525
19.5625	73.875	73.875	54.3125	4	54.28	-0.0325
12.6563	80.75	80.75	68.09375	5	67.85	-0.24375
6.15625	87.21875	87.21875	81.0625	6	81.42	0.3575

Table B2. Maymom® Breast Pump Duckbill Negative Pressure Test Calculations

z_1 (in H2O)	z_2 (in H2O)	Corrected z_2 (in H_2O)	z_2-z_1 (in H_2O)	Δh_{pump} (in Hg)	Δh_{pump} (in H_2O)	$z_1 + \Delta h_{pump} - z_2$ (in H_2O)
46.6875	46.6875	46.6875	0	0	0	0
33.625	60	60	26.375	2	27.14	0.765
26.9375	66.6875	66.6875	39.75	3	40.71	0.96
20.1875	73.4375	73.4375	53.25	4	54.28	1.03
13.3125	80.3125	80.3125	67	5	67.85	0.85
6.5625	87.0625	87.0625	80.5	6	81.42	0.92

Table B3. Sealand® Vacuum Pump Duckbill Negative Pressure Test Calculations

z_1 (in H2O)	z_2 (in H2O)	Corrected z_2 (in H_2O)	z_2-z_1 (in H_2O)	Δh_{pump} (in Hg)	Δh_{pump} (in H_2O)	$z_1 + \Delta h_{pump} - z_2$ (in H_2O)
46.9375	46.75	46.9375	0	0	0	0
33.5625	60.03125	60.21875	26.65625	2	27.14	0.48375
26.5938	66.96875	67.15625	40.5625	3	40.71	0.1475
20.0938	73.5	73.6875	53.59375	4	54.28	0.68625
13.0313	80.59375	80.78125	67.75	5	67.85	0.1
6.65625	86.96875	87.15625	80.5	6	81.42	0.92