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for Drip Irrigation in Developing Countries*

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**BIO-INSPIRED, LOW-COST, SELF-REGULATING VALVES FOR DRIP IRRIGATION IN
DEVELOPING COUNTRIES**

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ABSTRACT

We use nonlinear behavior of thin-walled structures - an approach inspired by biological systems (the human airway, for example) - to address one of the most important problems facing subsistence farmers in developing countries: lack of access to inexpensive, water-efficient irrigation systems. An effective way of delivering water to crops is through a network of emitters, with up to 85% of the water delivered being absorbed by plants. However, of the 140 million hectares of cropped land in India alone, only 61 million are irrigated and just 5 million through drip irrigation. This is, in part, due to the relatively high cost of drip irrigation. The main cost comes from the requirement to pump the water at relatively high pressure (>1 bar), to minimize the effect of uneven terrain and viscous losses in the network, and to ensure that each plant receives the same amount of water. Using a prototype, we demonstrate that the pressure required to drive the system can be reduced significantly by using thin-walled structures to design emitters with completely passive self-regulation

that activates at approximately 0.1bar. This reduction in driving pressure could help bring the price of drip irrigation systems from several thousand dollars to approximately \$300, which is within reach of small-scale farmers. Using order-of-magnitude calculations, we show that due to increased sensitivity of the proposed design to the applied pressure differential, a pressure compensating valve for drip irrigation could be built without using costly silicone membranes.

INTRODUCTION

This paper describes the design and proof-of-concept testing of a bio-inspired pressure-compensating valve for use in drip irrigation systems, primarily in developing countries. Drip irrigation is an effective and well-established method of water delivery in agriculture [1, 2]. Water is pumped through a network of tubes to 'emitters' - valves which regulate the flow of water to plants, making sure water is delivered only where it is needed (Fig. 1b). The main strength of drip irrigation is its low water consumption compared to traditional flood irrigation methods,

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where deep ditches in the field are flooded with water, much of which evaporates or seeps into the ground (Fig. 1a). Its main weakness is its relatively high cost. While flood irrigation requires mostly unskilled labor, drip irrigation requires a network of tubes, thousands of emitters per acre and, most importantly, a pump and a source of power.

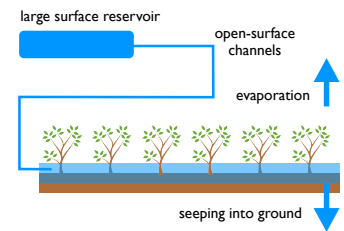
As water becomes a scarce resource and the world's population continues to grow, agriculture faces an increased pressure to conserve water. For example, in India, overall water use is projected to increase from 540 km^3 to 1020 km^3 between 1985 and 2025 [1]. With continuously increasing population, annual per capita water availability is projected to decrease from $1,250 \text{ m}^3$ to 760 m^3 between 2004 and 2025 [1]. While water consumption for industrial purposes continues to increase, and the water table levels drop, agriculture must become more water efficient [1]. This has resulted in increased interest in wide scale adoption of drip irrigation.

However, the relatively high cost of drip irrigation poses significant challenges to millions of subsistence farmers, who typically cultivate 1 acre (0.4 ha) of land or less [2]. These farmers have minimal resources for investment in new equipment, yet they are the ones who need it most, particularly as the ability to grow more and higher value crops would significantly improve their quality of life [2]. Drip irrigation has been proven to deliver very good results, increasing the crop yield by up to 100% while decreasing water consumption by about 50%, depending on the crop type. For example, in the case of bananas, a significant cash crop in India, drip irrigation increases yield by 52% while reducing water consumption by 45% [1]. To be within reach of subsistence farmers, a drip irrigation system for a 1 acre field cannot exceed \$300 [3]¹. Currently such systems cost several thousand dollars.

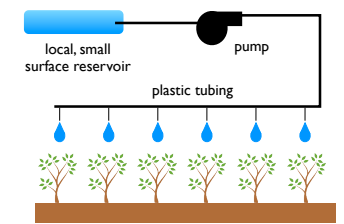
A direct route to decreasing both the capital and ongoing costs of drip irrigation systems is reducing the required pumping pressure, by far the most important determinant of the power consumption and cost of the pump [3]. However, maintaining uniform water delivery throughout the network at low pressures requires pressure-compensated emitters, as viscous losses and variations in field elevation make pressure distribution in the network non-uniform. Pressure compensation (PC) is the ability of a valve to deliver a constant flow rate regardless of the pressure difference applied across the valve. The pressure-compensated behavior exists above a threshold pressure, which we call *activation pressure*, $\Delta P_{\text{activation}}$.

Although pressure compensated emitters for use in irrigation are already available, they do not meet the requirements of low-power, low-cost irrigation. These emitters utilize a membrane design, wherein a flexible silicone membrane deforms to regulate the flow. Small clearances required by the membrane increase

a) Flood irrigation



b) Drip irrigation



c) Target system

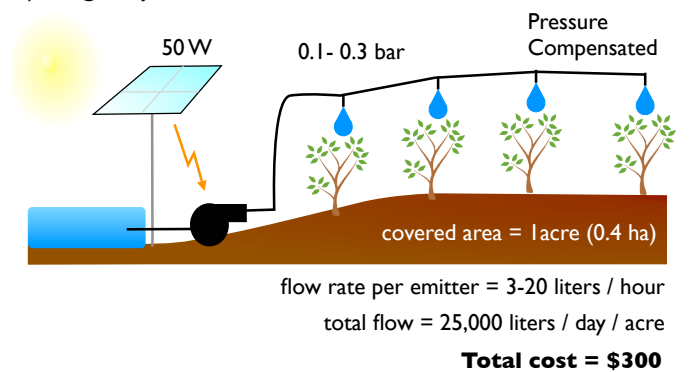


FIGURE 1. Various irrigation methods. a) Flood irrigation, a system that is widely popular in developing countries. Water from a remote reservoir, delivered by means of open surface channels, is used to flood the field. While it requires only unskilled labor, this irrigation method does not use water efficiently, as much of it evaporates or seeps into the ground. Photo by Jeff Vanuga, USDA Natural Resources Conservation Service. b) Drip irrigation, a method by which a plastic network of tubes (drip lines) delivers water directly to plants. With this method, as much as 90% of the water delivered is used by plants. A significant disadvantage of this method is the requirement for power and specialized equipment, which increases the cost and contributes to low adaptation of this method by subsistence farmers. c) Schematic of a drip irrigation system within the reach of subsistence farmers. The low overall cost is achieved by lowering the pumping pressure and by utilizing renewable energy to minimize dependence on electrical grids or gasoline.

the risk of clogging. More importantly, the use of silicone, which is a relatively expensive material, increases the cost of emitters.

¹This value was determined in an internal market and productivity analysis by Jain Irrigation Ltd.

Currently, the unit cost of low-end PC emitters is approximately \$0.055, of which \$0.025 is the cost of the membrane alone. In contrast, in order for the target price of the entire system to reach \$300, the target for a single emitter is \$0.025 [3].

Therefore, a need arises for low cost, pressure-compensating valves activated at low pressure to act as emitters in drip irrigation systems. To meet low power requirements, the emitters must activate at approximately 0.1 – 0.3 bar, which is at least a 5-fold reduction in $\Delta P_{activation}$ from currently available emitters [3, 4]. In addition, they must enable flow in the range 3 – 20 liters per hour, depending upon on the crop and soil type [3, 4]. They must also be robust enough to withstand handling in the field. In addition, large flow channels are a desirable attribute, in order to minimize the risk of clogging due to scale buildup, sand or organic matter [3].

In this paper, we describe a design concept for such a valve inspired by the deformation of collapsible tubes in the human body, e.g. the human airway and blood vessels [5]. The nonlinear deformation characteristics of such compliant valves result in pressure-compensating behavior, while their structural simplicity and increased compliance promise savings in processing and material costs. Together with savings in power consumption, the design described here aims to contribute to the wide-scale adoption of drip irrigation and contribute to sustainable agriculture practices.

BIO-INSPIRED PRESSURE-COMPENSATION

In order to design a low power, inexpensive valve for use in drip irrigation systems, we looked for inspiration to the human body, where flow of fluids is carefully regulated through a variety of mechanisms.

First, we describe a simple model for pressure compensation by means of a variable area valve, and then apply this model to explain pressure compensation in thin-walled structures, as exemplified by the human airway and blood vessels. In the context of physiological flows, this phenomenon was first modelled by Ascher Shapiro [5, 6], on whose work this section is based.

Pressure Compensation Through Variable Flow Area

When an incompressible fluid passes through a pressure-reducing (throttling) valve, the fluid's pressure is decreased by viscous losses inside the valve. By dimensional analysis, in the turbulent regime the change in pressure ΔP can be expressed as

$$\Delta P = \frac{1}{2} \mathcal{K}_f \rho u^2, \quad (1)$$

where ρ is the density of the fluid, u is the velocity of the fluid through the valve and \mathcal{K}_f is a dimensionless parameter dependent on the geometry of the valve [7]. \mathcal{K}_f is typically $O(1)$, and

doesn't vary significantly with the Reynolds number, so it can be treated as a constant [7]. As the velocity of the fluid inside the valve is typically not constant, u is chosen with respect to some reference area A . The choice of the reference area affects the value of the constant \mathcal{K}_f .

To model pressure-compensation by means of variable flow area, consider a very simple model of a valve - a straight conduit with variable area. The pressure drop expressed as a function of the flow rate Q is

$$\Delta P = \frac{1}{2} \mathcal{K}_f \rho \left(\frac{Q}{A} \right)^2. \quad (2)$$

The reference area A is the cross-sectional area of the conduit, and \mathcal{K}_f for this simple geometry is $\mathcal{K}_f = fL/D$ where L is the length of the duct, D is its hydraulic diameter and f is the Moody friction factor [7].

Using this simple model, and to achieve pressure compensation (that is, lack of dependence of flow rate on the driving pressure difference,) we require $\Delta P \sim A^{-2}$. This signifies non-linear dependence of the conduit area on the driving pressure difference. Importantly, in order to achieve pressure-compensation in this model, a degree of nonlinearity must be present in the system. This is provided by the deformation of flexible tubes.

Examples In Human Physiology

One of the most salient examples of pressure compensation in human physiology is the negative effort dependency of the respiratory system. When the pressure exerted on the lungs by a patient is measured against the volumetric flow rate of exhausted air, the flow rate plateaus at a certain point, and sometimes decreases (Fig. 2a) [8]. Beyond this point, increased pressure difference (effort) does not yield increased flow rate.

As Shapiro demonstrated [5, 6], this behavior can be explained using the model described above. Consider an elastic tube of radius r , thickness h , and modulus of elasticity E , connected to rigid mounts on both ends (Fig 2b). An incompressible fluid of density ρ enters the tube at a pressure P_{in} and exists at pressure P_{out} . The elastic tube represents the human bronchi. P_{in} is the pressure exerted on the chest by muscles, and P_{out} is assumed to be atmospheric pressure. As the muscles exert pressure that drives air out of alveoli, they also compress the bronchi, which restricts the flow of air. This can be modelled as a flexible tube enclosed in a chamber pressurized at P_{in} , as shown in Fig. 2d [5].

The crucial element of the pressure compensating behavior is the buckling of elastic tubes under negative transmural pressure, when the pressure outside the tube is greater than the pressure inside it. In this example, transmural pressure is given by $\Delta P = P_{out} - P_{in}$. While at positive transmural pressures the response of the tube is governed by tension, at negative transmural

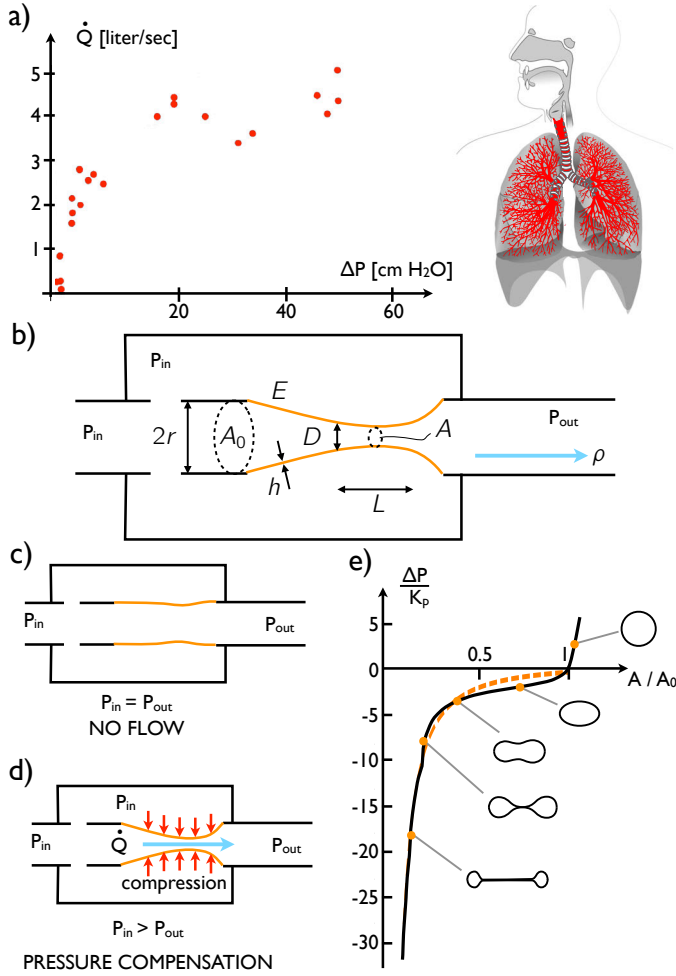


FIGURE 2. Bio-inspired pressure-compensation. a) Flow rate - pressure relationship in the human airway, as measured by Afschrift *et.al*. The graphic is partially based on the image available at http://en.wikipedia.org/wiki/File:Respiratory_system_complete_en.svg (accessed January 5, 2013) [8]. b) Simple model of the human airway: a flexible tube (orange) fixed on two rigid supports (black) and placed in a chamber open to the inlet pressure. To represent all variables used, the valve is drawn in the pressure-compensating configuration. c) Relaxed configuration of the valve. When the inlet and outlet pressures are equal, there is no differential pressure acting across the flexible tube, whose diameter is constant. d) Pressure compensating configuration. When $P_{in} > P_{out}$, a difference in pressure across the flexible tube causes its collapse and gradual variation in cross sectional area, which obstructs the flow. e) *Tube Law*. The variation of cross sectional area of a flexible cylinder with transmural pressure. Black solid line represents empirical relationship. Orange dashed line represents equation 3 with $n = 3/2$. The inset shapes represent the cross-sectional area of the tube at various pressures. . Figure 2e) is based on Fig. 1 in [6].

pressures, the walls of the tube cave in and the response is governed by bending of the tube walls. This asymmetry is shown in Fig. 2e. The relationship between cross sectional area and transmural pressure in elastic tubes is commonly called the *tube law*, and is determined experimentally [9]. However, in the interest of simplicity, following Shapiro [6], a dimensionless analytical expression can be fitted to the experimental curve, of the form

$$\frac{\Delta P}{K_p} = \alpha^{-n} - 1, \quad (3)$$

where $\alpha = A/A_0$, $A_0 = \pi r^2$, n is an empirical factor between 1 and 2, and K_p represents the bending stiffness of the tube's walls, and is proportional to $E(h/r)^3$. Subtracting 1 ensures there is no predicted area change for zero transmural pressure.

The system shown in Fig. 2b,c,d is one version of a device often called the Starling Resistor, which is a simplified but very useful model of physiological flows in the lungs and blood vessels [10].

Combining equations 2 and 3, Shapiro [6] arrived at the following relationship,

$$\frac{\left(\frac{\Delta P}{K_p}\right)^{1/2}}{\left(\frac{\Delta P}{K_p} + 1\right)^{1/n}} = Q \left(\frac{\mathcal{K}_f \rho}{2K_p A_0^2} \right)^{1/2}, \quad (4)$$

which describes the relationship between the applied pressure difference ΔP and the flow rate \dot{Q} through the tube. This expression is plotted in Fig. 3 for n ranging between 1 and 2. In all cases, the pressure-compensating effect is strong beyond $\Delta P/K_p \approx 2$, which marks the activation pressure of the valve. The case for $n = 2$ and $\Delta P \gg K_p$ approaches the exact pressure compensation as derived in the previous section. This is evident in the asymptotic approach of the curve for $n = 2$ to $\dot{Q} \left(\frac{\mathcal{K}_f \rho}{2K_p A_0^2} \right)^{1/2} = 1$. We note that, following Shapiro [6], we assume that $L \propto D$, that is the friction loss occurs near the exit, over a length proportional to the smallest diameter of the constriction.

PROOF-OF-CONCEPT PROTOTYPE

To demonstrate that elastic tube deformation can result in pressure-compensation in the range of pressures and flow rates required by drip irrigation, we constructed a laboratory-scale prototype of a PC valve modelled on the human airway. In this section, we describe our methods and results of testing the prototype.

Prototype Design and Construction

One benefit of the simple features of the elastic tube PC valve design is that it can be realized in a variety of ways. In

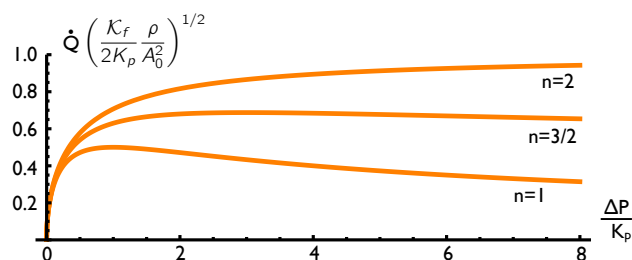


FIGURE 3. Pressure compensation in elastic tubes. Equation 4 plotted for $n = 1$, $n = 3/2$, and $n = 2$.

the interest of simplicity, we constructed the prototype from widely available materials and a single, custom-made part. At the heart of the prototype is an elastic tube made out of ZHER-MACK polyvinylsiloxane rubber with elastic modulus 1.0 MPa (Fig. 4a). The thin section of the tube is the flow passage, while the widened ends allow the tube to be secured to a perforated tube, which provides structural support (Fig. 4b). The perforations allow the inlet pressure to deform the flexible flow passage. This subassembly was then placed in a large diameter tube which serves as the reservoir. The assembled valve is shown in Figure 4c.

The flexible tube was manufactured by dip-coating a cylindrical form into the polyvinylsiloxane polymer mixed with a catalyst. The polymer cured within several minutes, after which the flexible tube could be removed from the form. Due to significant variations of viscosity of uncured polymer during the process, the coat thickness and uniformity could not be precisely controlled. The thickness was measured to be in the range of 0.3 – 0.5 mm.

Prototype Performance

To measure the performance of the prototype, we connected the valve to a small laboratory pump with a flow meter connected in series and a pressure meter connected across the valve. As the power output of the pump was varied, both pressure across and flow rate through the valve changed. The power was varied in both upwards and downward ramps consisting of discrete measurement points. At each measurement point, equilibrium was established before a reading was made. Results are shown in Figure 5. The valve achieved good pressure-compensation at a flow rate of approximately 17 liters/ hour, within the required range of flow rates. The activation pressure of the prototype was approximately 0.1 bar, which is also in the required range. Therefore, the elastic tube PC valve design is capable of operation in the range of pressures and flow rates required for operation in low-pressure drip irrigation systems.

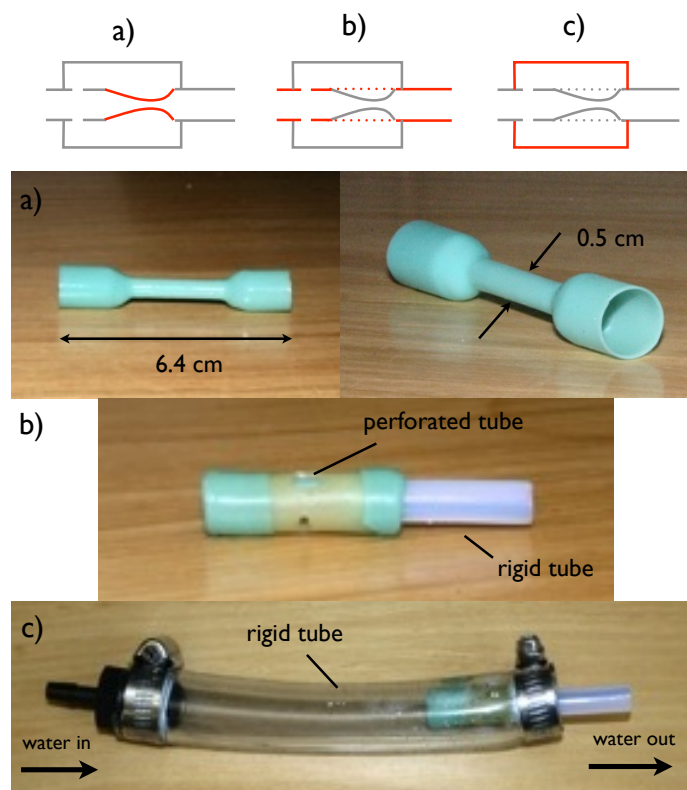


FIGURE 4. Construction of the prototype. Red elements in diagrams at the top of the figure indicate the component shown in respective photographs. a) The flexible tube, manufactured out of silicone rubber by dip-coating. The thin central section is the flow passage. The widened end sections are used to secure the tube on the perforated supporting tube. b) Subassembly showing the flexible tube supported on a perforated tube with a rigid tube press-fit on one end. The rigid tube forms the outlet of the valve. c) The complete valve assembly, with the subassembly from b) shown inside a large diameter tube section. The large diameter tube acts as a pressure reservoir equilibrated at the inlet pressure.

COMPARISON WITH CURRENTLY AVAILABLE DESIGNS

The most popular pressure-compensated emitter design produced by Jain Irrigation Ltd. today is based on a membrane serving as a pressure regulator which maintains a steady pressure differential between two chambers, as shown in Figure 6 [3]. The membrane is placed between two injection-molded Low Density Polyethylene (LDPE) elements with grooves, which route the flow of water through the valve. The stiffness of the membrane determines the activation pressure, while the resistance of a measuring orifice between the two chambers with regulated pressure difference determines the regulated flow rate. The membrane is manufactured out of silicone rubber, and the activation pressure

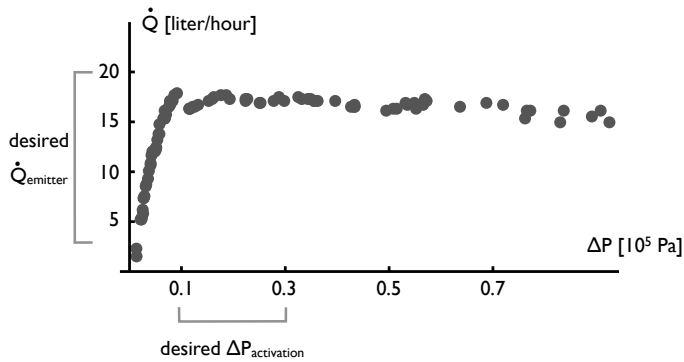


FIGURE 5. Pressure compensation of the prototype valve. The activation pressure is approximately 0.1 bar, and the regulated flow rate is approximately 17 liters per hour. Both values fit within the range desired in drip irrigation applications. These data represent 3 separate experiments (3 upwards and 3 downwards pump power ramps), for a total of over 90 measurement points.

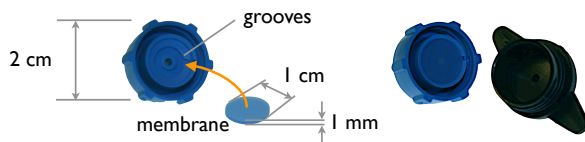


FIGURE 6. Typical membrane-based pressure compensated emitter design produced by Jain Irrigation Ltd.

is between 0.6 and 1.0 bar [4]. While the activation pressure could be lowered by changing the geometry of the membrane or the injection-molded parts, this would not eliminate the need for the silicone membrane, and thus would not reduce the relatively high cost of \$0.055 per emitter.

The bio-inspired design presented here offers the possibility of achieving a target price of \$0.025 per emitter by eliminating the silicone membrane. The qualitative difference between this design and the membrane design is that the flexible element is placed between regions with the largest available pressure differential. In contrast, the pressure difference across the membrane is regulated to stay within a prescribed range. Larger pressure difference could allow the use of LDPE, a material that is much stiffer than silicone rubber and significantly cheaper.

The theoretical activation pressure for the tube design is determined by the parameter $K_p = GEh^3/r^3$, where G is a geometrical constant. Assuming that activation pressure is $\Delta P = 2K_p$ (Fig. 3) and using the data from prototype testing, we can esti-

mate the constant as

$$G = \frac{0.1 \times 10^5 \text{ Pa}}{2 \times 10^6 \text{ Pa} \times \frac{0.3 \text{ mm}}{2.5 \text{ mm}}} = 2.9. \quad (5)$$

Using this value, we deduce that an LDPE ($E \approx 100 \text{ MPa}$) tube of thickness 0.2 mm and diameter 1.4 cm would yield activation pressure in the range 0.1 bar, meeting drip irrigation requirements. The flow rate through the valve can be controlled with an orifice located at the entrance of the flexible tube.

Using LDPE in tubular geometry instead of flat silicone membrane offers several advantages. First, LDPE is a cheaper material, offering the possibility of decreasing the material costs of emitters. Second, a pressure-compensating LDPE tube could be manufactured using methods already widely used in production of drip irrigation equipment, e.g. pulltrusion [3]. Finally, both the geometry and the material offer the possibility of manufacturing the device in a continuous fashion, which offers significant benefits, as component assembly would be avoided.

Physical toughness is an important consideration in designing the emitters, as they are exposed to the elements for extended periods. As thousands of emitters could be deployed on a 1 acre field, they cannot be regularly inspected and cleaned in case of blockage. Therefore, resistance to clogging by scale build-up, sand and biological matter is highly desired. The design proposed here does not contain small clearances, and would thus likely be more resistant to blockage than membrane emitters.

CONCLUSION

This paper presents a design concept for a low-cost pressure compensated valve inspired by the nonlinear deformations of thin-walled tubes in the human body. This concept is qualitatively different from currently prevalent membrane-based designs, in that it allows the deformable member to be acted upon by the largest possible pressure differential. This in turn rises the possibility of using stiffer, cheaper materials to construct the valve, with implications for accessibility of water-efficient drip irrigation systems to subsistence farmers in the developing world.

As availability of fresh water for irrigation continues to deteriorate, agriculture must reduce its water use to be sustainable. Drip irrigation, where water is delivered directly to the plants' root zones, offers a simple reliable way to achieve 30 – 60% reduction in water use for agricultural purposes [1, 3]. However, its relatively high cost prevents it from being used by millions of subsistence farmers in developing countries, who cannot afford it. A significant reduction in price of drip irrigation systems can be achieved by lowering the pressure at which water is pumped into the system, but this requires the use of pressure-compensating emitters.

As demonstrated by the prototype test presented here, the elastic tube design concept may be implemented to generate pressure compensation in the range of pressures and flow rates required for drip irrigation. Extrapolating these results onto possible future improvements, we showed that the design could be implemented using LDPE components only, offering the possibility to reduce the cost of PC emitters.

The overall goal of this project is to reduce the price of drip irrigation for subsistence farmers to a target of \$300. The next steps in reaching this goal will involve refining the basic design concept presented here. In particular, a second generation prototype will be constructed, using only LDPE to demonstrate that a PC valve using only low-cost materials is indeed feasible, as the calculations shown here indicate. Third generation prototype will involve design for mass manufacturing through injection molding or pulltrusion.

ACKNOWLEDGMENT

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