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A NOVEL PRESSURE COMPENSATING VALVE FOR LOW-COST DRIP IRRIGATION

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ABSTRACT

This paper presents a novel pressure-compensating flow restrictor for low-cost/low-pressure drip irrigation systems. There are nearly one billion subsistence farmers in the developing world who lack the resources and opportunities to rise out of poverty. Irrigation is an effective development strategy for this population, enabling farmers to increase crop yields and grow more lucrative plant varieties. Unfortunately, as a large fraction of subsistence farmers live off the electrical grid, the capital cost of solar or diesel powered irrigation systems makes them unobtainable. This cost could be drastically reduced by altering drip irrigation systems to operate at a decreased pressure such that lower pumping power is required. The work presented here aims to accomplish this by designing a drip emitter that operates at 0.1 bar, 1/10 the pressure of current products, while also providing pressure-compensation to uniformly distribute flow over a field.

Our proposed pressure compensating solution is inspired by the resonating nozzle of a deflating balloon. First, a reduced order model is developed to understand the physical principles which drive the cyclic collapse of the balloon nozzle. We then apply this understanding to propose a pressure compensating emitter consisting of compliant tube in series with a rigid diffuser. A scaling analysis is performed to determine the ideal geometry of the system and the reduced order model is applied to demonstrate that the proposed design is capable of pressure compensation in the required operation range. Preliminary experiments demon-

strating the collapse effect are presented, along with initial work to translate the concept to a robust physical device.

INTRODUCTION

As the world's growing population begins to strain global water resources, agriculture faces an increased pressure to adopt water conserving techniques. For example, in India overall water use is projected to increase from 540km³ to 1020km³ between 1985 and 2025 [1]. At the same time, annual per capita water availability is projected to decrease from 1250m³ to 760m³ between 2004 and 2025 [1]. Increasing water scarcity coupled with rising demand has motivated many agriculture sectors to begin using drip irrigation methods. 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 (as shown in Fig. 1).

The main strength of drip irrigation is its low water consumption compared to traditional flood irrigation methods where large quantities of water are lost to evaporation and ground seepage. Its main weakness is monetary cost. While flood irrigation requires mostly unskilled labor, drip irrigation requires a network of tubes, thousands of emitters per acre, and a pump and a power source. This relatively high cost makes drip irrigation infeasible for millions of subsistence farmers, who typically cultivate one acre (0.4ha) of land or less [2]. These farmers have minimal resources for investment in new equipment, yet they are the

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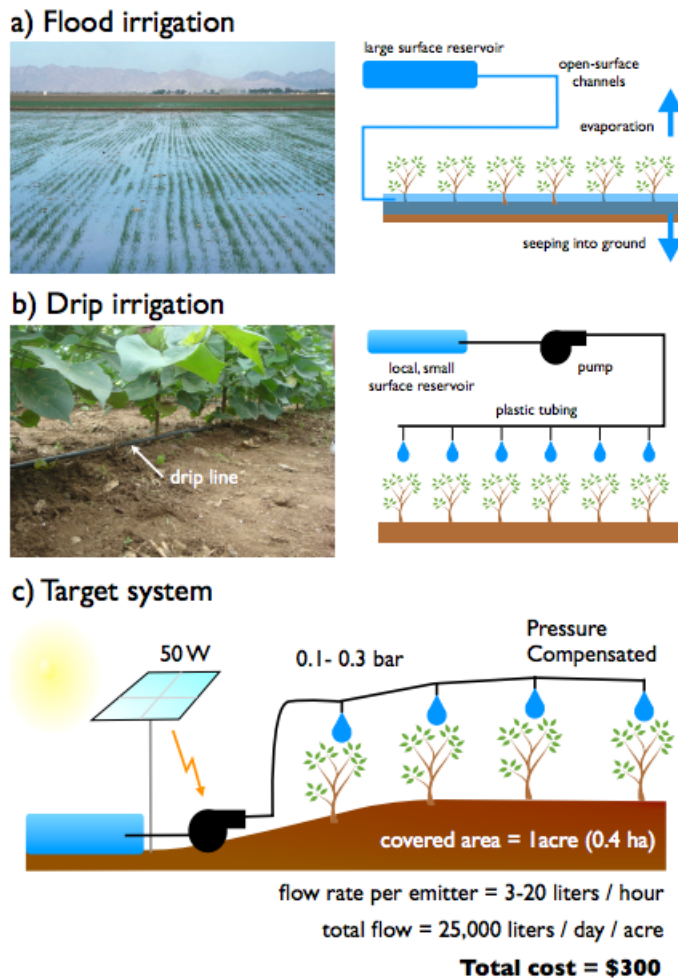


FIGURE 1. SCHEMATICS DEPICTING THE WATER DISTRIBUTION PROCESS FOR (A) FLOOD IRRIGATION, (B) CONVENTIONAL DRIP IRRIGATION, AND (C) THE PROPOSED PRESSURE COMPENSATED DRIP SYSTEM [4].

ones who need it most, as higher agricultural yields would significantly improve their quality of life. To be financially feasible for subsistence farmers, a one acre drip irrigation system cannot exceed \$300 [3], however, the current cost of such systems is several thousand dollars.

Both the capital and ongoing cost of drip irrigation systems could be drastically reduced by lowering the required pumping pressure. Pumping pressure is the primary determinant of both power consumption and pump cost [3]. However, maintaining uniform water delivery at low pressures requires pressure-compensated emitters, as viscous losses and variations in field elevation make pressure distribution in the network non-uniform. Pressure Compensating (PC) emitters are designed to passively deliver a constant flow rate, regardless of the pressure differential applied across the valve.

There are a number of commercially available PC emitter designs, however, they do not meet the requirements of low-power, low-cost irrigation. The cheapest of these utilize a membrane design, wherein a flexible silicone membrane deforms to regulate the flow. Unfortunately the required material, silicone, is too expensive for low-cost applications. 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 order to reach the \$300 system price, the target for a single emitter is \$0.025 [3, 5].

A second major constraint is the low operation pressure of the proposed system. Currently available PC emitters require a minimum pressure of roughly 1 bar to activate the pressure compensating effect, however the proposed low-cost system will require activation pressures as low as 0.1-0.3 bar. Additionally, they must enable flow in the range of 3-20 liters per hour, depending upon the crop and soil type [3]. They must also be robust enough to withstand handling in the field. Existing membrane emitters have small clearances; a new emitter design with large flow channels, would be much more desirable as this minimizes the risk of clogging due to scale build up, sand, or organic matter.

In previous work [4], we developed a bio-inspired pressure compensating solution which exploits the nonlinear behavior of thin-walled structures such as blood vessels. The work within this paper presents an alternative to this approach which exploits the physics observed in the resonating nozzle of a deflating balloon. Although it is still the early stages of development, the current method has the potential to provide improved clog resistance and a simpler design relative to the previous approach, merits which are valuable for the target low-cost application.

To begin, a reduced order model is used to extract the key effects which drive the cyclic collapse of the resonating balloon nozzle. It is then shown that these effects can be used to achieve static collapsed states by combining a compliant tube with a rigid diffuser. Following this, a feasibility study is conducted to demonstrate that the required geometry and elasticity of the system are suitable for drip irrigation systems and can be realized within the target constraints. Scaling arguments are applied to determine the required size of the nozzle and a theoretical model is used to evaluate the required elastic properties. To conclude, preliminary experiments are presented, demonstrating that collapse effect can be produced in a physical system.

A Novel Method for Pressure Compensation: From Inspiration to Concept

The lack of existing pressure compensation solutions which meet the design requirements for low pressure drip irrigation motivates us to consider instances of flow limitation in natural systems which have yet to be exploited in an engineering context. The oscillatory collapse of a compliant nozzle conveying fluid (Fig. 2) is a well-documented phenomena and previous studies have demonstrated that this oscillation is linked to flow limiting

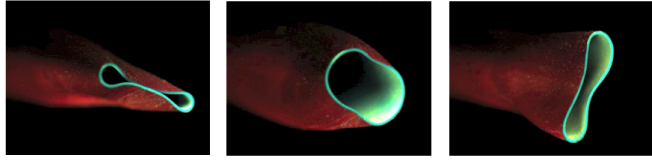


FIGURE 2. SEQUENTIAL SNAPSHOTS OF A BALLOON NOZZLE DURING 2ND MODE OSCILLATION. NOZZLE DIAMETER IS APPROXIMATELY 1cm [7],

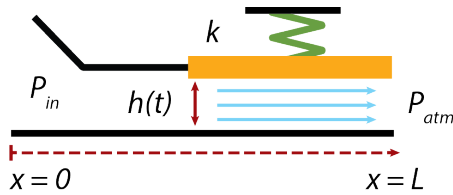


FIGURE 3. PLANAR SIMPLIFICATION OF CYLINDRICAL COMPLIANT NOZZLE WITH ONE DIMENSIONAL FLOW. THE OUT OF PLANE AREA OF THE PLATE IS A_p .

behavior [6]. However, in its raw form this effect is unsuitable for a robust low-cost device; it is difficult to control and fatigue failure would likely present an insurmountable issue. Within the following section a reduced order model is applied to extract the key physical principles which drive the cyclic collapse of a resonating nozzle. A novel solution is then proposed which exploits these principles to produce pressure compensating behavior.

Collapse of a Resonating Nozzle

The physics of nozzle collapse are modeled using a reduced order approach, similar to 1-D models in previous work [8–10] for the study of flow in biological systems. The goal here is not to make precise numerical predications, but to instead lay out the key physical effects which drive the behavior of the system and understand how they interact with one another.

Three key assumptions are applied to simplify the three dimensional shell structure of the nozzle and the flow conveyed through it. First, the nozzle is reduced to a single plane (as shown in Fig. 3). Second, within this plane the flow is taken to be one dimensional, with streamlines aligned to the walls of the tube. Third, the compliant shell of the nozzle is modeled as a single rigid plate supported by a linear spring with stiffness k . Although viscous effects are present, they are neglected here as the goal of the analysis is to study how the collapse of the nozzle initiates and they do not play a major role in this behavior.

The system contains three dependent variables: pressure $P(x,t)$, flow velocity $V(x,t)$, and the height of the plate $h(t)$. The governing equations of the system are constructed using conservation of mass, conservation of momentum (Bernoulli's Equa-

tion), and the force equilibrium on the plate due to pressure distribution $P(x,t)$ and P_{atm} . Composing these three physical laws generates the following set of differential equations.

$$V(x,t) = V(0,t) - \frac{x}{h(t)} \frac{dh(t)}{dt}, \quad (1)$$

$$P(x,t) = P_{in} - \frac{1}{2} \rho V(x,t)^2 - \rho \frac{dV(x,t)}{dt}, \quad (2)$$

$$m \frac{d^2 h(t)}{dt^2} + k(h(t) - h(0)) = A_p \int_0^L (P(x,t) - P_{atm}) dx, \quad (3)$$

$$\text{BCx: } P(x \rightarrow L, t) = P_{atm} \text{ and } h(t \rightarrow 0) = h_0. \quad (4)$$

As shown in Eq. 4, the boundary conditions of the system are defined assuming that the nozzle is an uncollapsed state $h = h_0$ at $t = 0$, and that it is subject to a driving pressure P_{in} with the exit jet released to atmosphere.

Under these conditions the pressure of the exit jet, P_{atm} , extends from $x = L$ all the way to $x = 0$ as conservation of mass requires that velocity is constant throughout the nozzle when $dh/dt = 0$. Based on this, the pressure forces on either side of the elastic plate are in equilibrium and the system has no reason to spontaneously collapse. Progress can be made by assessing the stability of this equilibrium in the presence of a small perturbation to the nozzle height. As shown in Fig. 4 (a), a slight perturbation to the outer wall initiates a diffuser like effect in which the flow expands through the nozzle tip causing pressure to drop slightly below atmospheric in the necked region. In our simplified representation of the system, we model this perturbation as shown in Fig. 4 (b), where the exit width is fixed at h_0 while the rest of the nozzle is free to collapse. If we modify the system to include the diffuser as a small ramp in height at $x = L$, we can apply a small perturbation, $h = h_0 + \epsilon$, and then linearize the system about this state to conduct a stability analysis.

The results of this analysis indicate that the stability of the system is governed by a single dimensionless variable. This variable consists of a ratio of the restorative elastic forces which prop the nozzle open, and the perturbing pressure differential which instigates collapse. Mathematically, it is given as follows,

$$C_{collapse} = \frac{\rho V_0^2 A_p}{k h_0}. \quad (5)$$

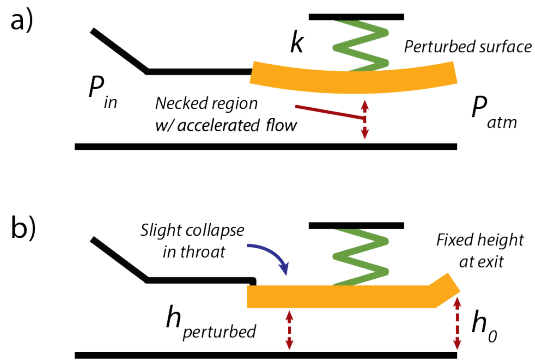


FIGURE 4. (A) RESPONSE OF CONTINUOUS COMPLIANT NOZZLE SURFACE TO EXTERNAL PERTURBATION. (B) DISCRETE APPROXIMATION OF DIFFUSER EFFECT CAUSED BY DISTURBANCE.

Where V_0 is the velocity throughout the nozzle prior to perturbation. When $C_{collapse}$ is less than 1 the elastic forces dominate the forces associated with the pressure change in the necked region and the nozzle remains open at $h = h_0$. When $C_{collapse}$ exceeds 1, the stiffness of the system can no longer restore equilibrium and the collapse process initiates. Within our model we take the spring force to be a simple linear function of x , however the shell like structure of a cylindrical tube exhibits highly nonlinear behavior. A representative plot of tube stiffness as a function of area is provided in Fig. 5. As can be seen from the elasticity curve, the stiffness of the collapsed circular tube is initially quite high as the tube must buckle to an elliptical state. After this, stiffness drops significantly until the walls of the tube begin to touch. This high initial stiffness means that a cylindrical nozzle will tend to collapse disastrously once it exceeds the initial stability threshold $C_{collapse}$. This explains the high amplitude of collapse in a resonating balloon nozzle.

Translating the Collapse to Pressure Compensation

Now that we have established basic physics of nozzle collapse, this understanding is applied to generate a concept solution for low-cost pressure compensation. The first major challenge in translating the nozzle physics to PC emitter design is that the flow limitation associated with a resonating system is not applicable in practice due to fatigue failure. To address this, the system must be modified to support static collapsed states in which the tube is constricted but not oscillating. To accomplish this, we propose to add a rigid diffuser to the tip of the nozzle as shown in Fig. 6. This modification mimics the necking observed in nozzle resonance, but allows the system to maintain a pressure differential across the tube while remaining below the stability threshold such that static collapse becomes possible. Flow expansion through the diffuser produces a constricting pressure differential across the wall of the compliant tube. This differential rises as

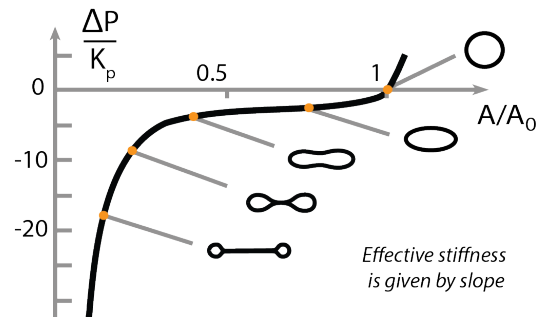


FIGURE 5. DIMENSIONLESS LAW DESCRIBING TUBE COLLAPSE, TAKEN FROM [4, 10]. NOTE THAT THE EFFECTIVE STIFFNESS, THE EQUIVALENT OF k IN OUR MODEL, IS GIVEN BY THE SLOPE OF THE CURVE. A/A_0 IS A RATIO OF THE CONSTRICTED TUBE AREA OVER THE INITIAL AREA AND ΔP IS THE COLLAPSING PRESSURE DIFFERENTIAL. κ_f IS A CONSTANT FOR THE ELASTIC PROPERTIES OF THE TUBE MATERIAL.

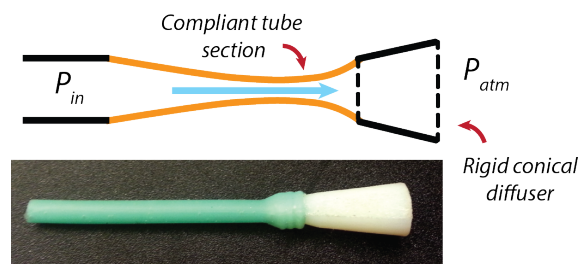


FIGURE 6. PROPOSED COMPLIANT TUBE - RIGID DIFFUSER SYSTEM. A PROTOTYPE NOZZLE IS PICTURED ALONG SIDE THE SCHEMATIC.

driving pressure is increased leading to further constriction and thus producing a compensating effect.

This approach has the potential to provide a number of key benefits relative to previous pressure compensating emitters. The first is cost, the design consists of only two simple components, a compliant tube and a rigid diffuser, both of which can be manufactured using low cost materials and methods. The second is clog resistance, existing pressure compensating emitters employ driving pressure to generate a collapse effect. This gives the system a tendency to clamp shut in the presence of a blockage. In contrast, our novel diffuser approach naturally ejects any obstruction within tube since the collapsing force disappears when flow is stopped.

Demonstrating Feasibility of the Compliant Tube-Diffuser Emitter

Prior to the development a physical device, there are a number of key issues which must be addressed to assess the feasibility of the tube-diffuser emitter design. These issues, listed in the order they will be discussed, are given as follows:

1. Viscous losses provide the primary mechanism for flow limitation within the system. Using scaling arguments we demonstrate that the geometry of the emitter can be selected to ensure that these losses are of the appropriate magnitude for pressure compensation in our target operation range.
2. The required tube stiffness must be physically feasible using low cost materials. In addition to this, the required elasticity profile must monotonically increase during the collapse process to ensure stability across all operation points. We apply a reduced order model of the system to demonstrate that both of these requirements are satisfied.
3. The final issue is diffuser performance. Although our simplified model assumes perfect pressure recovery, we demonstrate that realistic diffuser efficiencies still provide adequate pressure differential for collapse. Preliminary experiments are presented, showing that the system can be designed to circumvent issues associated flow separation in the diffuser as collapse progresses.

Scaling for Pressure Compensation

Viscous losses within the compliant section of the proposed valve provide the primary mechanism for flow limitation. Assuming the system will operate at intermediate to high Reynolds number, the pressure loss (ΔP_{loss}) can be approximated using the Darcy-Weisbach equation as follows,

$$\Delta P_{loss} = f \frac{L}{D} \frac{\rho V^2}{2} \quad (6)$$

For pressure compensation, the total viscous pressure loss (ΔP_{loss}) within the system must be on the same order as the driving pressure P_{in} . Based on our target operation pressure we can then set the left side of Eq. 6 to 0.1 Bar ($10^4 Pa$). We also know that the target application requires a flow rate of 3-20 gallons per hour, which translates to $10^{-5} m^3/s$. For a cylindrical tube, V is approximately equal to Q/D^2 . If we substitute this relation into the left side of Eq. 6 we arrive at the expression,

$$\Delta P_{loss} = f \frac{L}{D} \frac{\rho Q^2}{2 D^4} \rightarrow 10^4 Pa = (10^{-9} Pa \cdot m^4) \frac{L}{D^5}, \quad (7)$$

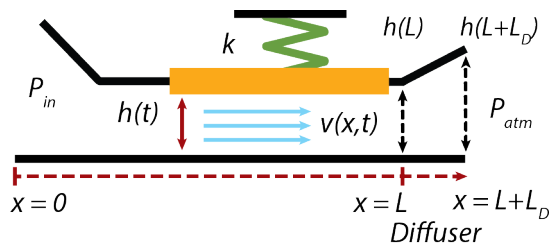


FIGURE 7. DIAGRAM OF REDUCED ORDER MODEL USED TO STUDY COLLAPSE OF THE COMPLIANT TUBE IN SERIES WITH THE PROPOSED DIFFUSER.

which is satisfied by the following length, L , and diameter, D , values,

$$L \approx 1cm, \quad D \approx 1mm. \quad (8)$$

This sizing is ideally suited to the typical dimensions of irrigation drip emitters and can be achieved using low-cost conventional manufacturing methods like injection moulding. The Reynolds number of the scaled system is roughly $10^3 - 10^4$ which ensures that inertial pressure recovery is still possible within the rigid diffuser.

Tuning Elastic Properties for Collapse

To investigate elastic behavior we apply a reduced order model, similar to the one used for nozzle collapse (Fig. 7). Once again the flow is assumed to be 1-dimensional and the compliant tube is represented as a rigid plate supported by a linear spring. In this case the exit side of the compliant tube is attached to a two-dimensional diffuser. It is assumed that the angle of the diffuser can vary to accommodate changes in the height of the plate relative to the fixed exit height, h_0 . Since the goal of this analysis is to produce qualitative and order of magnitude estimates of the elastic properties required for pressure compensation, pressure recovery is taken to be perfectly efficient. A more detailed discussion of diffuser performance is provided in the preceding section.

The governing equations of the system consist of conservation of mass, Bernoulli's equation, and the force balance on the plate. In this case Bernoulli's equation is modified to include a pressure loss term representing the viscous effects required for pressure compensation, and the boundary conditions are modified to account for flow expansion through the diffuser. All time dependent terms are removed as we only wish to study static equilibrium states. In mathematical form the system is given as follows,

$$V(x) = V(0), \quad (9)$$

$$P(x) = P_{in} - \frac{1}{2}\rho V(x)^2 - \Delta P_{loss}, \quad (10)$$

$$k(h_{collapsed} - h_0) = A_p \int_0^L (P(x,t) - P_{atm}) dx. \quad (11)$$

Two additional equations are required to account for the conservation of mass and momentum throughout the diffuser section of the nozzle,

$$P(L) + \frac{1}{2}\rho V(L)^2 = P(L+L_d) + \frac{1}{2}\rho V(L+L_d)^2, \quad (12)$$

$$\rho V(L)h_{collapsed} = \rho V(L+L_d)h(L+L_d), \quad (13)$$

$$\text{BCx: } P(x \rightarrow L+L_d) = P_{atm}. \quad (14)$$

Given a driving pressure, P_{in} , and a initial channel width of h_0 , we can solve for the equilibrium collapsed channel width $h_{collapsed}$ as a function of spring stiffness, k . This produces a fourth order polynomial in $h_{collapsed}$ which can generate up to four real solutions for the collapsed channel width at any given spring stiffness value. If we apply the length and initial channel width dimensions from the scaling of the previous subsection and then vary the spring stiffness from $10^0 - 10^5 N/m$ the four roots of the equation trace out two distinct real solution branches (Fig. 8). For very low stiffnesses ($k < 5 \cdot 10^2 N/m^3$) there are three possible equilibrium states, two of which actually correspond an expansion of the tube rather than constriction. Fortunately, for intermediate stiffnesses the tube exhibits only one possible equilibrium state which ranges from 10% to 99% of the initial channel width as k is varied from $5 \cdot 10^2$ up to $10^4 N/m^3$.

If the solution branch corresponding to gradual collapse is plotted over a grid of stiffness and pressure values, the result is a surface of equilibrium states (Fig. 9). Within the large plateau, to the left of the dashed lined, the channel remains in an uncollapsed state, indicating that the pressure compensating effect is not active. As we move along the pressure axis and cross to the right side of the dashed lined, the equilibrium channel width begins to collapse and gradually decreases as P_{in} rises. Based on this, the dashed line represents the activation pressure, P_{active} , of the system. Using the provided plot, the activation pressure can be set by simply designing the initial stiffness of the nozzle to match the corresponding stiffness value on the k -axis. For our

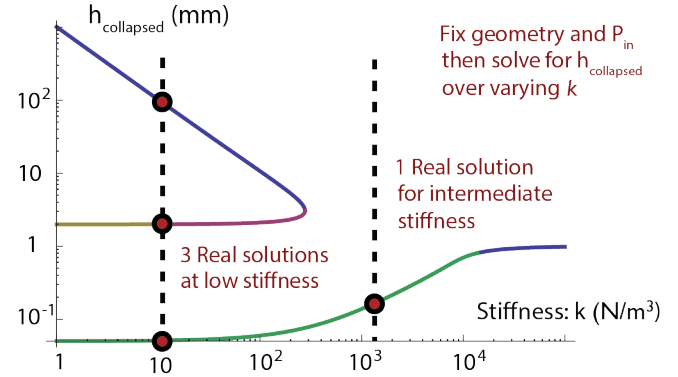


FIGURE 8. EQUILIBRIUM SOLUTIONS FOR COLLAPSE NOZZLE WIDTH FOR $P_{in} = 1$ Bar OVER VARYING STIFFNESS VALUES AND $h(L+L_d)/h(L) = 2$

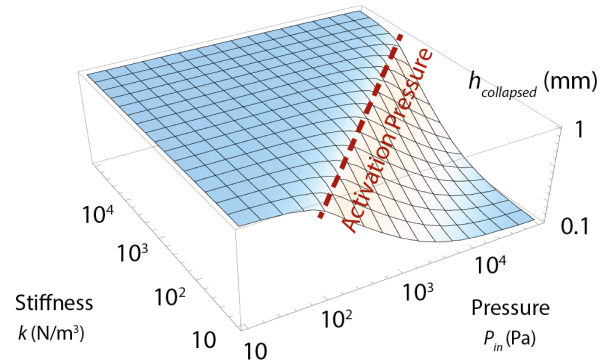


FIGURE 9. EQUILIBRIUM SOLUTIONS FOR COLLAPSED NOZZLE WIDTH OVER GRID OF PRESSURE AND STIFFNESS VALUES. THE DASHED RED LINE HIGHLIGHTS THE ACTIVATION POINT OF THE COLLAPSE EFFECT.

target activation point of $10^4 Pa$, this indicates a required stiffness of $10^3 N/m$. Based on a tube diameter of $1 - 3 mm$ and a wall thickness of $0.25 - 1 mm$, this corresponds to a material Young's modulus of $10 - 100 MPa$ which falls within the range of compliant polymers such as silicone and low density polyethylene.

Having established that the system is well-behaved within the target operation range, we can apply the model to analytically determine how elasticity must vary as a function of channel width to provide complete pressure compensation. To accomplish this we first lay out a mathematical definition of perfect pressure compensating conditions. For any given channel width, the system sees an effective pressure, P_{eff} . Applying Bernoulli's equation P_{eff} between $x = 0$ and $x = L$, P_{eff} be expressed as follows,

$$P_{in} = \frac{1}{2}\rho V_{out}^2 + \Delta P_{loss} \quad (15)$$

$$P_{eff} = (P_{in} - \Delta P_{loss}) = \frac{1}{2}\rho V_{out}^2 \quad (16)$$

For pressure compensation P_{eff} must remain constant as P_{in} changes in value. This provides a constant flow velocity V_{out} at the diffuser exit for all driving pressures. Since the exit area of the rigid diffuser is also constant this will provide the constant, pressure independent flow rate we desire. This is accomplished by tuning the elasticity of the system to ensure that the ΔP_{loss} term perfectly cancels variations in the driving pressure. By calculating the P_{eff} corresponding to each point on the surface in Fig. 9, a contour plot of effective pressure can be produced (Fig. 10). Lines of perfect pressure compensation can then be easily identified by simply tracing out the level curves with in the plot. The bold arrow within the plot highlights the line of constant P_{eff} corresponding to an activation pressure of 0.1 Bar, as required for the proposed drip irrigation system. In Fig. 11 the spring values along the 0.1 Bar level curve in Fig. 10 are plotted against the corresponding collapsed channel width values in Fig. 9. Based on the resulting curve can be concluded that pressure compensation requires a progressive rise in spring stiffness which controls a gradual collapse in channel width as P_{in} increases. The resulting stiffness profile for pressure compensation is stable over operating pressures ranging from 0 to $10^6 Pa$. A change from increasing to decreasing stiffness is observed around $P_{in} = 10^6$, indicating that system cannot operate past this point as the equilibrium states become unstable.

Diffuser Performance and Experimental Demonstration of the Collapse Effect

For the previous analyses we assumed full pressure recovery throughout the diffuser section of the nozzle. In reality, energy losses and separation limit the total pressure rise that can be achieved through the expansion effect. There is a large amount empirical data on diffuser performance, however it is difficult to apply these results in the context of the tube-diffuser nozzle since the geometry of the flow expansion region is quite complex. As shown in Fig. 12, the necked region of the collapsed tube acts as a secondary diffuser in series with the rigid conical section. The angle of this necked region increases as the collapse progresses playing a key role in the pressure compensating behavior of the nozzle. Since it is not possible to model the expanding flow in the compliant necked region using reduced order theory, we instead use experimental methods to evaluate flow expansion characteristics of the nozzle.

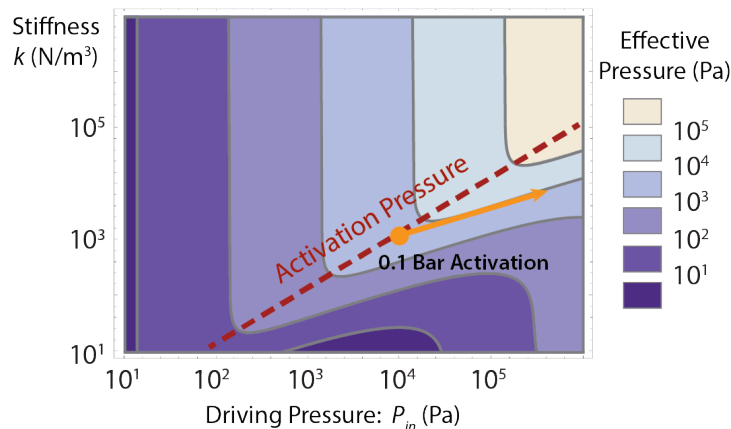


FIGURE 10. EFFECTIVE PRESSURE BASED ON COLLAPSED NOZZLE WIDTH OVER A GRID OF DRIVING PRESSURE AND STIFFNESS VALUES. THE YELLOW ARROW HIGHLIGHTS THE CONTOUR FOR PERFECT PRESSURE COMPENSATION AT 0.1 Bar.

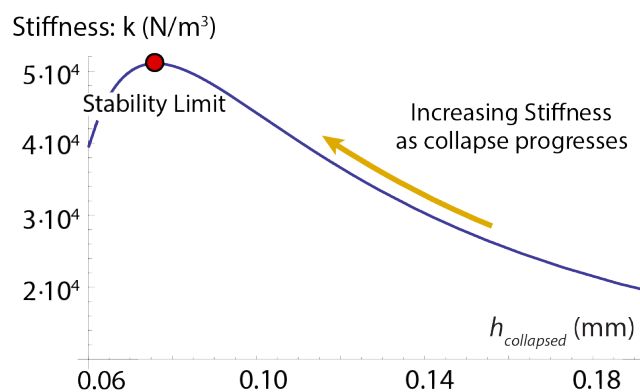


FIGURE 11. ELASTICITY PLOTTED AGAINST COLLAPSED NOZZLE WIDTH FOR THE 0.1 Bar PRESSURE COMPENSATING CONTOUR HIGHLIGHTED IN THE CONTOUR PLOT.

To run physical tests, a water tank charged with regulated compressed air is used to provide a constant driving pressure at the nozzle inlet. Flow rate is measured using a variable area flowmeter in line with the nozzle and driving pressure is measured using a static pressure gauge at the tank outlet. A typical test nozzle is shown in Fig. 13. The tube is moulded from silicone elastomer and has an inner diameter of 2mm with a wall thickness of 0.25mm. The diffuser is made from rigid plastic with a smooth inner surface. The diffuser has a half angle of 2.5° and an area ratio of 3.

Tests with the nozzle produce a very localized collapse adjacent to the inlet of the rigid diffuser. As pressure is increased and the collapse progresses, the flow in the necked section sepa-

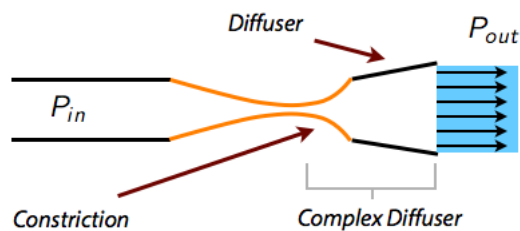


FIGURE 12. SCHEMATIC OF COMPLEX DIFFUSER FORMED BY COMPLIANT TUBE AND RIGID SECTION.

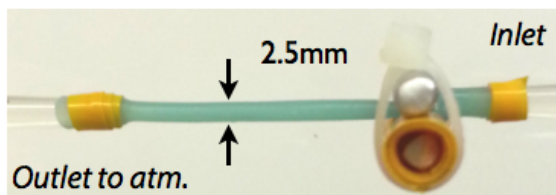


FIGURE 13. STRUCTURE OF NOZZLES USED THROUGHOUT EXPERIMENTAL TESTING. COMPLIANT SECTION HAS AN INNER DIAMETER OF 2mm WITH A WALL THICKNESS OF 0.25mm. THE DIFFUSER HAS A 2mm DIAMETER INLET, A HALF ANGLE OF 2.5 DEGREES, AND AN INLET TO OULET AREA RATIO OF 3.

rates. This creates a fluid jet to atmosphere at the necked region that eliminates the pressure recovery effect and causes the tube to reopen. This cycle of collapse and separation then repeats itself, generating high frequency oscillations in the system. This phenomenon of localized collapse in the downstream section of the nozzle is well documented in previous work on flow in compliant tubes [11]. It can be attributed to the viscous losses in the system which produce a linearly decreasing pressure profile along tube, generating a minimum pressure at the diffuser inlet.

To eliminate this localized necking effect and prevent separation, the system must be designed to encourage distributed collapsed such that relatively low diffuser angles ($\leq 10^\circ$) are maintained throughout the tube [12]. To accomplish this, we propose a slight modification to the basic nozzle design: a small clamp is attached to the base of the nozzle (Fig. 14 (a)). The clamped base modifies the resting shape of the tube to include a slight angle which allows for gradual pressure recovery to compensate for the viscous losses along the tube. In addition to this, the clamp pre-buckles the upstream section of the tube, encouraging the collapse to initiate in this region. In Fig. 14 (b) it can be seen that the addition of the clamp allows constriction along the full length of the compliant section. Preliminary tests also show that the severity of the collapse increases at higher driving pressures, as is required for pressure compensating behavior. At the time of writing, the nozzle in Fig. 14 did not exhibit full pressure compensating behavior, however these preliminary experiments demonstrate that the basic effects required for compensation can be realized within a physical prototype. At this point a full ex-

(a) Clamped Nozzle - 0 Bar P_{in} (No Flow)



(b) Clamped Nozzle - 0.15 Bar P_{in}

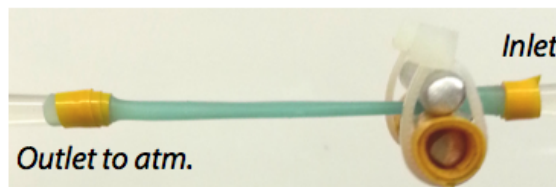


FIGURE 14. COMPARISON OF CLAMPED NOZZLE UNDER NO FLOW CONDITIONS AND COLLAPSING AT $P_{in} = 0.15$ Bar.

perimental study exploring the influence of variables such as tube length, diameter, stiffness, and cross-section shape is required to tune the collapse effect to provide pressure compensation. These experiments are the focus of our future work.

Conclusion and Future Work

As discussed earlier, a previous survey of irrigation methods and products has demonstrated that there is an opportunity to make drip-irrigation available to subsistence farms on global scale by redesigning the conventional drip emitter to employ pressure compensation. Unfortunately, commercially available pressure compensating valves are too expensive and cannot operate in the required pressure range. Within the work presented here, we develop a novel mechanism for pressure compensation which has the potential to meet both the pressure and cost constraints of the target application. The basic concept is inspired by the flow limiting behavior of a deflating balloon. We apply a reduced order model to extract the key effects which drive the cyclic collapse of the resonating balloon nozzle. It is then shown that these effects can be used to achieve static collapsed states by combining a compliant tube with a rigid diffuser.

With the concept still in its early stages, a feasibility study is conducted to demonstrate that the required geometry and elasticity of the system are suitable for the target application and can be realized with conventional manufacturing and materials. Scaling arguments are applied to determine the required size of the nozzle and a theoretical model is used to evaluate the required elastic properties. Preliminary experiments are presented, demonstrating that collapse effect can be produced in a physical system.

In terms of translating the concept to a robust physical de-

vice, it is clear that a considerable amount of further work is required. However, the work presented here provides a detailed understanding of physical effects within the system which will be invaluable in making effective, informed decisions throughout the coming design process. In future work, a set of systematic experiments will be conducted to fully develop the design of the system and to tune the collapse process to provide proper pressure compensation.

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REFERENCES

- [1] Government of India, M. o. A., 2004. *Salient Findings and Recommendations of Task Force on Microirrigation*.
- [2] Polak, P., 2008. *Out of Poverty: What Works When Traditional Approaches Fail*. Berrett-Koehler Publishers, San Francisco.
- [3] Jain, R.B. *et. al.*, 2012, Jain Irrigation Ltd., private communication.
- [4] Zimoch, P. J., Tixier, E., Joshi, A., Hosoi, A. E., and Winter, A. G., 2013. "Bio-inspired, Low-Cost, Self-Regulating Valves for Drip Irrigation in Developing Countries". *Proceedings of the ASME 2013 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*.
- [5] *Pressure Compensating Emitters Technical Sheet*. Jain Irrigation Ltd., from http://www.jainirrigationinc.com/downloads/pc-emitter_9100108.pdf (accessed January 5, 2013).
- [6] Luo, X. Y., and Pedley, T. J., 2000. "Multiple solutions and flow limitation in collapsible channel flows". *Journal of Fluid Mechanics*, **420**, 10, pp. 301–324.
- [7] Zimoch, P., Tixier, E., Hsu, J., Winter, A., and Hosoi, A., 2012. "Fast, large amplitude vibrations of compliant cylindrical shells carrying a fluid". *ArXiv e-prints*, Oct.
- [8] Pedley, T., 1980. *The Fluid Mechanics of Large Blood Vessels*. Cambridge University Press.
- [9] Conrad, W. A., 1969. "Pressure-flow relationships in collapsible tubes". *Biomedical Engineering, IEEE Transactions on*, **BME-16**(4), pp. 284–295.
- [10] Shapiro, A. H., 1977. "Steady Flow in Collapsible Tubes". *Journal of Biomechanical Engineering*, **99**, p. 126.
- [11] Jensen, O., 2013. "Instabilities of flows through deformable tubes and channels". In *Mechanics Down Under*, J. P. Denier and M. D. Finn, eds. Springer Netherlands, pp. 101–116.
- [12] McDonald, A., and Fox, R., 1966. "An experimental investigation of incompressible flow in conical diffusers". *International Journal of Mechanical Sciences*, **8**(2), pp. 125 – 139.