

**Design and Experimental Study on Pressure  
Compensating Emitters in Drip Irrigation**

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by

Teresa Lin

Submitted to the

Department of Mechanical Engineering

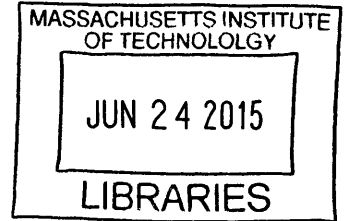
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# Design and Experimental Study on Pressure Compensating Emitters in Drip Irrigation

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Teresa Lin

Submitted to the Department of Mechanical Engineering  
on May 8, 2015, in partial fulfillment of the  
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## **Abstract**

This thesis aims to solve the basic physics behind the collapsible tube dripper design used in drip irrigation. A study was performed on the dynamics of the flow limitation of collapsible tubes. Two parameters were studied: outlet hole diameter and effective length. Prototypes were made varying these parameters, and flow tests were conducted to collect data on pressure and flow rate. Introducing a valve to control the flow significantly improved the control of experiments and the ability to test for pressure compensation. It was found that the outlet hole diameter is directly correlated with outlet flow rate and activation pressure, but indirectly correlated with constancy of flow rate. The impact of effective length on flow rate is still unclear but the results show that there is a possible correlation that may depend on other factors and characteristics of the flow.

Thesis Supervisor: Amos G. Winter V

Title: Assistant Professor and Robert N. Noyce Career Development Professor



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# Chapter 1

## Introduction

Due to climate change, population growth, and urbanization, water and food consumption around the globe continues to increase and it is becoming important to secure food supply while conserving water resources. In developing countries such as India, traditional furrow irrigation is the most common method of growing crops. However, much of the water is being wasted through evaporation or seepage into the ground without effectively irrigating the crops.

Drip irrigation is a promising solution to the water issue, reducing the water usage by up to 70% and increasing crop yield by 20-90% (varies by crop) [2]. Due to the high cost of drip irrigation (on the order of several thousands of dollars per acre), many farmers in developing countries cannot afford to install such a system. The price of such a system for a 1 acre field would need to be around \$300 to suit a large-scale adoption [4].

The high cost of drip irrigation stems from the high cost of providing pumping power to the pressure-compensating (PC) emitters. Pressure-compensation is the phenomenon of reaching a pressure whereby the flow rate emitted stays constant for any subsequent increase in pressure. The pressure at which pressure-compensation occurs is called the activation pressure. Current PC emitters operate at an activation

pressure of 1 bar [4]. Since pumping power is the product of pressure and flow rate, the required power could be lowered by reducing the minimum pressure needed. To attain the estimated pricing of \$300, the emitters would need to operate at a lower activation pressure of 0.1 bar [4]. This would result in a smaller pump and power system required, which contribute to most of the drip irrigation system cost [4].

The work done in this thesis is a continuation of research by Dr. Ruo-Qian Wang, Pulkit Shamsbery, and Professor Amos Winter. Their previous work determined theoretically and experimentally that the activation pressure could be lowered by decreasing the membrane thickness, decreasing the membrane Young's Modulus, increasing the membrane radius, and/or decreasing the outlet hole diameter of the drippers [2]. Additionally, PC behavior is governed by the effective length, perimeter, and area of the channel [2]. In this thesis, dripper prototypes modeled after the Starling resistor were made to study the effects of varying outlet hole diameter and effective length, in an ongoing effort to determine what combination of parameters can be optimized to achieve a new design that will guarantee high performance in practice and affordability for farmers in the developing world.

# Chapter 2

## Design Methodology

### 2.1 Design

The prototypes of the enlarged drippers were modeled after the Starling resistor (shown in Figure 2-1) - a device consisting of an elastic, collapsible tube mounted inside a static pressure chamber. The key parameters include the length and the inner diameter of the collapsible tube. Thus, the outlet hole diameter and the effective length were the design parameters to satisfy. The prototypes followed the schematic in Figure 2-2.

Instead of filling the pressure chamber of the drippers with air (as is usually done in a typical Starling resistor), the static pressure of the pressure chamber in the drippers was maintained using water. The pressure tank was driven by compressed air and controlled by a pressure regulator, and the pressure could be increased to 30 psi (approximately 2 bar).

The two parameters in question were outlet hole diameter (inner diameter of the inner tube) and effective length. Therefore, we manufactured end caps with different outlet hole diameters and the enclosing chamber with different lengths.



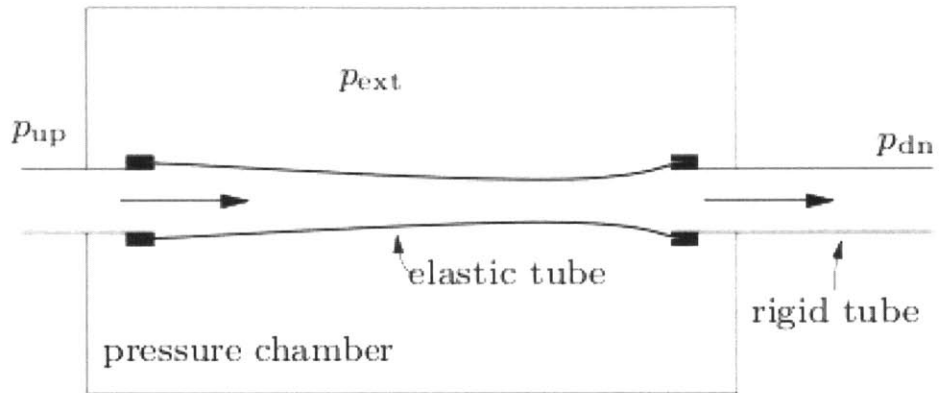


Figure 2-1: A Starling resistor, the model for the dripper prototypes. [3]

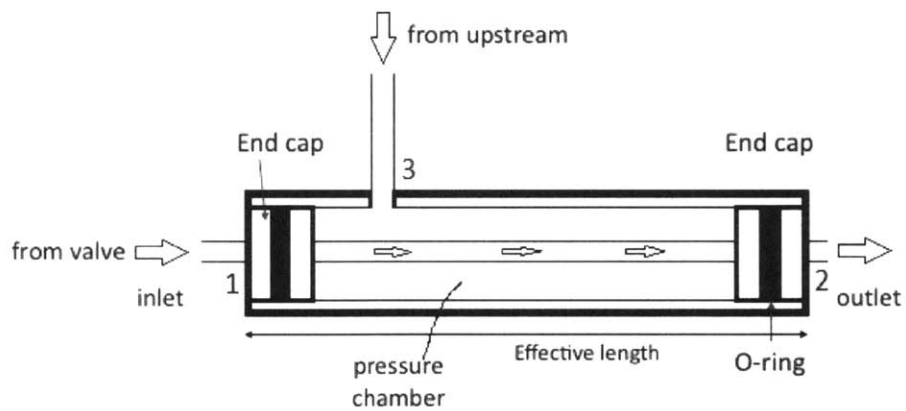


Figure 2-2: Schematic of the dripper prototypes built for testing

## 2.2 Materials

The following lists all the subcomponents and materials used to manufacture the enlarged drippers:

- Outermost chamber: impact-resistant clear polycarbonate, 2.25" OD, 2" ID
- End caps: white Delrin acetal resin rod, 2" diameter
- Inner tube with inner diameter:
  - 1/2": Shore A35 latex rubber, 1/2" ID, 1/16" wall thickness, semi-clear amber
  - 1/4": Shore A35 latex rubber, 1/4" ID, 1/32" wall thickness, semi-clear amber
  - 1/8": Shore A35 latex rubber, 1/8" ID, 1/32" wall thickness, semi-clear amber
- Barbed fittings
  - 1/2": Type 303 stainless steel, 1/2" ID
  - 1/4": Type 303 stainless steel, 1/4" ID
  - 1/8": Type 303 stainless steel, 1/8" ID
- O-Ring: oil-resistant Buna-N multipurpose O-Ring, 3/16 fractional width, dash number 326

## 2.3 Manufacturing

Each dripper tested was manufactured in the following method:

1. Cut the Delrin rod to approximately 1.7" in width (width being normal to the cross-section). This will later become the two end caps.
2. Using the lathe, carve out a hole through the center of the Delrin piece, of diameter 1/2", 1/4", or 1/8". (see Figure 2-3a)
3. Using the lathe, cut out the two O-ring grooves, one for each end piece. The O-ring grooves should follow the dimensions of  $a=0.170 - 0.173$ " and  $b=0.281 - 0.286$ " [1] (see Figure 2-3b for dimensions a and b).
4. Cut the Delrin piece in half using a circular cold saw.
5. Use the lathe to trim off the middle protruding lip of the barbed fittings, so that the barbed fittings will fit through the end caps.
6. Place an O-ring in each end cap groove and a fitting into the center of each end cap.
7. After cutting the rubber tubing to the right effective length (effective length = total length - total Delrin width), attach one end of the rubber tubing to one of the end caps, and zip tie to secure.
8. Cut the polycarbonate tube to the correct total length (1" or 1.25").
9. Drill a hole into the side of the polycarbonate tube (at an approximate location close to that labelled as 3 in Figure 2-2).
10. Insert the end cap and rubber tubing into the polycarbonate tube, far enough so the other end of the rubber tubing extends out of the polycarbonate tube. Attach the second end cap to the end of the rubber tube; zip tie to secure. Carefully insert the second end cap into the polycarbonate tube such that no

twisting of the rubber tube occurs. This is to ensure that there is no preload on the rubber tube.

11. Put C-clamps around the ends of the polycarbonate tube to fix the end positions of the caps. Then use the hole on the side of the polycarbonate chamber to pressurize it, forcing the end caps into position.

For testing, the dripper is attached to the water supply through a system of tubes and valves, detailed in Chapter 3.

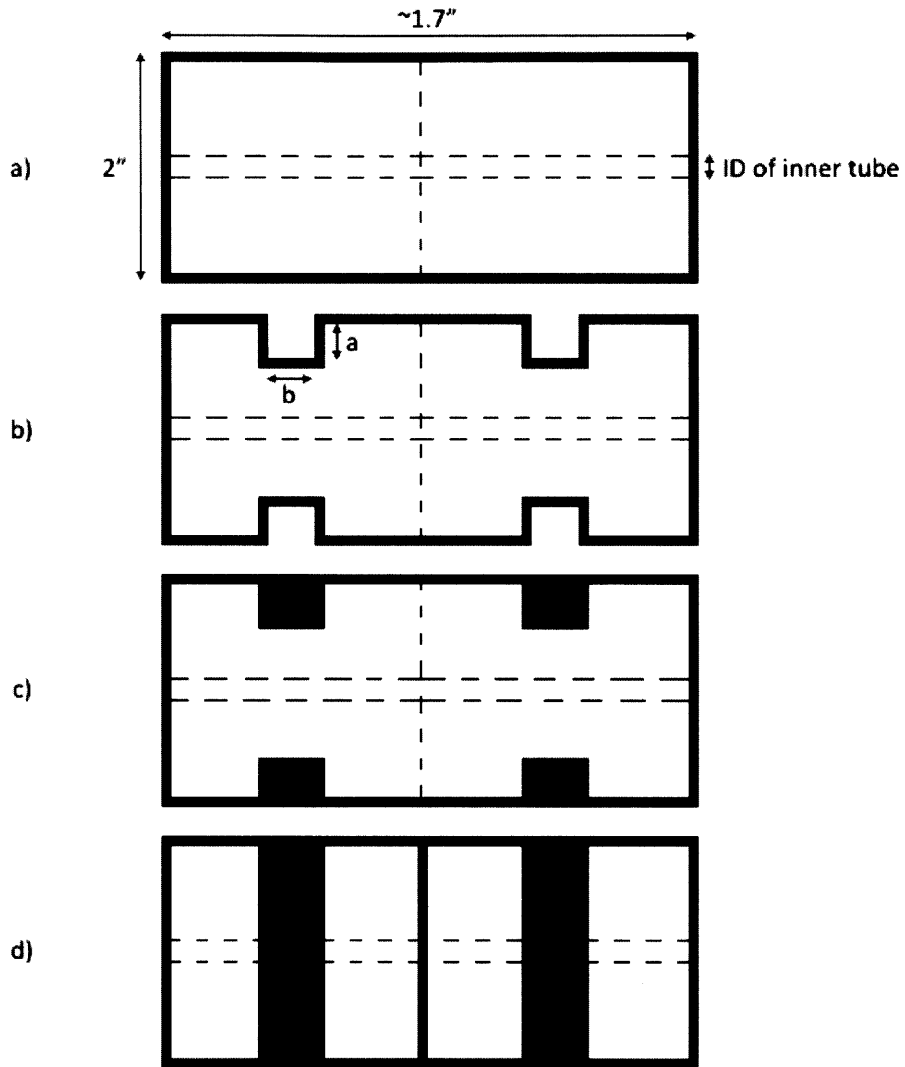


Figure 2-3: Side view of the manufacturing process of the end caps and placement of the O-rings (shaded in black).

# Chapter 3

## Experimental Setup and Methods

### 3.1 Equipment and Testing Setup

After the drippers were manufactured, they were connected to a pressure tank via a system of tubes, sensors, and valves for experiments (Figure 3-1). The major components are detailed in the following sections.

#### 3.1.1 Pressure sensor

The pressure sensor used was the Model 209 Industrial OEM Pressure Transducer, with a pressure range of 0-25 PSIG, an excitation of 5 VDC, and an output of 0-4.5 VDC. The pressure sensor measures the pressure difference between the outer chamber of the dripper and the atmospheric pressure, i.e. the gauge pressure. Assuming the water inside the chamber and within the tube that connects the pressure sensor is static, the gauge pressure is equivalent to the pressure difference between the outer chamber and the inner tube at the end of the dripper.

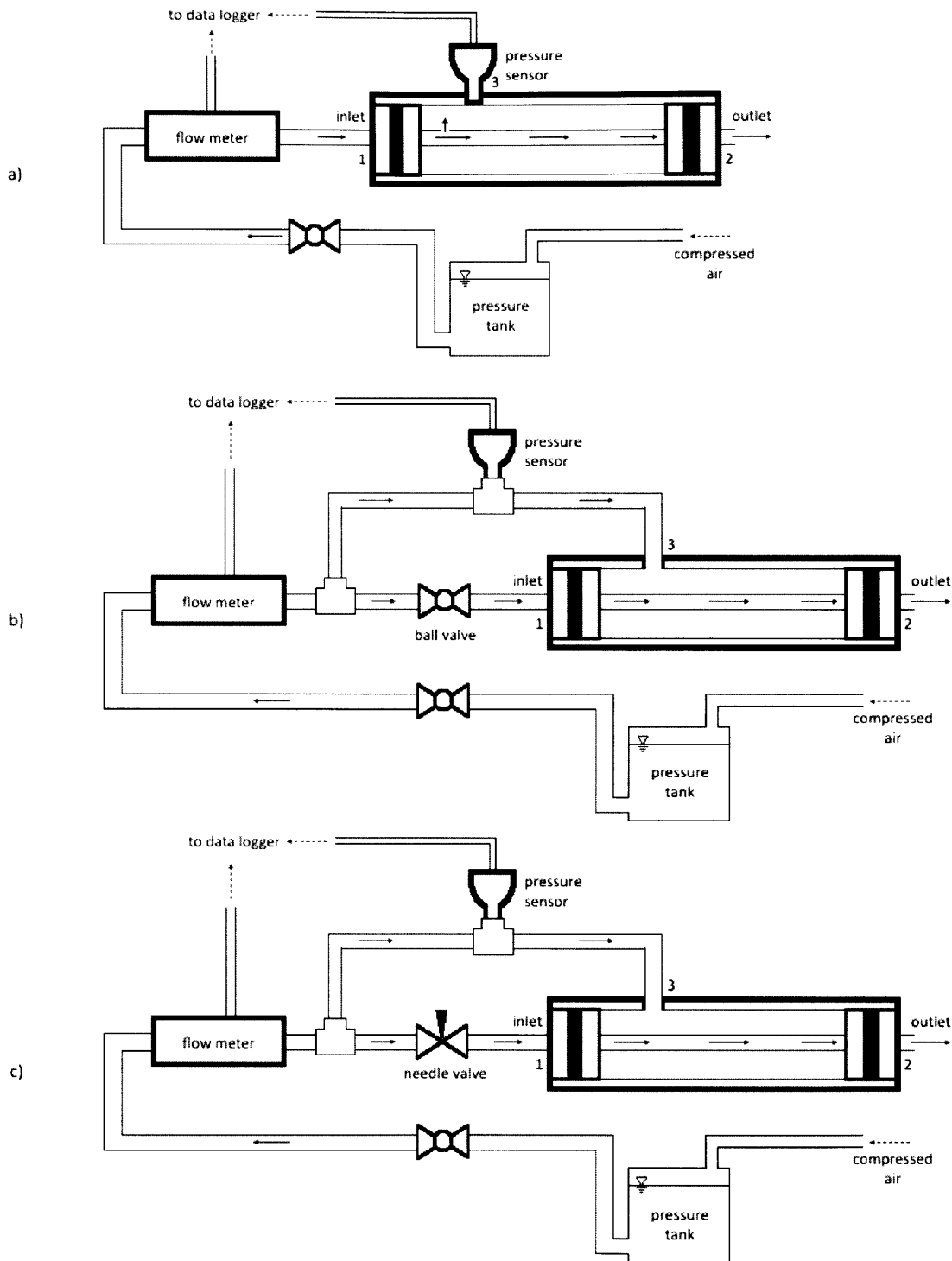


Figure 3-1: All variations of experimental setup. a) Initial setup with no valve control between flow meter and inlet of dripper. b) Setup with a ball valve controlling the flow into the dripper. c) Setup with a needle valve with angular control.

### **3.1.2 Flow meter**

The flow meter used in all experiments is the Seametrics Stainless Single-Jet Meter, 0.1-10 GPM (Gallons Per Minute), High-Resolution Rotor (SES-050-13). Both the flow meter and the pressure sensor are connected to the the data logger for data collection.

### **3.1.3 Valves**

Two kinds of valves were used in the latter two experimental setups (Figure 3-1b,c). The first kind was a ball valve that turns approximately  $90^\circ$  between fully on and fully off. The second kind were two different needle valves with angle markings, which was able to control the valve opening in greater accuracy than the ball valve. The first needle valve (labeled in experiments as Needle1) was the Swagelok Medium-Flow Metering Valve, 1/4" (SS-4MG-MH), with a flow coefficient  $C_v$  up to 0.04. The second needle valve (labeled Needle2 in experiments was the Swagelok Integral Bonnet Needle Valve, 1/4", with a  $C_v$  of 0.73. Flow coefficient is indirectly related to resistance; the higher the  $C_v$ , the lower the resistance. This means that Needle2 has a much lower internal resistance than Needle1. Needle1 requires 8.75 turns of the handle from fully open to fully closed, while Needle2 requires 9.5 turns.

### **3.1.4 Data logger**

The pressure sensor and flow meter were connected to the National Instruments (NI) myDAQ box, which was configured to NI ELVISmx Instrument Launcher.



## 3.2 Method of Collecting Data

### 3.2.1 Testing combinations

The two parameters chosen for testing were inner diameter (outlet hole diameter) and total length, which is proportional to effective length due to the unvaried end cap widths. For inner diameter, three diameters were chosen: 1/2", 1/4", and 1/8". Two different lengths, 1' and 1.25', were chosen for total length of the resistor. They are corresponding to inner tube lengths of 10.4" and 13.4", respectively. Three experimental valve setups were tested. The 18 total combinations of tests that could be run are tabulated in Table 3.1.

Inner Diameter	Total Length	Valve
1/8"	1'	Ball
		Needle1 Needle 2
	1.25'	Ball
		Needle1 Needle 2
1/4"	1'	Ball
		Needle1 Needle 2
	1.25'	Ball
		Needle1 Needle 2
1/2"	1'	Ball
		Needle1 Needle 2
	1.25'	Ball
		Needle1 Needle 2

Table 3.1: All possible testing combinations of inner diameter (outlet hole diameter), total length, and valve type, given the numbers chosen for study.

However, the preliminary results indicated that the initial valveless setup, along

with Ball and Needle1 setups, did not achieve pressure compensation or collapse, deeming later tests with those setups unnecessary. These results are explained in greater detail in Chapter 4. The final set of tests run are listed in Table 3.2.

Inner Diameter	Total Length	Valve
1/8"	1.25'	Ball
		Needle1
		Needle 2
1/4"	1'	Ball
	1.25'	Needle 2
		Needle 2
1/2"	1'	Needle 2
	1.25'	Needle 2

Table 3.2: The set of tests that were fully run (not listed in testing order).

### 3.2.2 Setup tips

To prevent as much leakage as possible, wrap sealing tape around pipe connections before putting them together, and zip-tie afterwards. Fill the dripper chamber with water before connecting to the rest of the setup; try to rid the chamber of any air bubbles. When connecting the dripper to the rest of the setup, in order to not introduce any air bubbles into the chamber, flow water through the pipe that will later connect at location 3 (see Figure 3-1b) and keep it running as you screw the pipe into the chamber. The pressure sensor, flow meter, and all tubes connecting to the dripper should be in the same horizontal plane as the resistor; this eliminated the hydrostatic pressure from the gauge measurements.

### 3.2.3 Data collection settings

The NI Instrument Launcher settings were set each time to a sampling rate of 200 samples per second. Other settings and tips include:

- Make sure both inputs (pressure and flow rate) are being shown as light blue. This indicates that data from both inputs will be read.
- Set min to -10 and max to +10.
- Turn Autoscale on.
- Click Start.
- Confirm that the setup is in the right configuration (valves on) for recording.
- Click Log to start logging data.
- Slowly and continuously increase the pressure up until the max of 30 psi. Then slowly let the air out until pressure has returned to 0 psi.
- Once recording is done, click Stop.

# Chapter 4

## Results and Discussion

Initial tests were performed on a “valveless” setup, i.e. no valve was installed between the pressure sensor branch and the dripper (Figure 3-1a). As a result, the transmural pressure at the end of the rubber tube is only induced by the frictional pressure loss over the rubber tube, which is not enough to collapse the rubber tube. Adding a valve between the pressure sensor branch and the dripper introduces a higher and adjustable resistance, resulting in a variable pressure at the inlet of the dripper. Thus, given the same amount of pressure loss along the length of the tube, the pressure at the outlet of a dripper with a valve can be adjusted to be much lower than the pressure at the outlet of a dripper without a valve. Inserting a valve into the system would therefore make it easier to achieve pressure compensation or collapse. In addition, the activation pressure and the limited flow rate (detailed later) can be separate, which allows a more flexible design of the dripper.

Three different valves were tested - a ball valve and two different needle valves as described in the last section. At least three trials were conducted for each setup and valve setting. Following are some results and some notes worth mentioning:

- Test cases are labeled as [Inner Diameter, Total Length] (e.g. “1/8”,1.25’ ”,

which is short for the case of 1/8 inch at the inner diameter and 1.25 feet at the nominal tube length).

- In the ball valve setup, 0° means the valve is fully open, and 90° means it is fully closed. Drippers were tested at 0°, 22.5°, 45°, 67.5°, and 90°.
- In the two needle valve setups, drippers were tested at every 360° turn of the valve until no measurable flow could be recorded.
- Pressure compensation happens when the flow rate stays constant for any further increases in pressure. In this study, flow rates are defined as constant if it stays within 5% above and below the average flow rate. If pressure compensation occurs, the activation pressure is defined as the pressure at which the flow rate can first be characterized as constant. The method of calculating the range of acceptable flow rates is detailed in Appendix D.

## 4.1 1/8", 1.25'

### 4.1.1 Ball valve

A ball valve is a quarter-turn valve, that is open when the hole of the hollow ball is parallel to the tangential of the pipe and closed when the hole of the ball is perpendicular. The 1/8", 1.25' dripper was tested with the ball valve at 0°, 22.5°, and 45°; results at 67.5° and 90° were not included because no flow could be measured.

Figures 4-1, 4-2, and 4-3 show the flow rate vs. pressure trends of the multiple trials done for each of the different valve settings. The trials were averaged and compiled into Figure 4-4.

As Figure 4-4 shows, these tests exhibit pressure over-compensation, i.e. when the peak flow rates continue to decrease. The peak pressure is approximately 0.45

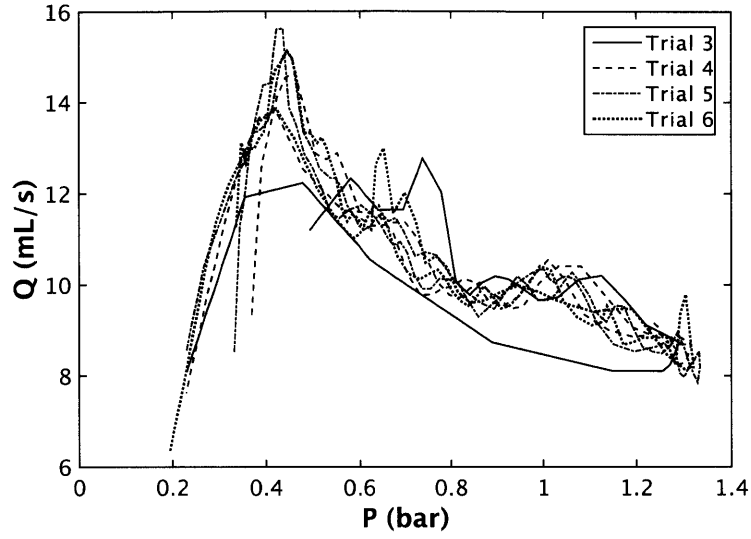


Figure 4-1: 1/8" inner diameter, 1.25' total length dripper, tested at fully open.

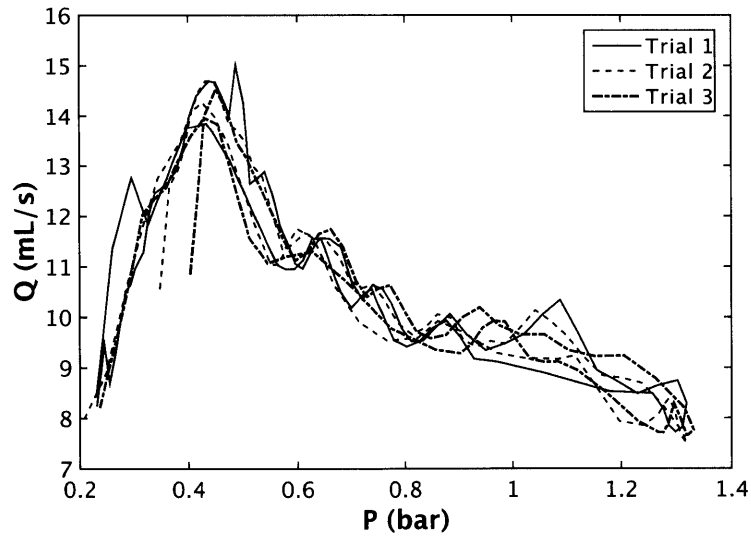


Figure 4-2: 1/8" inner diameter, 1.25' total length dripper, tested at 22.5°.

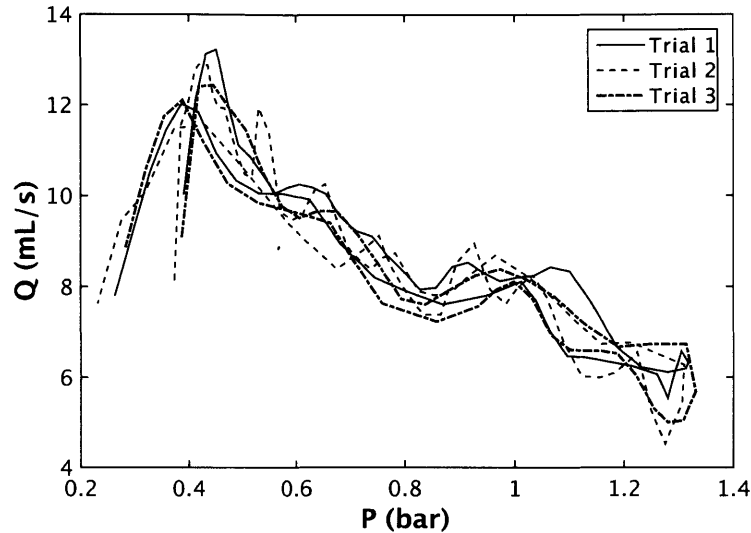


Figure 4-3: 1/8" inner diameter, 1.25' total length dripper, tested at 45°.

bar, which is higher than the desired 0.1 bar activation pressure. Thus, this dripper fails to meet the target specifications. Figure 4-4 also shows that as the valve opening is getting smaller, the peak flow rate and the entire trend shifts lower. This makes intuitive sense, since closing the ball valve increases the total resistance and decreases the flow rate.

The ball valve is not suitable for a systematic study, because there was no way to accurately control the opening. A protractor was used to enhance the repeatability, but the controllability is still unsatisfactory. Furthermore, no signal was obtained at 67.5° and 90°. This could be due to a few reasons: the flow may have been lower than the lower limitation of the flow meter (0.1 GPM = 6.3 mL/s), or the valve may have shut before reaching 67.5°. Due to the inaccuracy of the ball valve, it was replaced with a needle valve in subsequent tests.

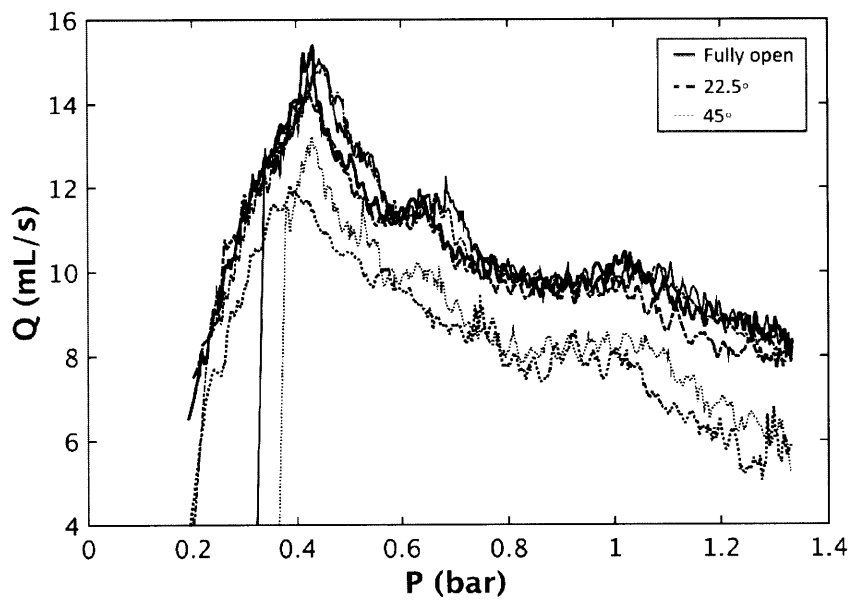


Figure 4-4: 1/8" inner diameter, 1.25' total length dripper, tested at 0° (continuous), 22.5° (dashed), and 45° (dotted). Each curve shows the average of the trials in a particular test.



### 4.1.2 First needle valve

Next, the 1/8", 1.25' dripper was tested with the first needle valve ( $C_v=0.04$ ). Unfortunately, the internal resistance of the valve was too high because even at a fully open state, the signal was out of range, as shown in Figure 4-5. Subsequent tests yielded similar results (see Figure ??). When the 1/4" dripper was connected to the first needle valve, no signal was obtained either; therefore no tests with the other drippers were conducted using the first needle valve.

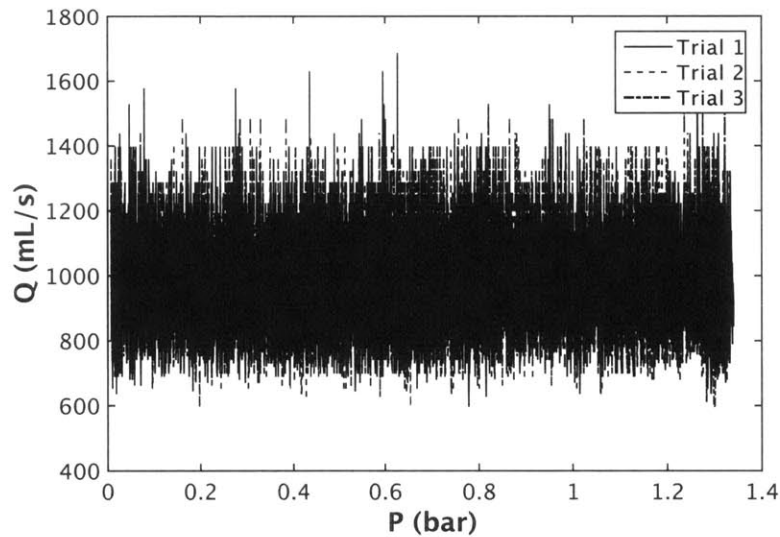


Figure 4-5: 1/8" inner diameter, 1.25' total length dripper, tested at fully open.

### 4.1.3 Second needle valve

Although the resistance for the second needle valve ( $C_v=0.73$ ) was lower than that of the first needle valve, similar results were obtained when the 1/8", 1.25' dripper was tested with it, i.e. no signal was obtained. However, usable results for the other two drippers were obtained and are discussed in the next section.

Because both needle valve setups yielded unusable results with the 1/8" inner diameter, 1.25' total length dripper, the pressure loss along a shorter tube such as a 1/8", 1' dripper would be even less (since pressure loss is directly correlated with length of the tube), which would not improve the signal. Therefore, the 1/8", 1' dripper was not tested further.

## 4.2 1/4", 1'

### 4.2.1 Ball valve

Before the ball valve was replaced with the needle valves, the 1/4", 1' dripper was also tested with the ball valve. (The remaining drippers were tested on the second needle valve only.) Figure 4-6 shows the behavior for the three trials performed. Trials 2 and 3 are very close and achieve pressure compensation at activation pressures of 0.39 and 0.43 bar, respectively. However, trial 1 yielded much lower flow rates than trials 2 and 3.

Because trial 1 was so different from trials 2 and 3, it was considered an outlier due to unknown reason and taken out when averaged. The remaining two trials were averaged in Figure 4-7, showing an average pressure-compensated flow rate of  $28.58 \pm 1.42$  mL/s, from approx 0.45 to 0.91 bar. The average activation pressure was therefore 0.45 bar. The average flow rate peaked at 41.28 mL/s at a pressure of 0.11 bar.

Once the valve was set to  $22.5^\circ$ , the results obtained were drastically different. Instead of achieving pressure compensation, the flow rate continued to drop at a reasonably linear rate until it reached full collapse, where a sharp drop was recorded (Figure 4-8). The flow rate in this test was also much lower than at the fully open state; the highest flow rate reached was 21.58 mL/s, which is 47.3% lower than the

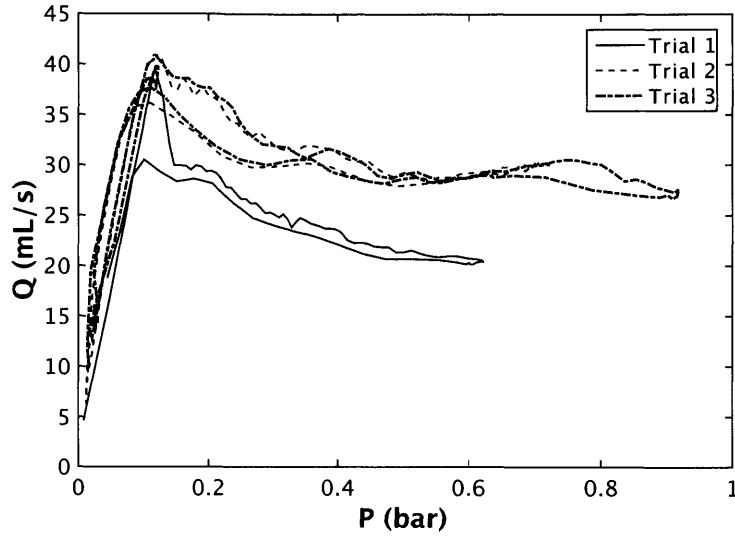


Figure 4-6: 1/4" inner diameter, 1' total length dripper, tested at fully open.

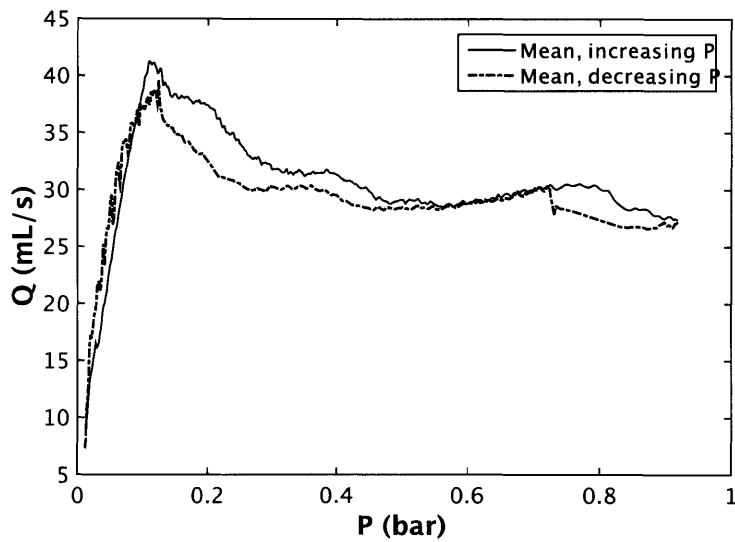


Figure 4-7: 1/4" inner diameter, 1' total length dripper, tested at fully open. Trials 2 and 3 were averaged; trial 1 was excluded from the average.

highest flow rate reached when the valve was fully open (40.91 mL/s).

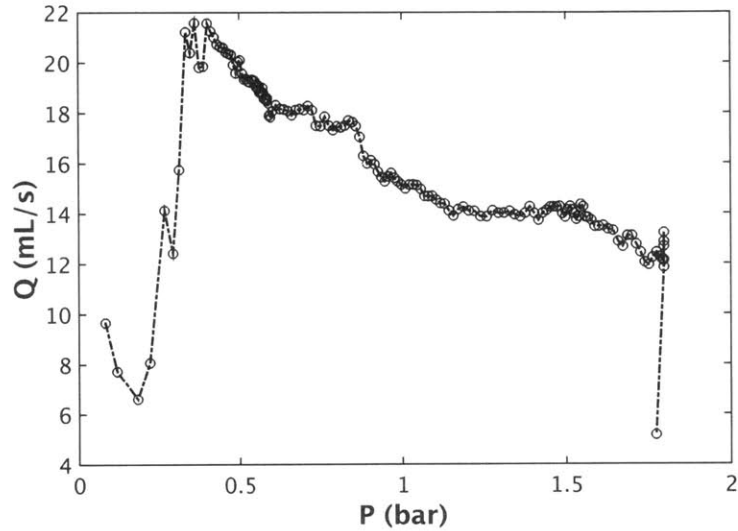


Figure 4-8: 1/4" inner diameter, 1' total length dripper, tested at 22.5°.

When the valve was set at 45°, no signal was obtained. If the decrease in flow rate is proportional to the decrease in openness of the valve (increase in degree of turn), then it could explain why no signal could be measured: since 50% of the flow rate dropped between 0° and 22.5°, then by 45°, the flow rate should be close to 0.

The results from the fully open test show that the 1/4", 1' design does achieve pressure compensation, but not at the target activation pressure of 0.1 bar. Therefore, this design has more potential than the 1/8", 1.25' design but will require modifications in order to reach the desired activation pressure.

#### 4.2.2 Second needle valve

The 1/4", 1' dripper was tested further using the second needle valve. The trend for all three trials (Figure 4-9) is similar to that shown in the ball valve test (Figure 4-6).

However, the peak flow rates are 30.62 to 35.84% lower than those in the ball valve test, and the flow rate plateaus at a higher pressure and for a shorter period of time before the tube undergoes collapse. The internal resistance of the needle valve may account for the lower peak flow rates.

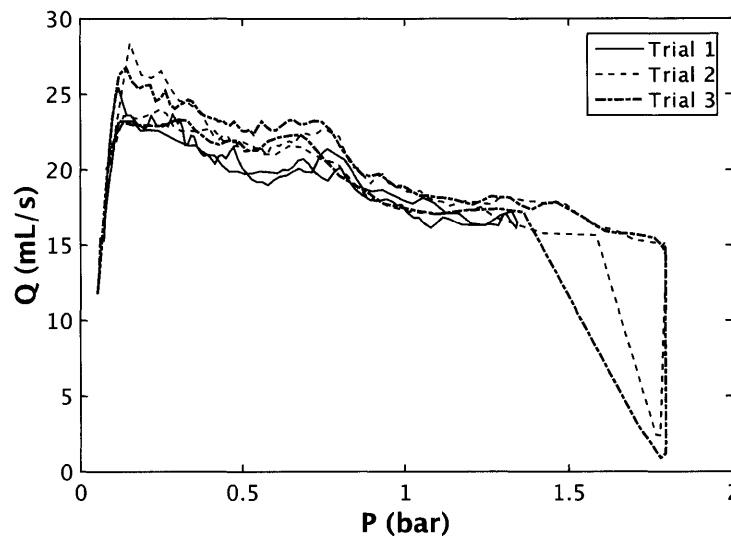


Figure 4-9: 1/4" inner diameter, 1' total length dripper, tested at fully open.

Figure 4-10 shows the average of the three trials. The average peak flow rate is 26.4 mL/s at a pressure of 0.11 bar; this flow rate is lower than the average peak flow rate in the ball valve setup, but the pressure is the same. The average flow rate at pressure compensation is  $18.3 \pm 0.9$  (from 0.9 to 1.5 bar). This is approximately 35.9% lower than the average flow rate in the ball valve test ( $28.58 \pm 1.42$  mL/s, Figure 4-7). Moreover, the activation pressure of 0.9 bar is twice the activation pressure of 0.45 bar needed in the ball valve test. These findings are intuitive because the higher resistance of the needle valve, as compared to the ball valve, will cause a lower flow rate and a higher activation pressure.

The 1/4", 1' dripper was also tested at one turn and two turns. The three trials

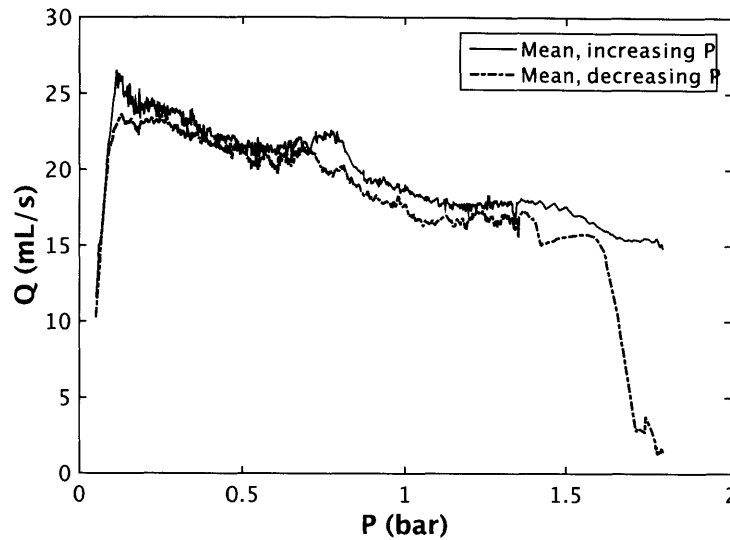


Figure 4-10: 1/4" inner diameter, 1' total length dripper, tested at fully open. The three trials performed were averaged.

for each of these valve settings were averaged and all three tests (fully open, one turn, two turns) are shown in Figure 4-11. Surprisingly, the average trend for 0 and 1 turns is very close; the average peak flow rate for the 1 turns test is 26.36 mL/s at a pressure of 0.127 bar, and the average pressure-compensated flow rate is  $17.3 \pm 0.8$  mL/s when the pressure is within 0.94 to 1.44 bar. This is very close to the averaged fully open test, which yielded an average flow rate of  $18.3 \pm 0.9$  mL/s from 0.9 to 1.5 bar. However, the average of the 2-turn test seems to output a much lower average pressure-compensated flow rate of  $13.51 \pm 0.67$  mL/s from 0.86 to 1.34 bar. As the valve further closes, it is logical that the flow rate should decrease as well, which explains why the curves shift downwards as the number of turns of the valve increases.

Although the 1/4", 1' dripper achieved pressure compensation, it did not achieve an activation pressure of 0.1 bar. The lowest activation pressure achieved across all

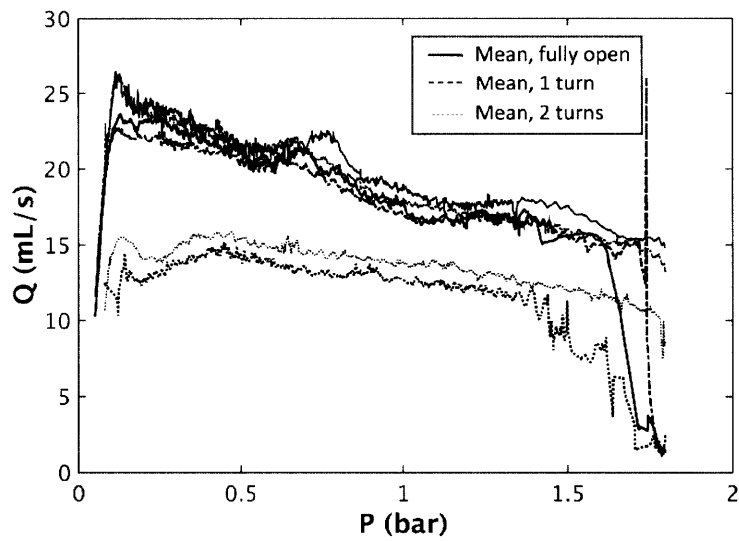


Figure 4-11: 1/4" inner diameter, 1' total length dripper, tested at 0 (continuous), 1 (dashed), and 2 (dotted) turns. Each curve shows the average of the trials in a particular test.

tests was 0.45 bar, in the fully open ball valve setup.

### 4.3 1/4", 1.25'

#### 4.3.1 Second needle valve

The 1/4", 1.25' dripper was tested only on the second needle valve setup. Figure 4-12 shows the three trials performed.

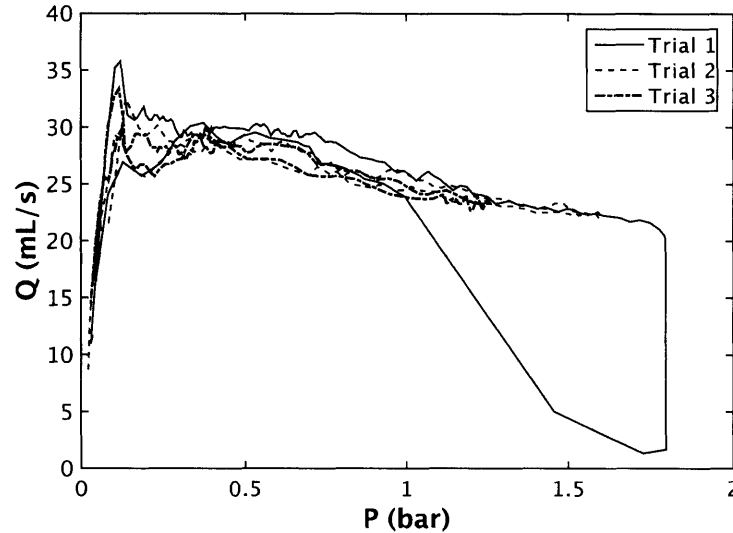


Figure 4-12: 1/4" inner diameter, 1.25' total length dripper, tested 3 times at fully open.

The three trials follow the same general trend, and their average is shown in Figure 4-13. The average flow rate slightly pressure compensates at two different pressure ranges. The first is from 0.16 to 0.72 bar, at which the average flow rate is  $29.1 \pm 1.5$  mL/s. The second pressure compensation is from 1.25 to 1.75 bar, at an average flow rate of  $22.6 \pm 1.13$  mL/s.



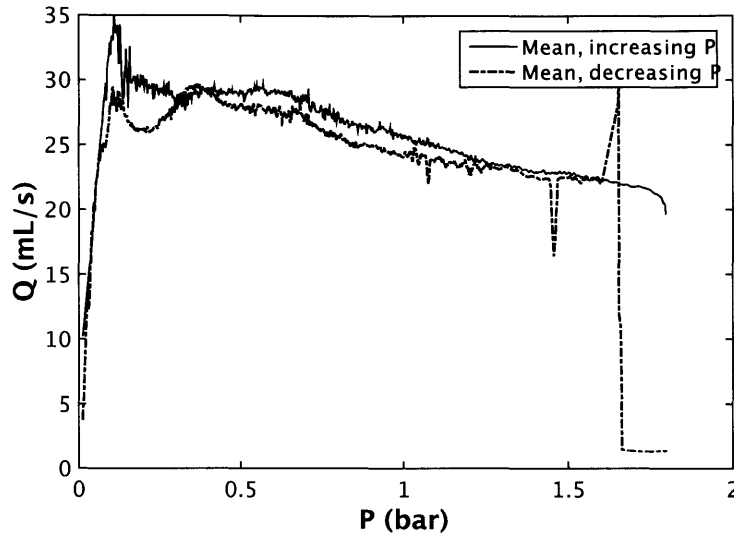


Figure 4-13: 1/4" inner diameter, 1.25' total length dripper, tested 3 times at fully open. The three trials performed were averaged.

However, the second half of trial 1 deviates from trials 2 and 3 because the rubber tube was fully collapsed. This can be seen in the big loop in Figure 4-12. Eliminating trial 1, the result is shown in Figure 4-14. Figure 4-15 then shows the average of trials 2 and 3, which exhibits pressure compensation in the pressure range 0.13-0.7 bar, at an average flow rate of  $29.2 \pm 1.5$  mL/s. This flow rate is very close to the average pressure-compensated flow rate in the last figure (Figure 4-13, average flow rate of  $29.1 \pm 1.5$  mL/s). However, the average for the two trials only yielded a lower activation pressure of 0.13 bar. This activation pressure is much lower than the 0.82 bar needed in the 1/4", 1' Needle2 test.

Next, the needle valve was closed by one turn. Similar to the fully open test, one of the trials (trial 3) deviated from the general trend of the other two trials, clearly shown by the loop in Figure 4-16. To minimize the outlier effects of trial 3, it was taken out in Figure 4-17. The two trials were then averaged in Figure 4-18.

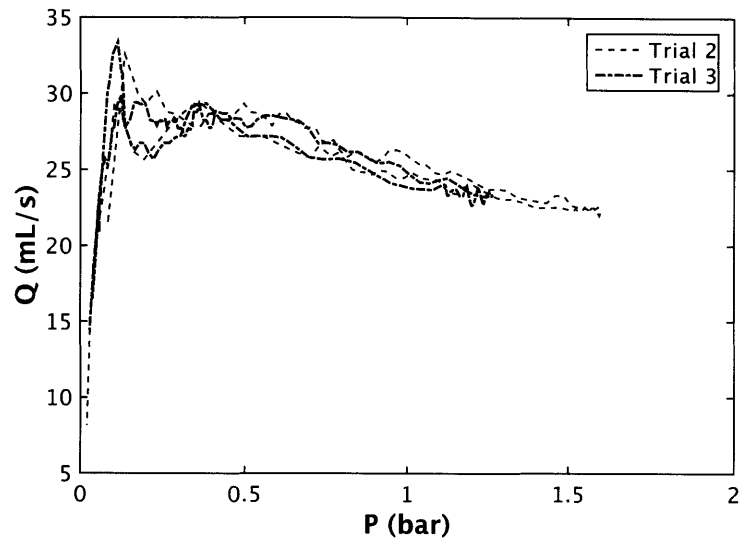


Figure 4-14: 1/4" inner diameter, 1.25' total length dripper, tested 2 times at fully open. Trial 1 was excluded.

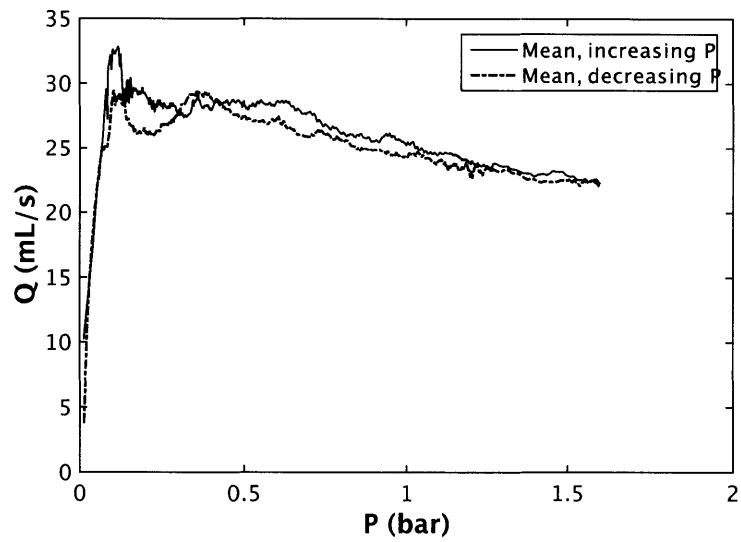


Figure 4-15: 1/4" inner diameter, 1.25' total length dripper, tested 2 times at fully open. Trial 1 was excluded; trials 2 and 3 were averaged.

As pressure is increased, the flow rate plateaus to an average flow rate of  $25.05 \pm 1.25$  mL/s, within the pressure range of 0.14 to 0.89 bar.

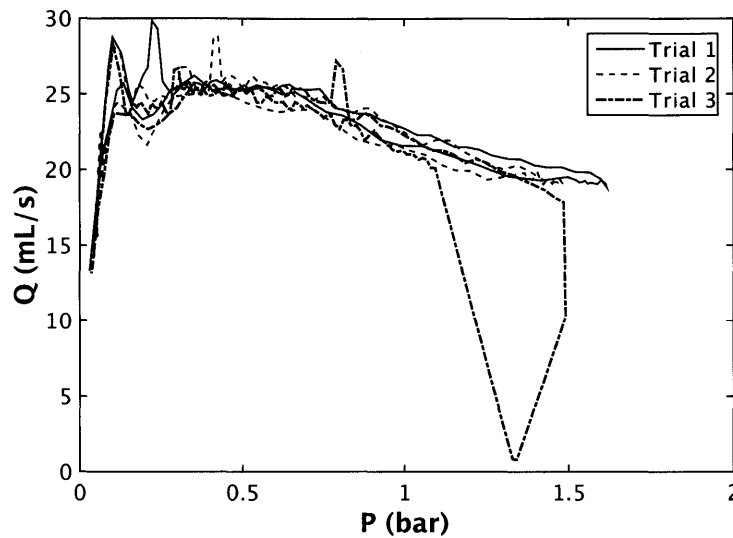


Figure 4-16: 1/4" inner diameter, 1.25' total length dripper, tested 3 times at one turn.

At two turns of the valve, the results are very different. The flow rate does not exhibit a large drop after reaching the threshold pressure (which has been seen frequently in the past tests), but rather exhibits a very small drop and plateaus very quickly to a constant flow rate (Figure 4-19). Figure ?? shows the average of the trials; pressure compensation occurs immediately after the threshold pressure of 0.11 bar (also the activation pressure in this case) is reached. The average flow rate at pressure compensation is  $16.73 \pm 0.83$  mL/s (from 0.11 to 0.39 bar). A second pressure compensation occurs at average flow rates of  $16.43 \pm 0.82$  bar, from 0.9 to 1.29 bar.

At three turns of the valve, the flow rate is much more unstable as pressure increases. All three trials in Figure 4-21 show the inner tube reaching total collapse, in which case the tube collapses in on itself, thus stopping the flow from exiting

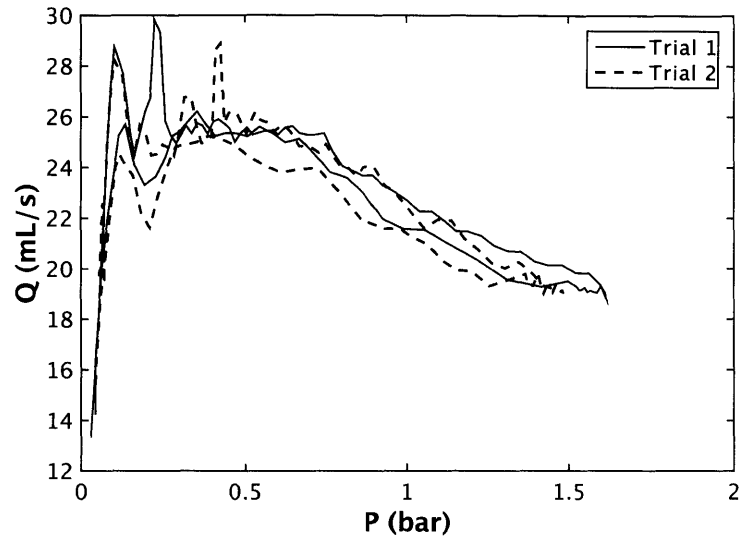


Figure 4-17: 1/4" inner diameter, 1.25' total length dripper, tested 2 times at one turn. Trial 3 was excluded.

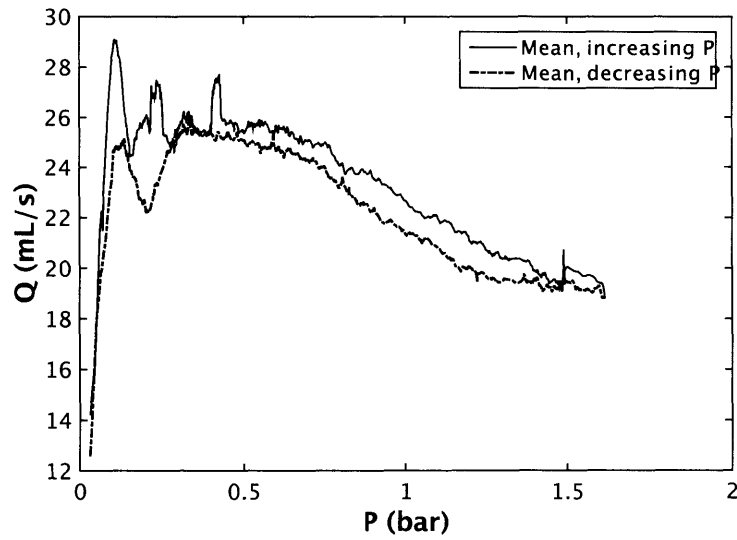


Figure 4-18: 1/4" inner diameter, 1.25' total length dripper, tested 2 times at one turn. Trial 3 was excluded; trials 1 and 2 were averaged.

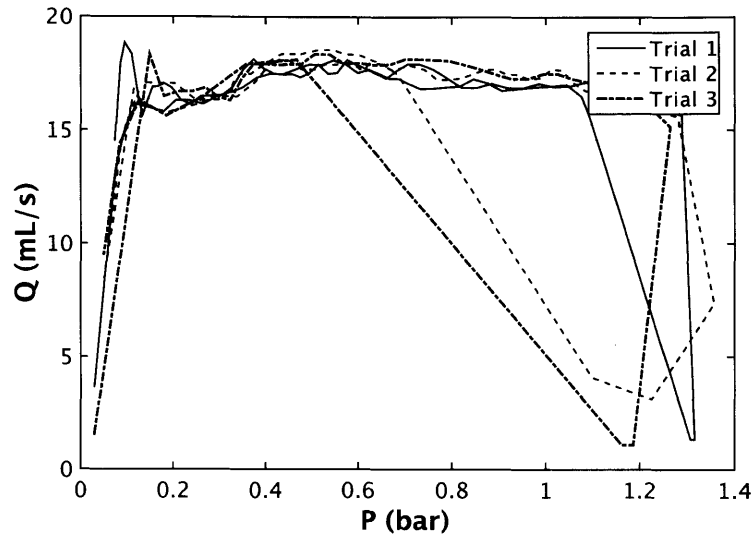


Figure 4-19: 1/4" inner diameter, 1.25' total length dripper, tested 3 times at two turns.

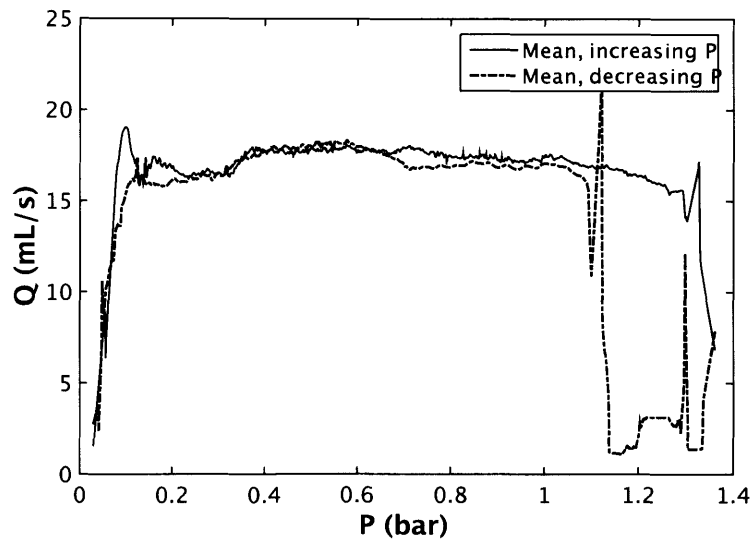


Figure 4-20: 1/4" inner diameter, 1.25' total length dripper, tested 3 times at two turns. The three trials performed were averaged.

the channel and causing the flow to become very low or reach 0. Slight pressure compensation occurs within the pressure range 0.12-0.76 bar, at an average flow rate of  $10.99 \pm 0.55$  mL/s (Figure 4-22).

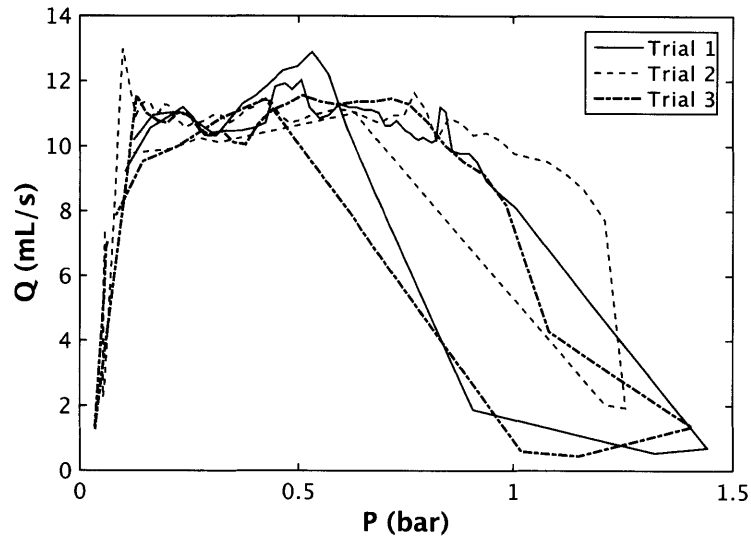


Figure 4-21: 1/4" inner diameter, 1.25' total length dripper, tested 3 times at three turns.

All four tests of 0 to 3 turns were averaged and compiled into Figure 4-23, which clearly shows the downwards shift of flow rate with each turn of the valve (closing of the valve). The average pressure-compensated flow rate of the fully open test is almost three times the average pressure-compensated flow rate of the 3 turns test.

Together, all these results suggest that the 1/4", 1.25' dripper has an even greater potential than the 1/4", 1' dripper to achieve pressure compensation and an activation pressure of 0.1 bar. At two turns of the needle valve, the 1/4", 1.25' dripper achieves pressure compensation at an average flow rate of 16.73 mL/s and an activation pressure of 0.11 bar.

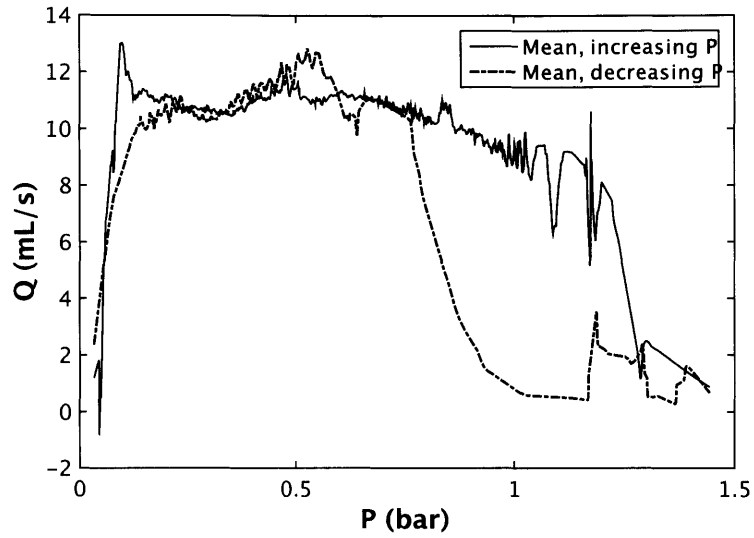


Figure 4-22: 1/4" inner diameter, 1.25' total length dripper, tested 3 times at three turns. The three trials performed were averaged.

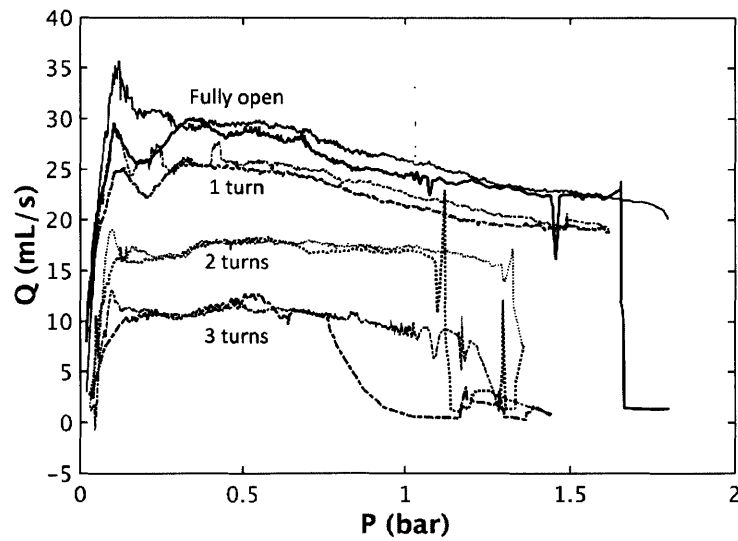


Figure 4-23: 1/4" inner diameter, 1.25' total length dripper, tested from 0 to 3 turns. Each curve shows the average of the trials in a particular test.

## 4.4 1/2", 1'

Next, 1/2" drippers were tested with Needle2.

### 4.4.1 Second needle valve

When the needle valve is fully open, one can see in Figure 4-24 that the flow undergoes overcompensation; there is a steady decline in flow rate as pressure is increased. Eventually, the dripper experiences total collapse.

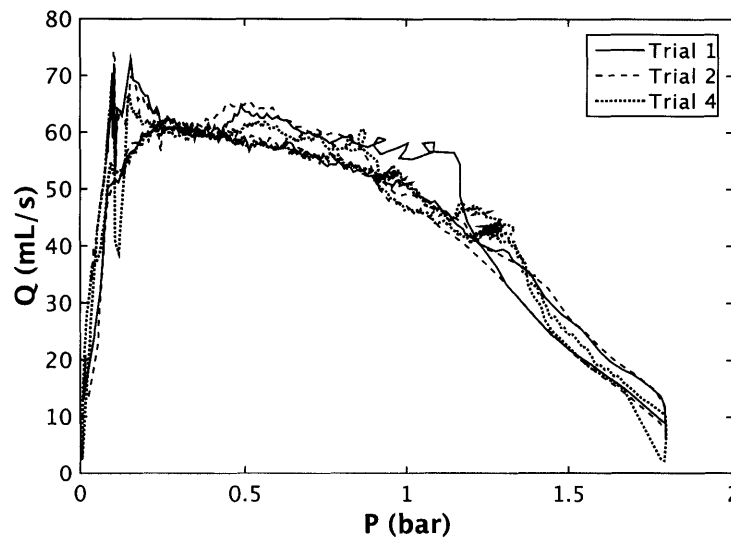


Figure 4-24: 1/2" inner diameter, 1' total length dripper, tested 3 times at fully open.

The average of the three trials (Figure 4-25) is very close to the original datasets. The flow peaks at an average rate of 69.77 mL/s at an average pressure of 0.1 bar. However, 0.1 bar is not the activation pressure because pressure compensation does not occur.

The same trend was repeatable for the rest of the tests, from one turn of the needle valve to seven turns of the needle valve. For each new setup, the trials were



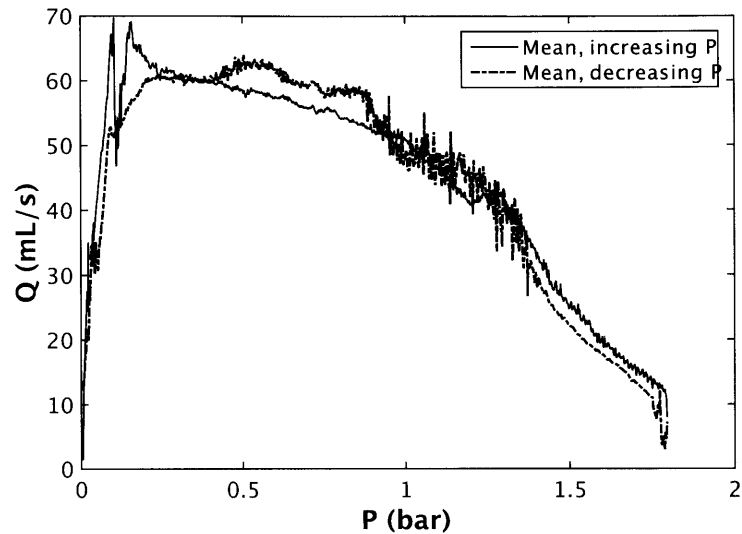


Figure 4-25: 1/2" inner diameter, 1' total length dripper, tested 3 times at fully open. The three trials performed were averaged.

averaged. All the averaged tests are compiled into Figure 4-26, which shows that as the valve opening is decreased by 1 turn, the flow rate peaks at a lower flow rate. However, the flow rates peak at about the same peak threshold pressure, and all of them overcompensate. Therefore, the 1/2", 1' dripper does not meet the desired characteristics of pressure compensation and a 0.1 bar activation pressure.

## 4.5 1/2", 1.25'

The last dripper to be tested was the 1/2", 1.25' dripper.

### 4.5.1 Second needle valve

As with most of the drippers, the 1/2", 1.25' dripper experienced oscillations once the pressure reached a certain point. The oscillations of the 1/2", 1.25' dripper, however,

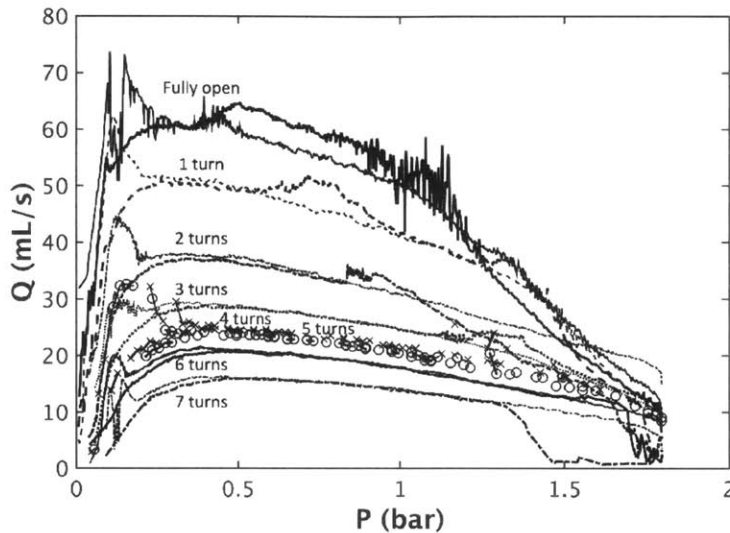


Figure 4-26: 1/2" inner diameter, 1' total length dripper, tested from 0 to 7 turns. Each curve shows the average of the trials in a particular test.

were large enough to be measured by the flow meter and pressure sensor and can be seen in the flow rate vs. pressure graphs for each valve setting. Figure 4-27 shows the three trials done when the valve is fully open. Circled are the oscillations that have been sensed by the flow meter and pressure sensor and that are now visible in the trend. As the figure shows, once a certain pressure has been reached (in this case, approximately 0.5 bar) the inner tube starts oscillating until the pressure becomes too high, causing the inner tube to start to collapse (approximately 1.25 bar in this case). When these trials are averaged (as in Figure 4-28), one can see more clearly the pressure range of oscillation. For the fully open test, the pressure range of oscillation (when the pressure is being increased) is approximately 0.6-1.28 bar. Because of the higher amplitude of these oscillations, the flow across this pressure range cannot be characterized as constant. However, there is a small pressure-compensating region from 0.19 to 0.59 bar, where the flow rate stays on average at  $59.3 \pm 2.97$  mL/s. (R:

Should include the description of the tube oscillation)

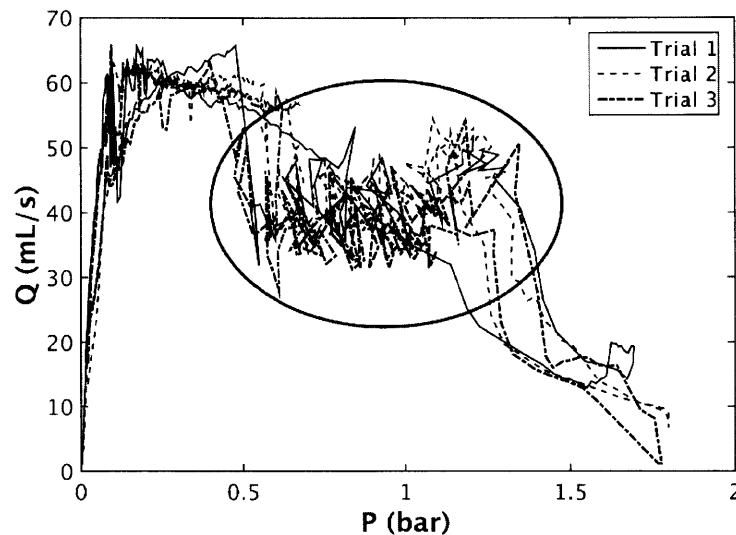


Figure 4-27: 1/2" inner diameter, 1.25' total length dripper, tested 3 times at fully open.

The dripper was tested at 0-6 turns of the valve; past six turns of the valve, no signal can be obtained. Each of the subsequent tests revealed similar results. The average of all the trials at each of the different valve settings is shown together in Figure 4-29. Once again, the average flow rate decreases as the valve becomes more closed (more turns of the valve). When the pressure is being increased, the inner tube seems to oscillate for increasingly smaller pressure ranges; at one turn of the valve, the pressure range of oscillation is 0.76-1.3 bar, and at two turns, the pressure range is 1.05-1.3 bar. At three or more turns of the valve, the oscillation is no longer measurable when the pressure is being increased; instead, the oscillation is only measurable when the pressure is being decreased (see Appendix A, Figures A-56-A-63). Regardless, the approximate pressure range for oscillation for all setups is 0.5-1.3 bar. One and two turns of the valve do not produce pressure-compensating

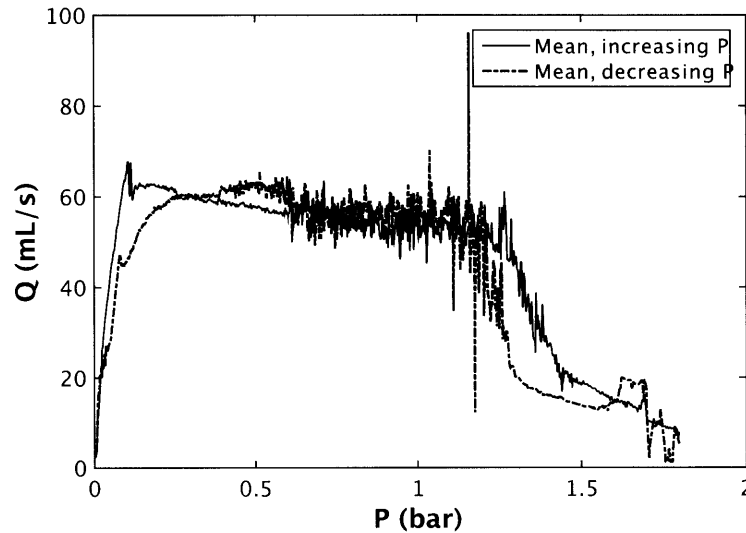


Figure 4-28: 1/2" inner diameter, 1.25' total length dripper, tested 3 times at fully open. The three trials performed were averaged.

regions, but three turns or more do produce small pressure-compensating regions. The activation pressures for these regions, however, all exceed the desired 0.1 bar activation pressure. Thus, the 1/2", 1.25' dripper does not meet target specifications.

## 4.6 The Effect of Key Design Parameters

The two parameters specifically tested were effective length and inner diameter. The effects of each parameter are explained in the following sections.

### 4.6.1 Total length

The effect of effective length on flow rate was different for the 1/2" than for the 1/4" dripper. For the 1/4" dripper, the trends for the 1' and 1.25' were very similar but shifted, as shown in Figure 4-30. The trend for the 1.25' was shifted slightly

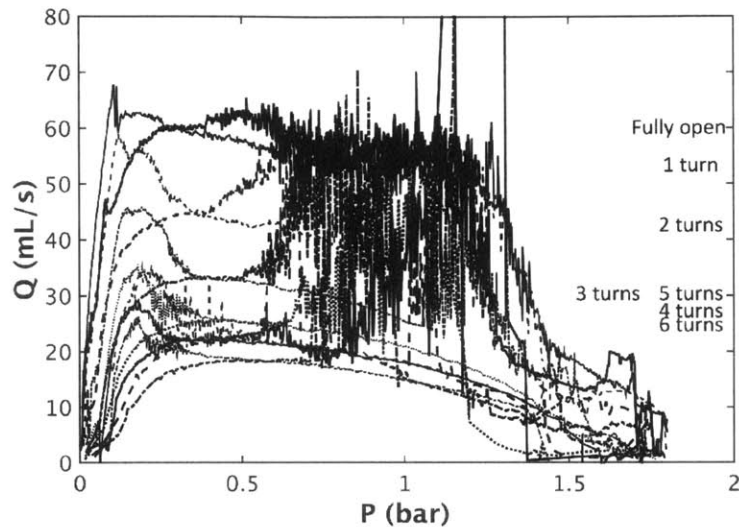


Figure 4-29: 1/2" inner diameter, 1.25' total length dripper, tested from 0 to 6 turns. Each curve shows the average of the trials in a particular test.

higher than the 1' for each of the valve settings (0-2 turns, see Appendix A, Figures A-65-A-67). This observation suggests that a longer dripper leads to higher flow rates.

The effect of total length on flow rate for the 1/2" dripper was different, however. As Figure 4-31 shows, the longer dripper (1.25') actually yields a similar or slightly lower flow rate than the shorter dripper (1'). The same relationship can be seen in the other valve settings in Appendix A (Figures A-68-A-74). This contradicts the effect seen earlier with the 1/4" dripper, which suggested that a longer dripper yields higher flow rates. The oscillatory behavior of the 1/2", 1.25' dripper may be able to explain why the flow rate yielded is lower than the flow rate for the 1/2", 1' dripper: as the graphs for the 1/2", 1' dripper show, the oscillation of the dripper was not large enough to be measured by the pressure sensor and flow meter, whereas the oscillation was easily picked up for the 1/2", 1.25' dripper. This suggests that perhaps the oscillation is impeding the flow and causing a back flow, which could lead

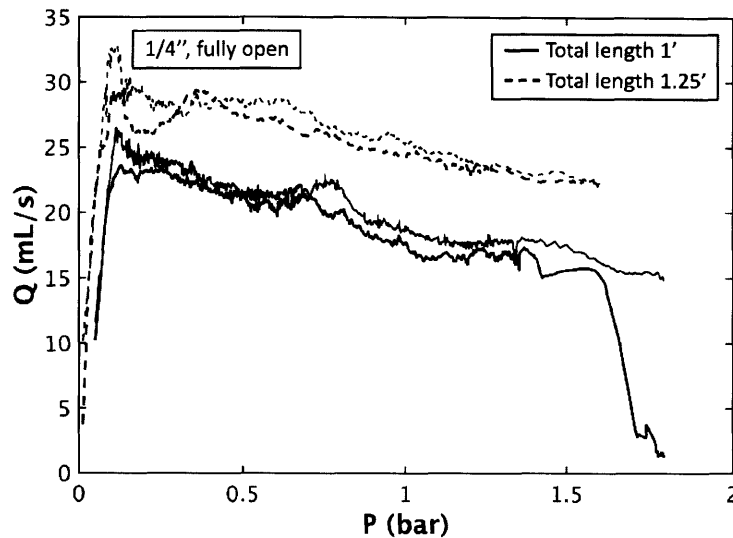


Figure 4-30: Comparison of 1' and 1.25' drippers, each with 1/4" inner diameter, tested with a fully open valve.

to the flow rate for the longer 1.25' dripper being slightly less than the flow rate for the 1' dripper.

The total length of the drippers did not seem to play a major role in influencing the activation pressure. The peak flow rates occur at approximately the same pressure for each of the different drippers and valve settings.

#### 4.6.2 Inner diameter

The effect of inner diameter on flow rate and pressure was much more straightforward. Figure 4-32 compares the flow rate vs. pressure curves for the 1/2" and 1/4" drippers, keeping the total length and valve setting the same. It shows that the 1/2" drippers yielded much higher flow rates than the 1/4" drippers, but the 1/4" drippers were able to maintain a much flatter and more constant flow rate throughout the test. Other comparisons of 1' and 1.25' drippers at various valve settings showed a similar

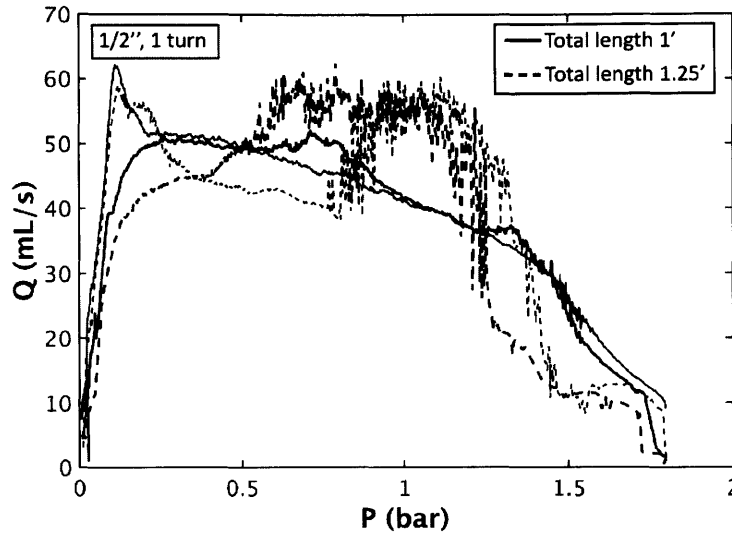


Figure 4-31: Comparison of 1' and 1.25' drippers, each with 1/2" inner diameter, tested with at one turn.

relationship and are shown in Appendix A, Figures A-75-A-81. Hence, a larger inner diameter of the collapsible tube yields larger flow rate but a higher chance of over-compensating. In this study, the 1/4" seems to be a better choice than the 1/2" in terms of maintaining a constant flow rate.

## 4.7 Summary of Results

The main results are summarized in Table 4.1. The drippers with the lowest activation pressures were 1/4", 1.25' at 2 turns (0.11 bar) and 1/2", 1.25' at 0 turns (0.19 bar). The 1/4", 1.25' dripper might be the best choice within the range of this study because of its low activation pressure and a stable flow rate-pressure relationship (as the discussion on the effect of inner diameter mentioned), but the 1/2", 1.25' is capable of outputting 3.5 times as much water. Modifications that may improve either

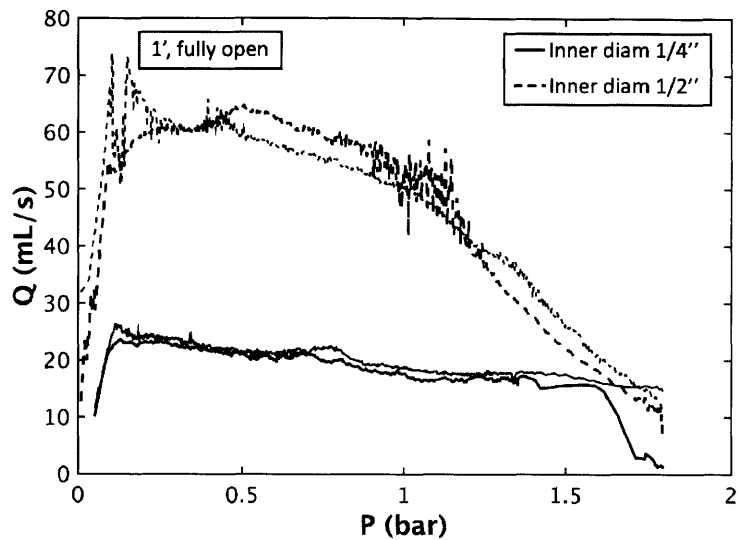


Figure 4-32: Comparison of 1/2" and 1/4" drippers, each 1' long, tested with a fully open valve.

design include using a needle valve with a lower internal resistance, changing the total length of the dripper (increasing it may aid pressure compensation, but decreasing it may lower stiffness of the inner tube), etc. Nevertheless, both dripper designs have the potential to achieve the target specifications and should be investigated further in future tests.



ID	TL	Valve	PC?	Min. AP (bar)	PC FR (mL/s)	PC Conditions
1/8"	1.25'	Ball	No	—	—	—
		N1	No	—	—	—
		N2	No	—	—	—
1/4"	1'	Ball	Yes	0.45	28.58±1.42	0° (fully open)
	1.25'	N2	Yes	0.86	13.51±0.67	2 turns of valve
		N2	Yes	0.11	16.73±0.83	2 turns of valve
1/2"	1'	N2	No	—	—	—
	1.25'	N2	Yes	0.19	59.3±2.97	0 turns of valve

Table 4.1: Main results for each test; for pressure-compensating (PC) drippers, only the smallest activation pressure (AP) and the conditions at which that pressure was achieved are listed. [ID refers to inner diameter of the inner tube, TL refers to total length of the dripper, and FR refers to flow rate.]

# Chapter 5

## Conclusions and Next Steps

As the global population continues to increase, efficient use of water is becoming more and more essential. Methods such as traditional furrow irrigation are wasteful and should be replaced by more efficient irrigation methods such as drip irrigation. In order for farmers to adopt drip irrigation, it must first be affordable. The estimated pricing of \$300 can be achieved by designing drippers to pressure-compensate at an activation pressure of 0.1 bar.

In this study, five different dripper designs with varying length, inner diameter, and valve setup, were investigated. From the flow tests, it was determined that two drippers have the potential to achieve pressure compensation and the target activation pressure of 0.1 bar. One was the 1/4" inner diameter, 1.25' long dripper, which had an activation pressure of 0.11 bar when tested at 2 turns of the second needle valve. The other was the 1/2" inner diameter, 1.25' long dripper with an activation pressure of 0.19 bar when tested on a fully open (second) needle valve. Each have different capabilities, as described in Chapter 4, and merit further testing.

The current designs are merely for experimental purpose and will be drastically scaled down for adoption and manufacture. The flow rates measured in this study exceed the flow rates desired for practical implementation, so future work will include

modifications to the dripper and setup design to lower the flow rates. The needle valve could help in this aspect; introducing a higher resistance needle valve and/or decreasing the valve opening could potentially aid in meeting the target flow rates. Other future experiments will investigate different wall thicknesses and materials to complete our understanding of the necessary parameters for the design of the dripper and the collapsible tube. The results will be normalized to generate empirical formulae to guide the final design. A theoretical model with the nonlinear fluid-structure interaction will be developed to predict the tube behavior. The final design will be manufactured and tested in the field.

# Appendix A

## Graphs of Flow Rate vs. Pressure

### A.1 1/8", 1.25', Ball Valve

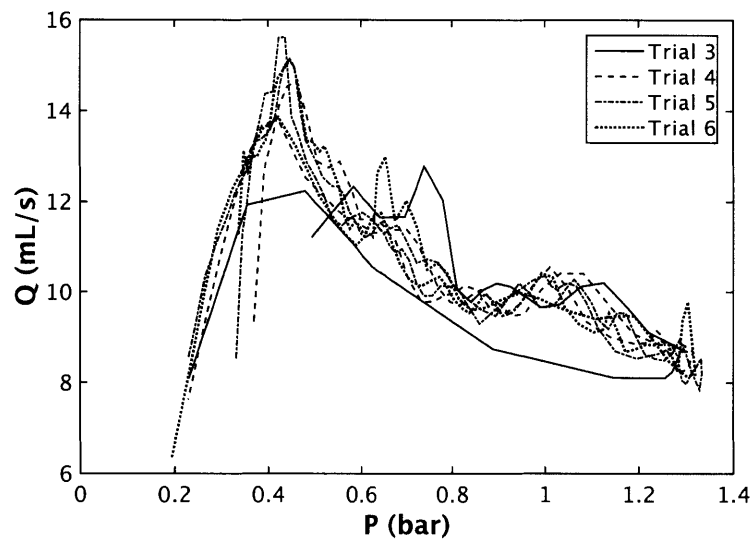


Figure A-1: 1/8" inner diameter, 1.25' total length dripper, tested at fully open.

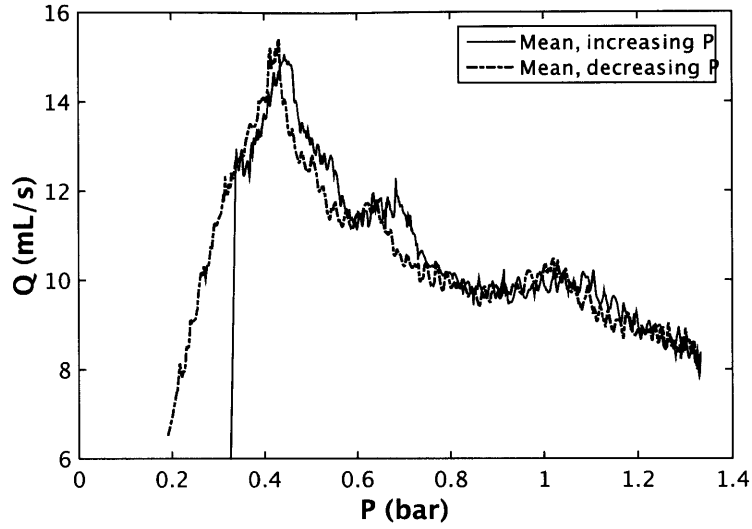


Figure A-2: 1/8" inner diameter, 1.25' total length dripper, tested at fully open. The three trials performed were averaged.

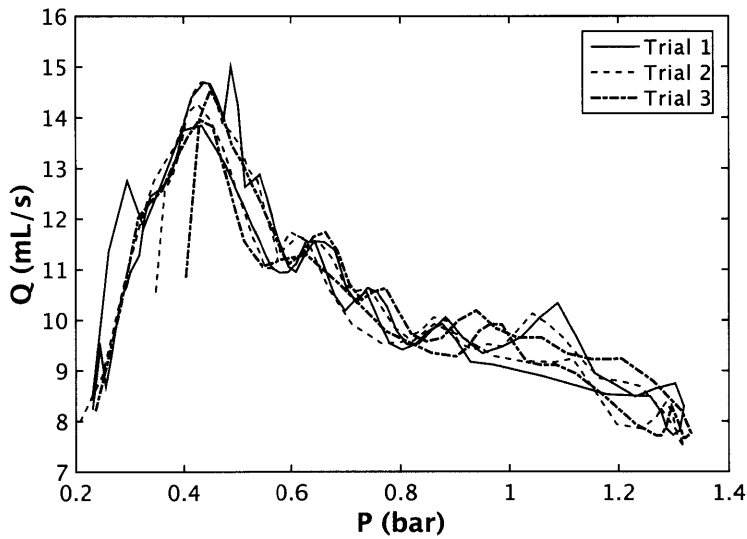


Figure A-3: 1/8" inner diameter, 1.25' total length dripper, tested at 22.5°.

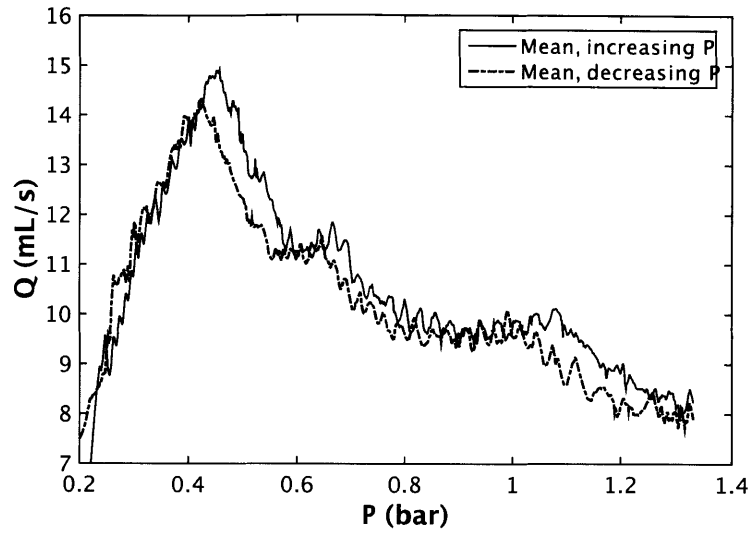


Figure A-4: 1/8" inner diameter, 1.25' total length dripper, tested at 22.5°. The three trials performed were averaged.

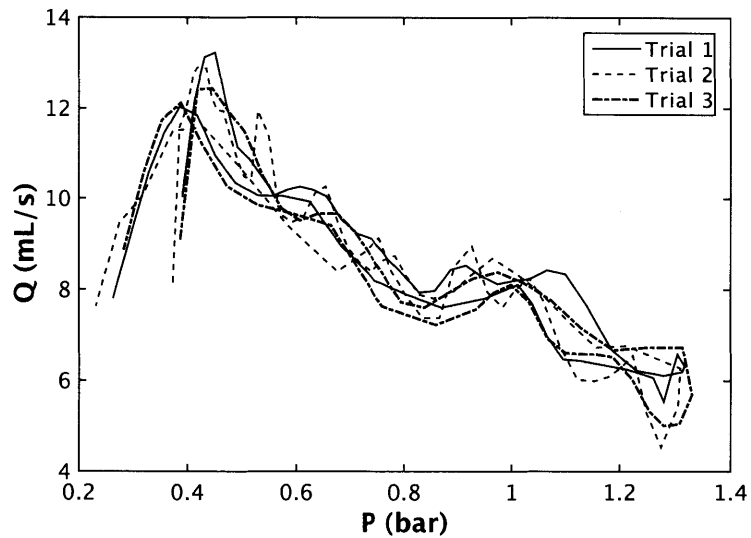


Figure A-5: 1/8" inner diameter, 1.25' total length dripper, tested at 45°.

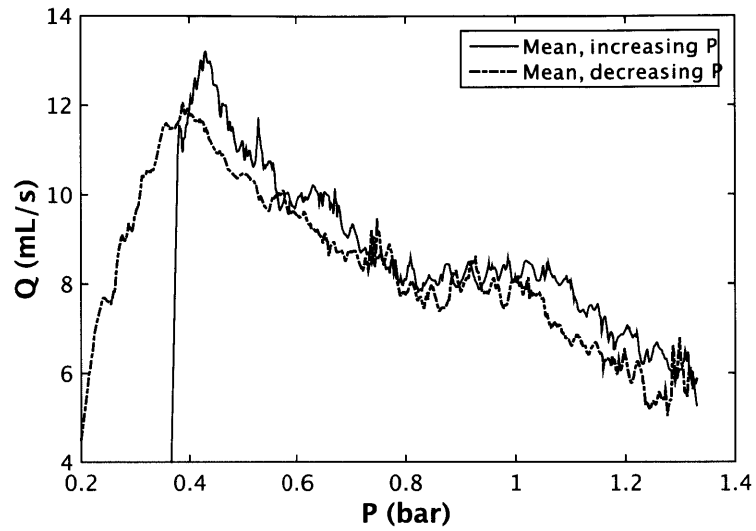


Figure A-6: 1/8" inner diameter, 1.25' total length dripper, tested at 45°. The three trials performed were averaged.

## A.2 1/8", 1.25', Needle Valve 1

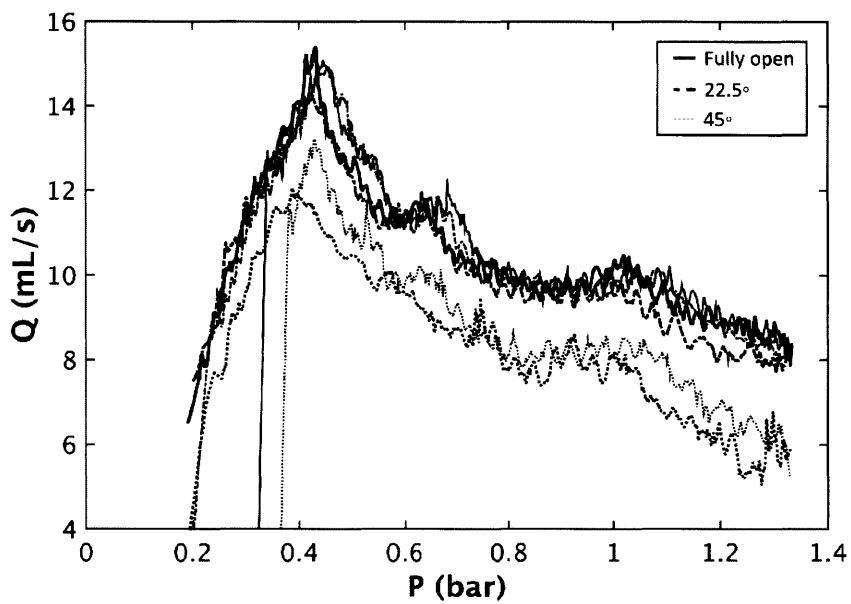


Figure A-7: 1/8" inner diameter, 1.25' total length dripper, tested at 0° (continuous), 22.5° (dashed), and 45° (dotted). Each curve shows the average of the trials in a particular test.



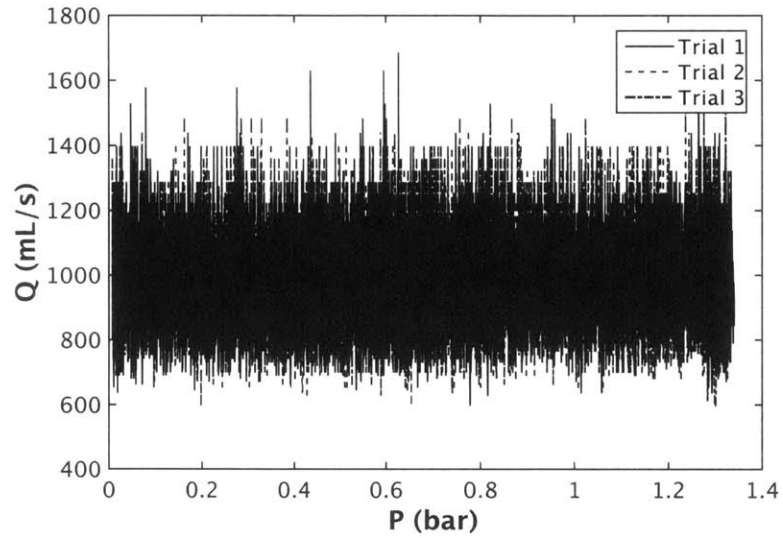


Figure A-8: 1/8" inner diameter, 1.25' total length dripper, tested at fully open.

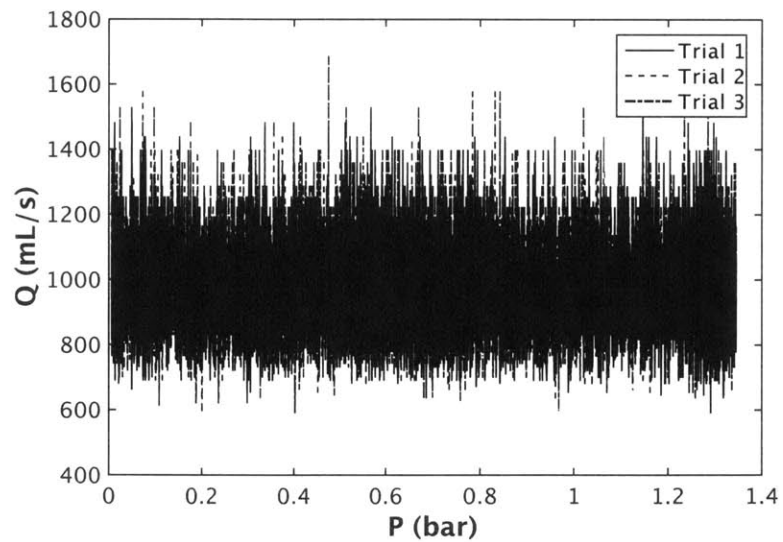


Figure A-9: 1/8" inner diameter, 1.25' total length resistor, tested at 22.5°.

### A.3 1/4", 1', Ball Valve

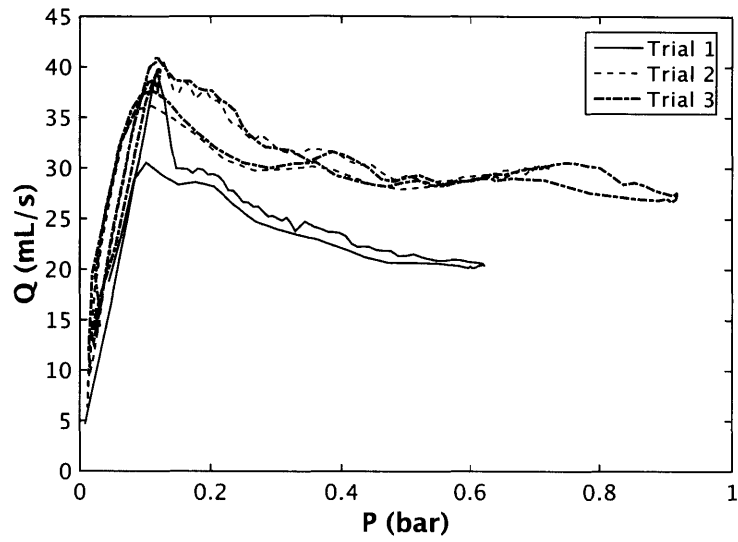


Figure A-10: 1/4" inner diameter, 1' total length dripper, tested at fully open.

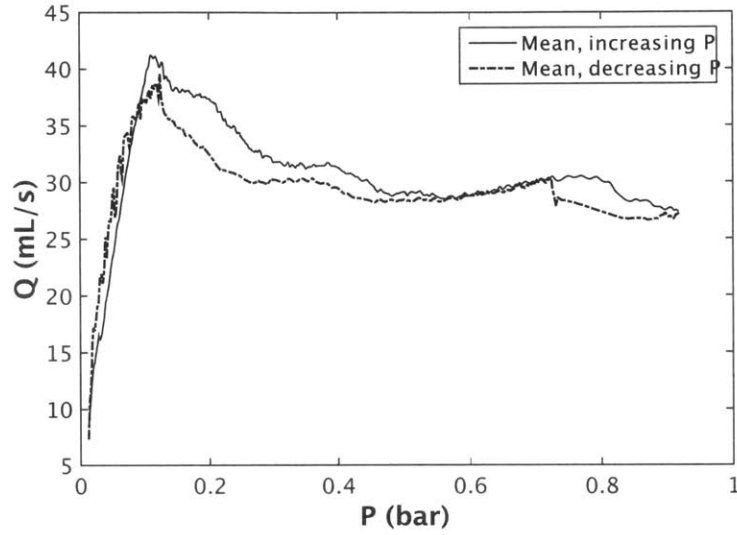


Figure A-11: 1/4" inner diameter, 1' total length dripper, tested at fully open. Trials 2 and 3 were averaged; trial 1 was excluded from the average.

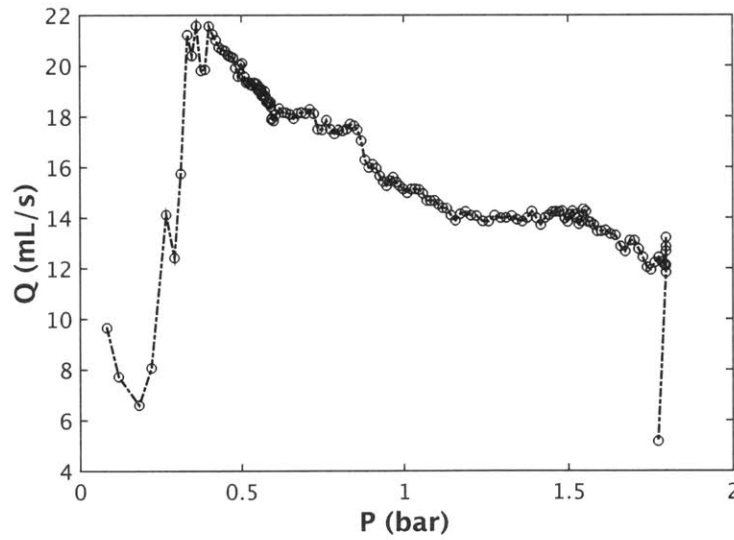


Figure A-12: 1/4" inner diameter, 1' total length dripper, tested at 22.5°.

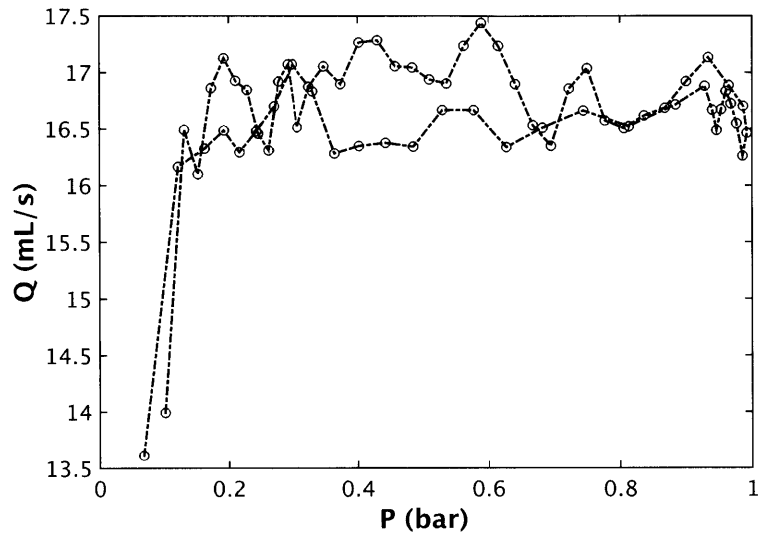


Figure A-13: 1/4" inner diameter, 1' total length dripper, tested at 45°.

#### A.4 1/4", 1', Needle Valve 2

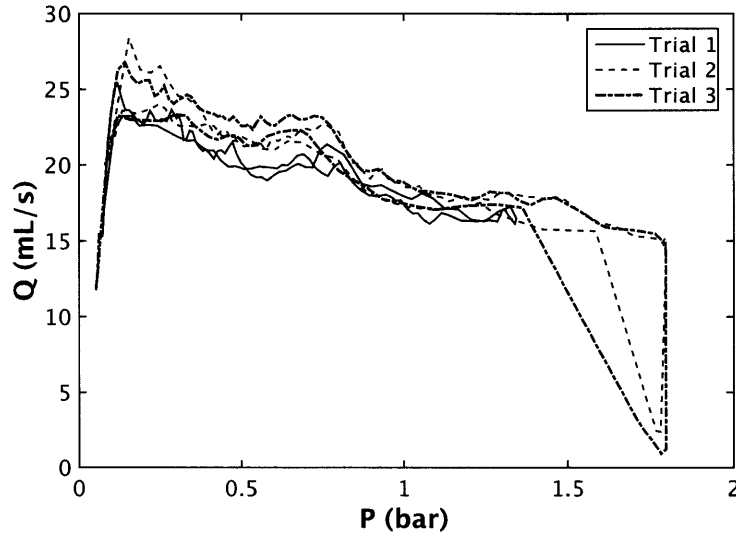


Figure A-14: 1/4" inner diameter, 1' total length dripper, tested at fully open.

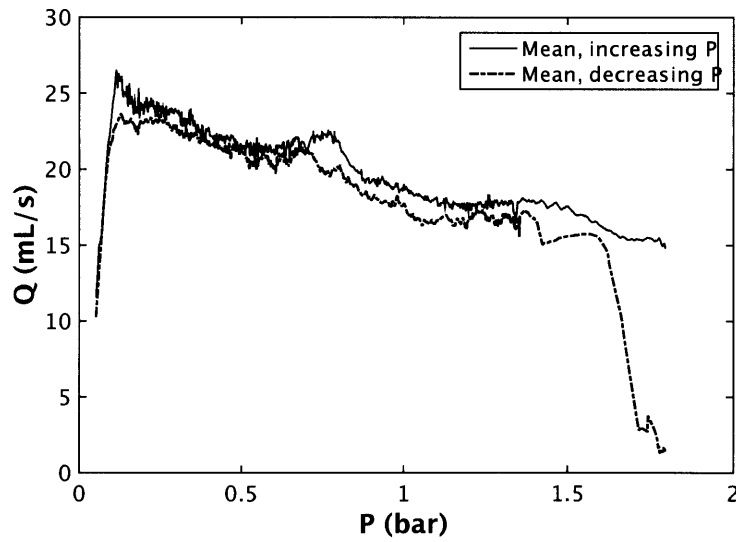


Figure A-15: 1/4" inner diameter, 1' total length dripper, tested at fully open. The three trials performed were averaged.

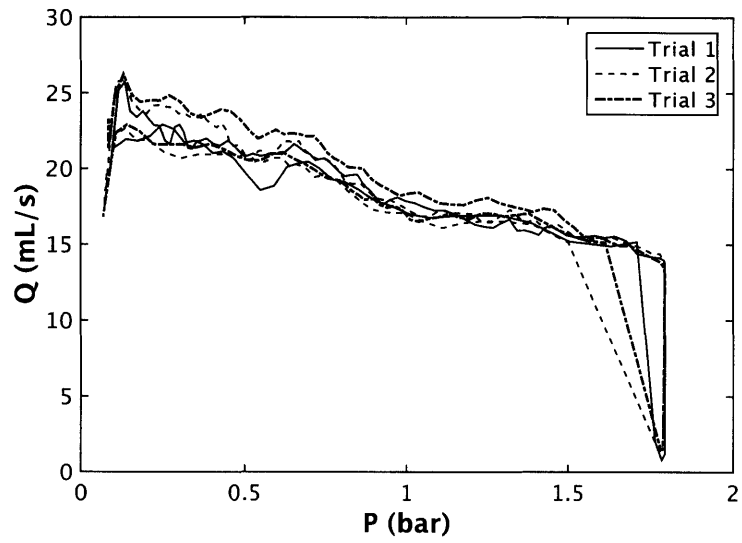


Figure A-16: 1/4" inner diameter, 1' total length dripper, tested at one turn.

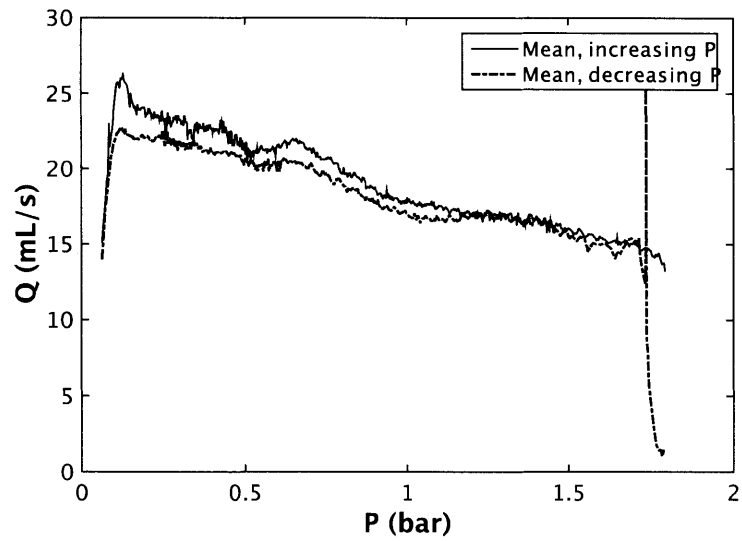


Figure A-17: 1/4" inner diameter, 1' total length dripper, tested at one turn. The three trials performed were averaged.

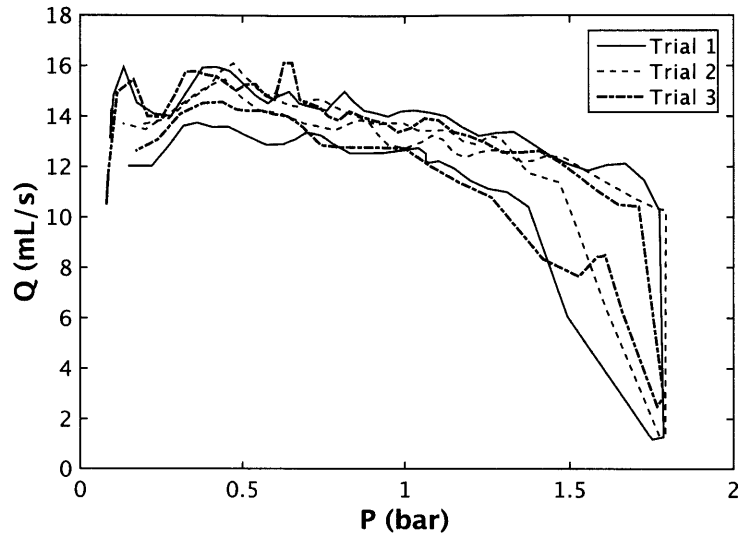


Figure A-18: 1/4" inner diameter, 1' total length dripper, tested at two turns.

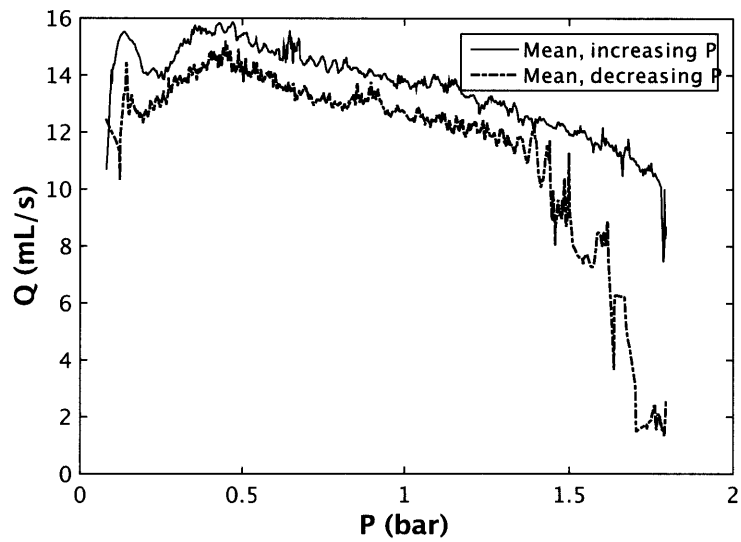


Figure A-19: 1/4" inner diameter, 1' total length dripper, tested at two turns. The three trials performed were averaged.

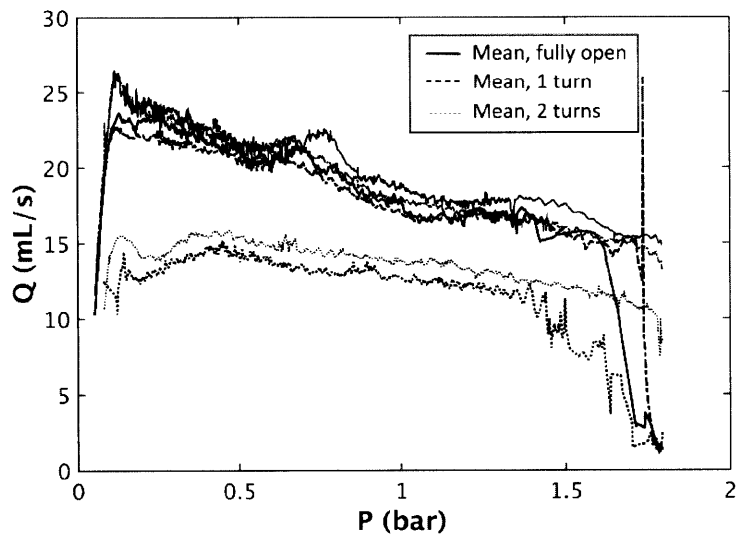


Figure A-20: 1/4" inner diameter, 1' total length dripper, tested at 0 (continuous), 1 (dashed), and 2 (dotted) turns. Each curve shows the average of the trials in a particular test.



## A.5 1/4", 1.25', Needle Valve 2

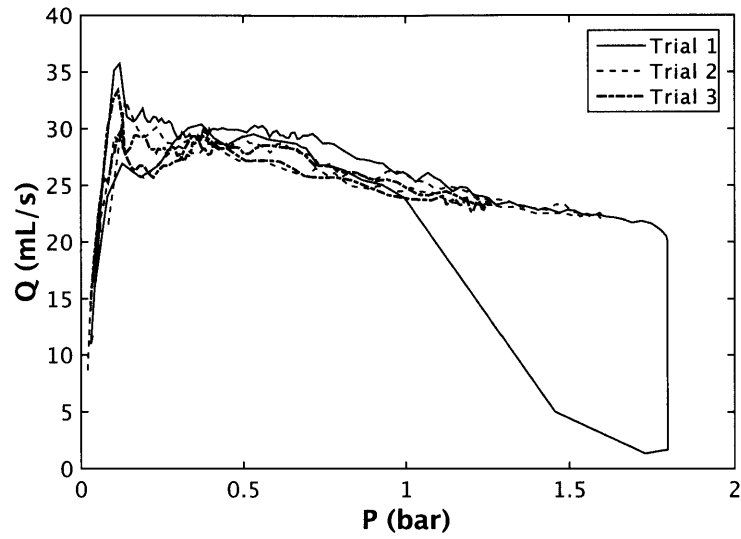


Figure A-21: 1/4" inner diameter, 1.25' total length dripper, tested 3 times at fully open.

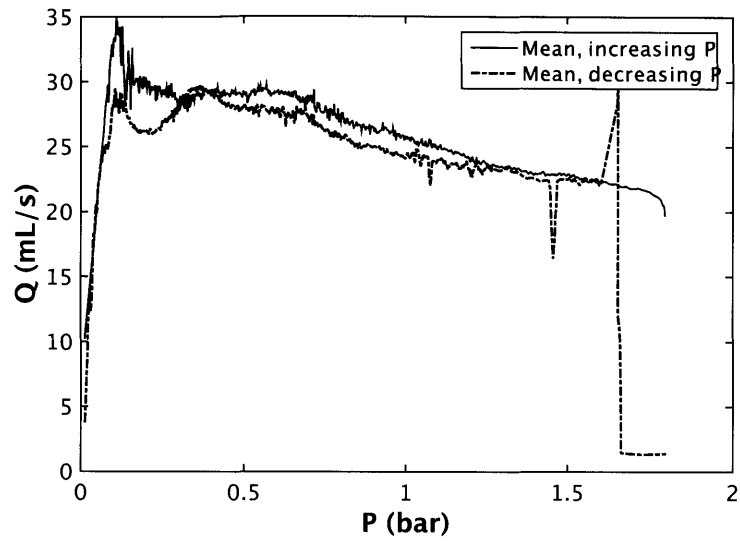


Figure A-22: 1/4" inner diameter, 1.25' total length dripper, tested 3 times at fully open. The three trials performed were averaged.

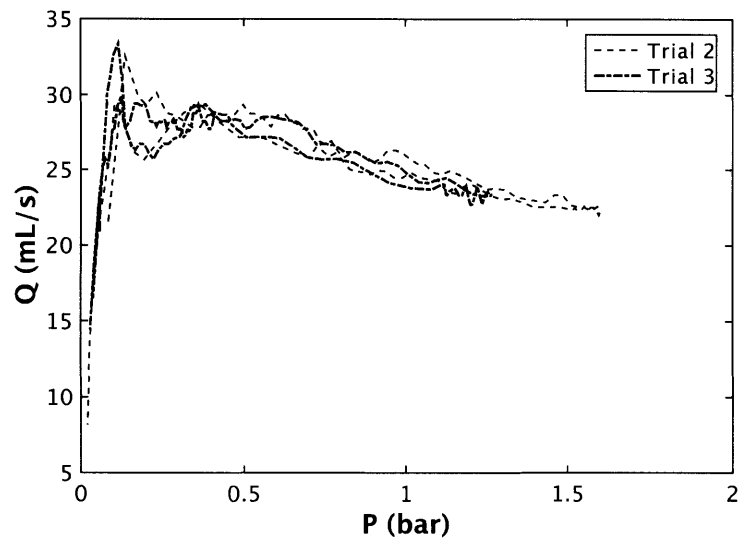


Figure A-23: 1/4" inner diameter, 1.25' total length dripper, tested 2 times at fully open. Trial 1 was excluded.

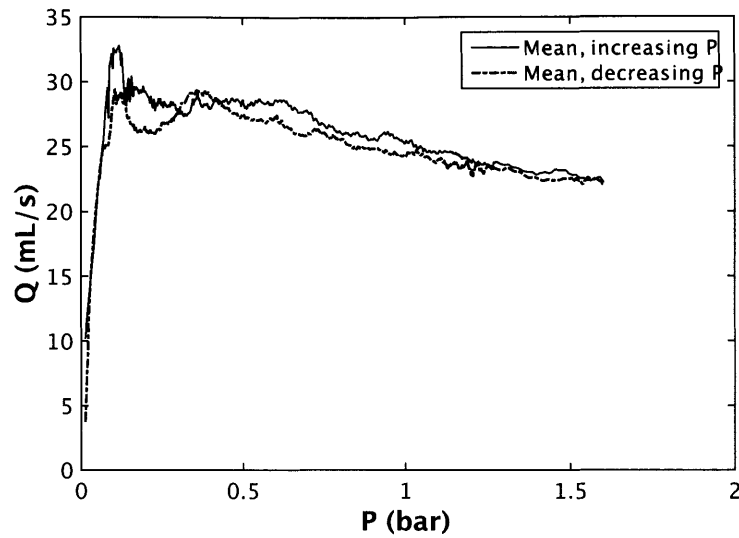


Figure A-24: 1/4" inner diameter, 1.25' total length dripper, tested 2 times at fully open. Trial 1 was excluded; trials 2 and 3 were averaged.

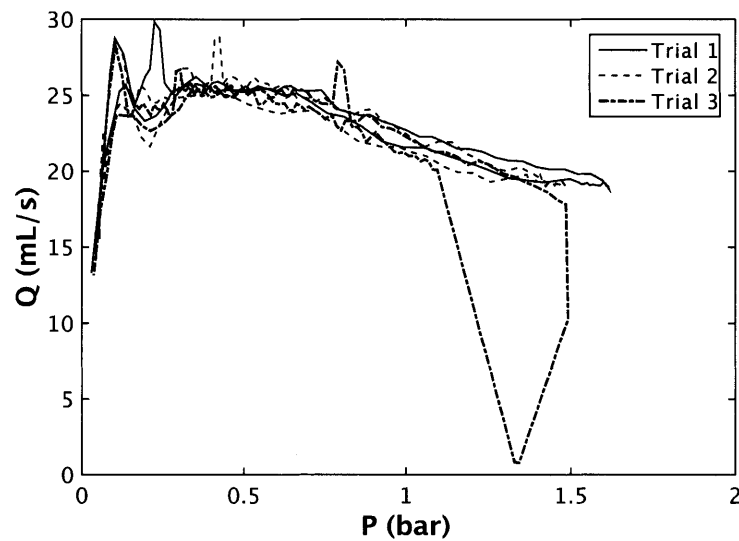


Figure A-25: 1/4" inner diameter, 1.25' total length dripper, tested 3 times at one turn.

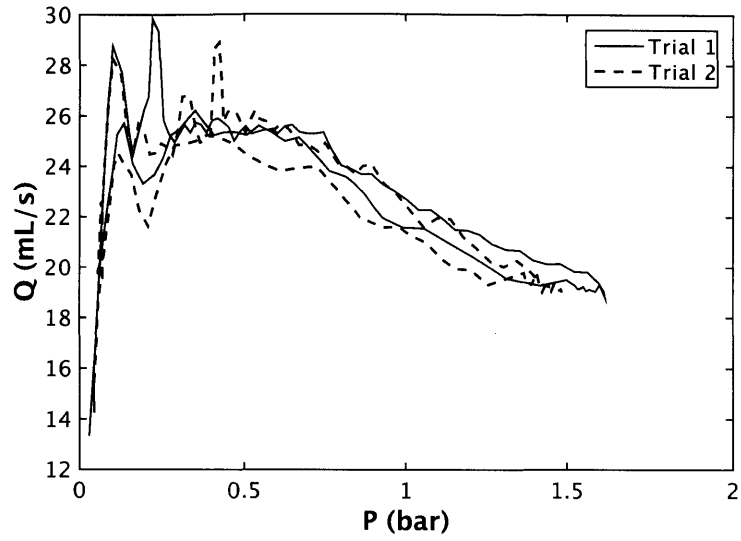


Figure A-26: 1/4" inner diameter, 1.25' total length dripper, tested 2 times at one turn. Trial 3 was excluded.

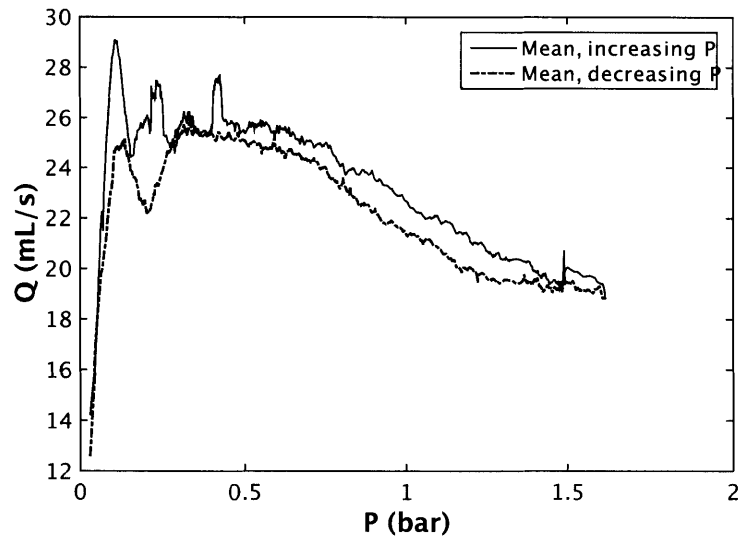


Figure A-27: 1/4" inner diameter, 1.25' total length dripper, tested 2 times at one turn. Trial 3 was excluded; trials 1 and 2 were averaged.

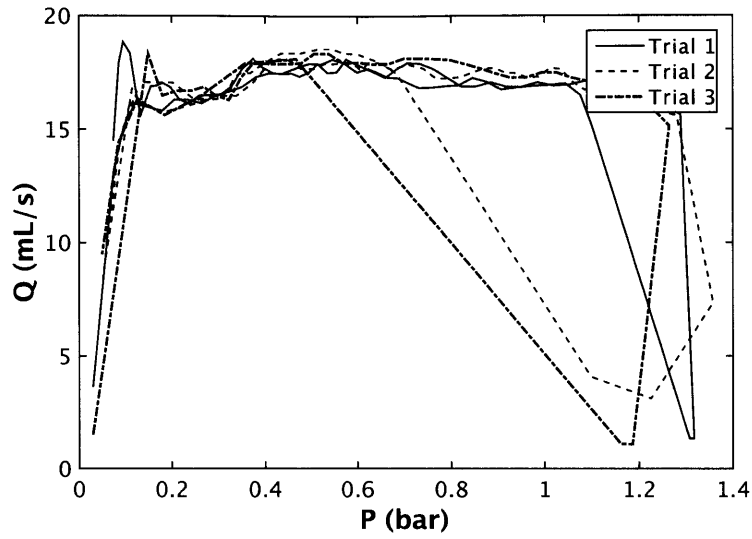


Figure A-28: 1/4" inner diameter, 1.25' total length dripper, tested 3 times at two turns.

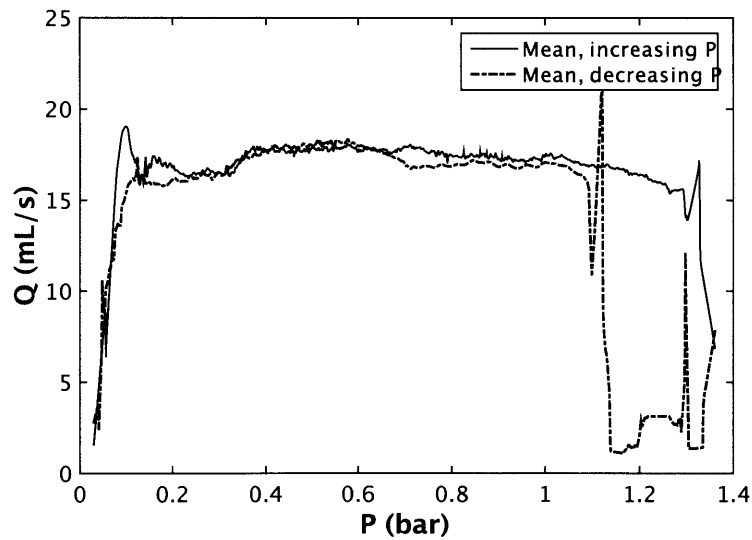


Figure A-29: 1/4" inner diameter, 1.25' total length dripper, tested 3 times at two turns. The three trials performed were averaged.

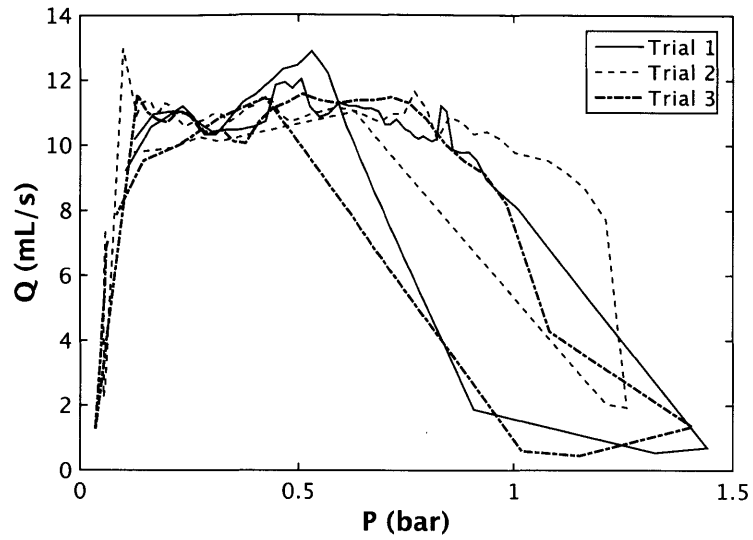


Figure A-30: 1/4" inner diameter, 1.25' total length dripper, tested 3 times at three turns.

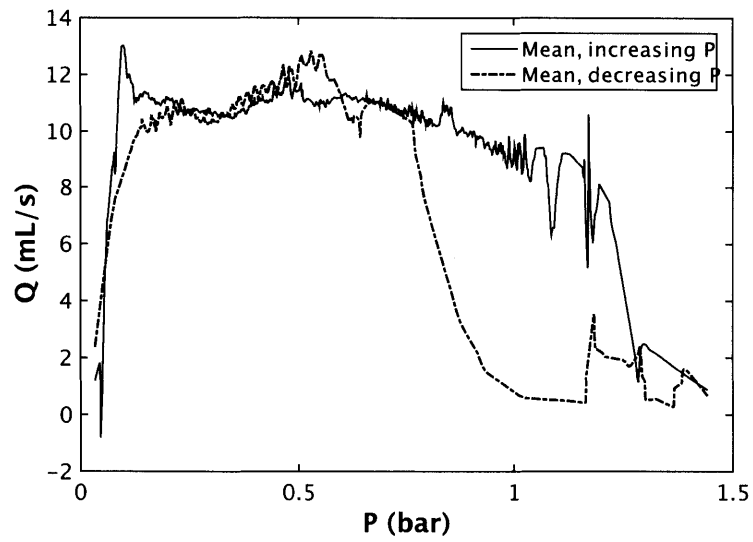


Figure A-31: 1/4" inner diameter, 1.25' total length dripper, tested 3 times at three turns. The three trials performed were averaged.

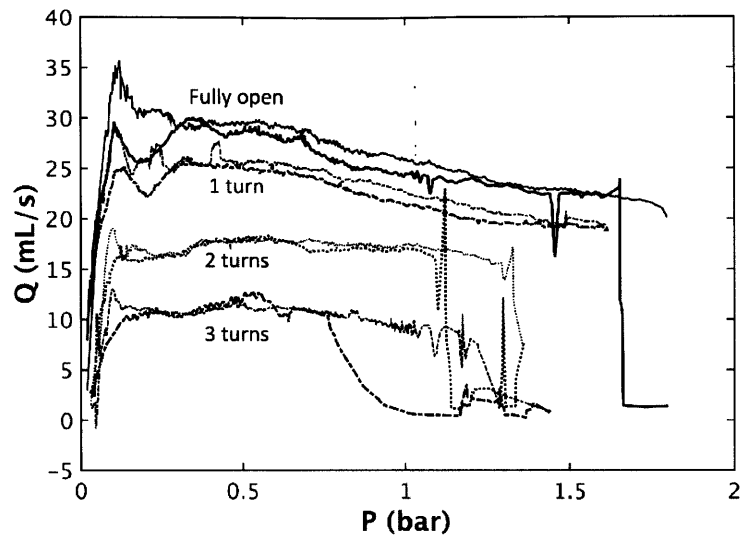


Figure A-32: 1/4" inner diameter, 1.25' total length dripper, tested from 0 to 3 turns. Each curve shows the average of the trials in a particular test.

## A.6 1/2", 1', Needle Valve 2

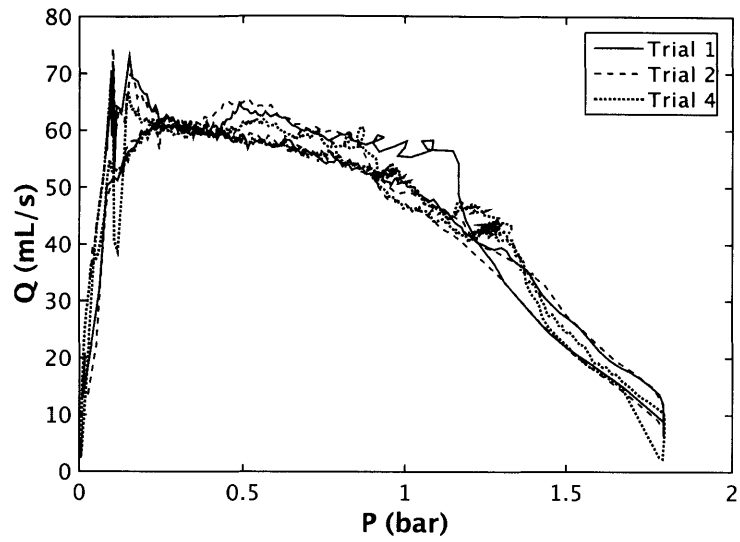


Figure A-33: 1/2" inner diameter, 1' total length dripper, tested 3 times at fully open.

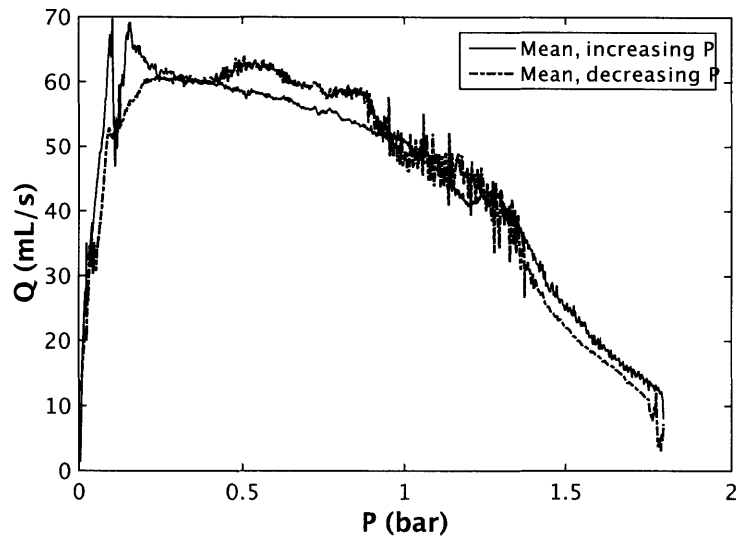


Figure A-34: 1/2" inner diameter, 1' total length dripper, tested 3 times at fully open. The three trials performed were averaged.



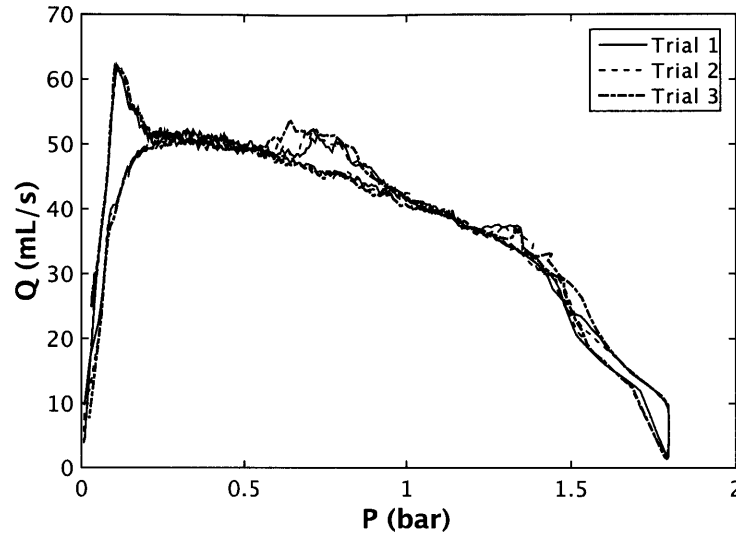


Figure A-35: 1/2" inner diameter, 1' total length dripper, tested 3 times at one turn.

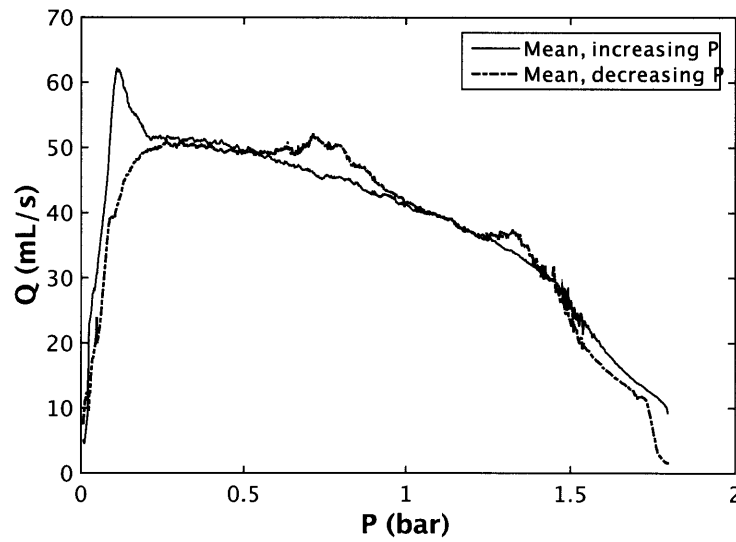


Figure A-36: 1/2" inner diameter, 1' total length dripper, tested 3 times at one turn. The three trials performed were averaged.

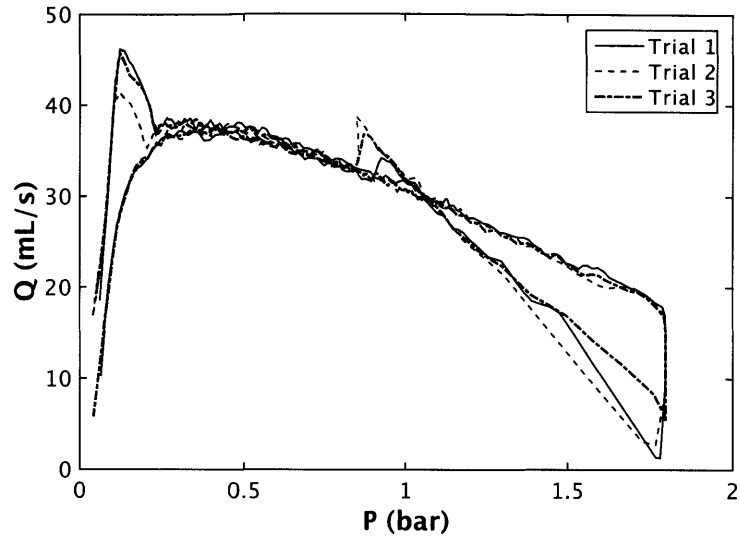


Figure A-37: 1/2" inner diameter, 1' total length dripper, tested 3 times at two turns.

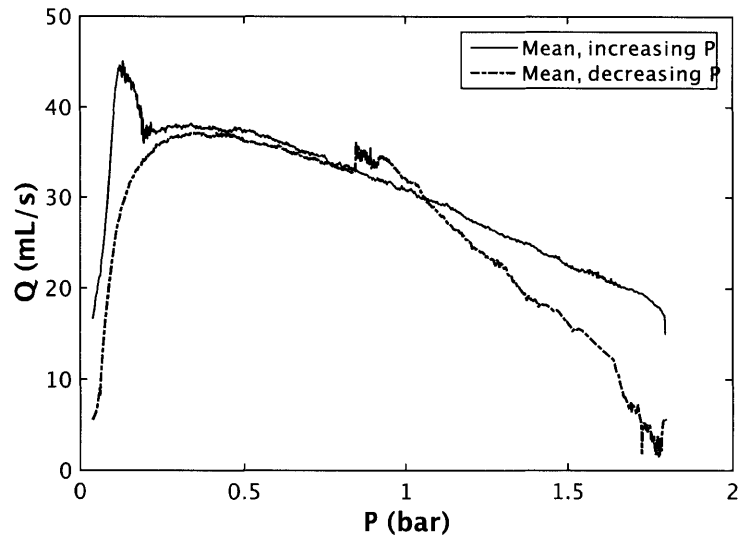


Figure A-38: 1/2" inner diameter, 1' total length dripper, tested 3 times at two turns. The three trials performed were averaged.

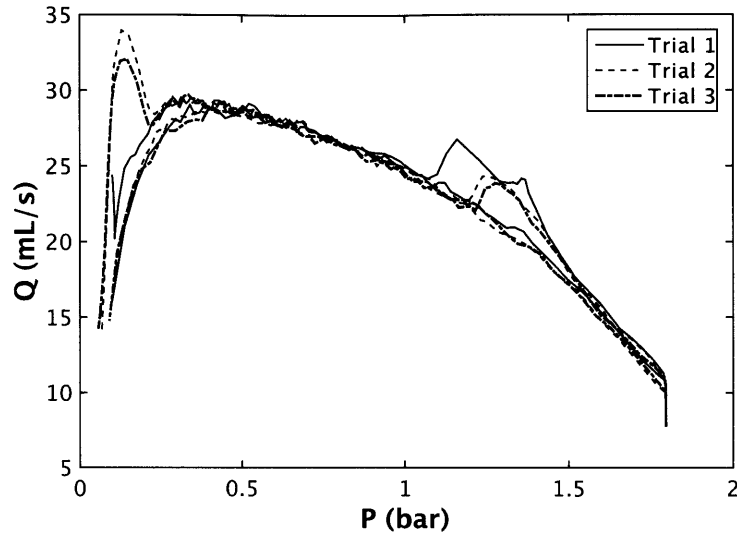


Figure A-39: 1/2" inner diameter, 1' total length dripper, tested 3 times at three turns.

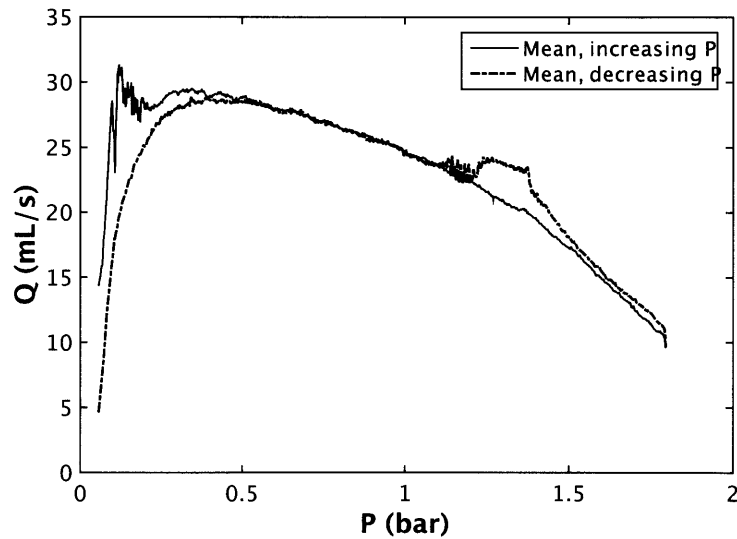


Figure A-40: 1/2" inner diameter, 1' total length dripper, tested 3 times at three turns. The three trials performed were averaged.

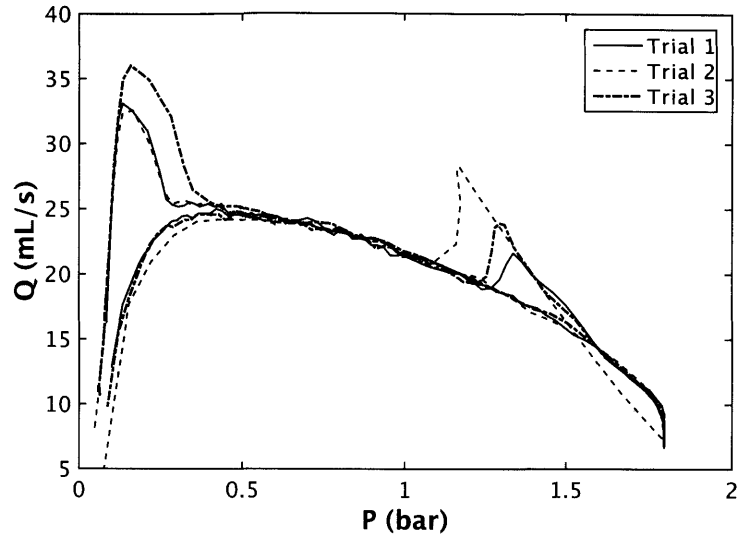


Figure A-41: 1/2" inner diameter, 1' total length dripper, tested 3 times at four turns.

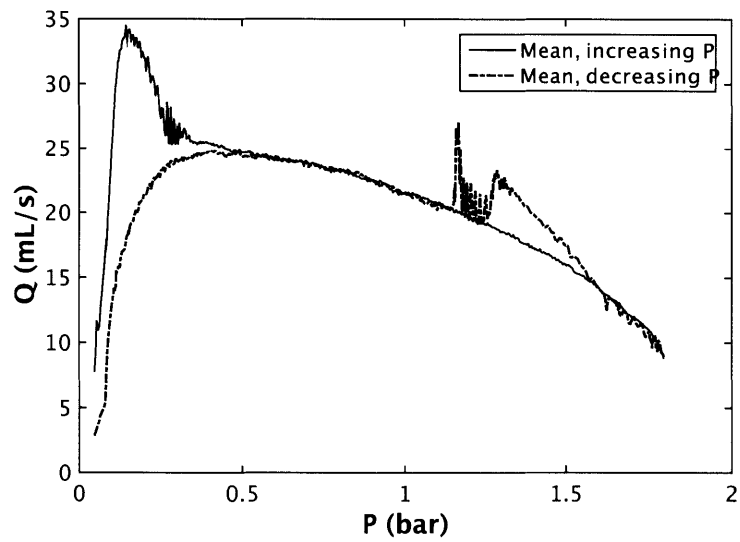


Figure A-42: 1/2" inner diameter, 1' total length dripper, tested 3 times at four turns. The three trials performed were averaged.

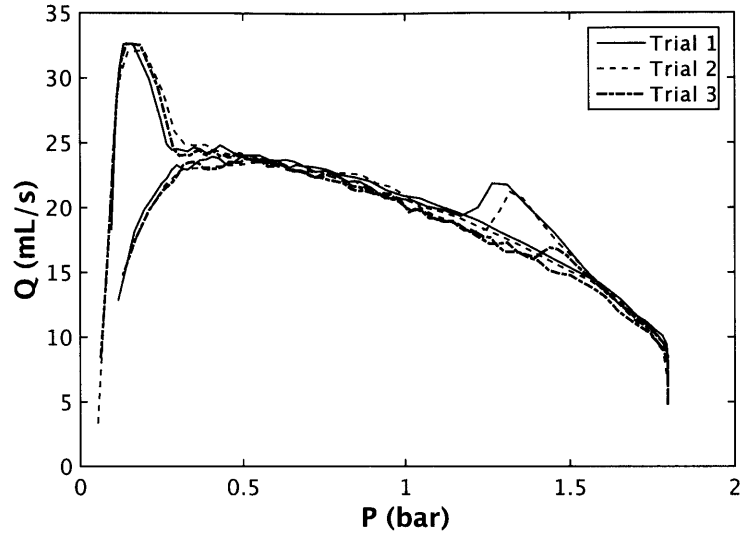


Figure A-43: 1/2" inner diameter, 1' total length dripper, tested 3 times at five turns.

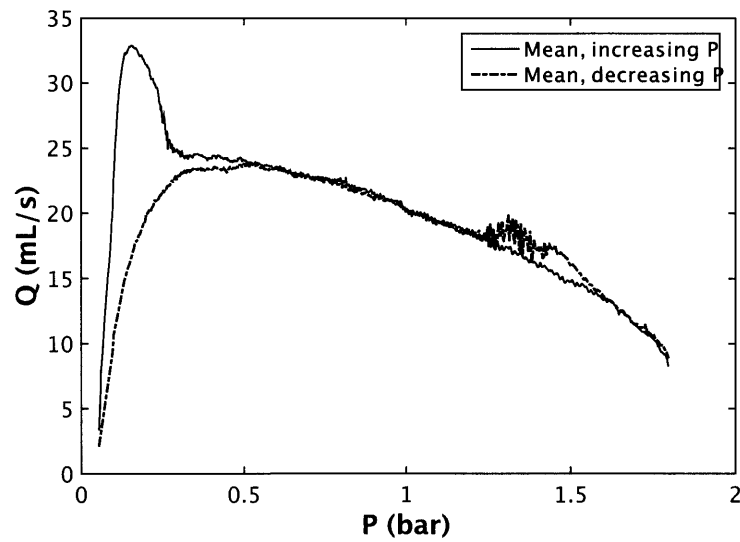


Figure A-44: 1/2" inner diameter, 1' total length dripper, tested 3 times at five turns. The three trials performed were averaged.

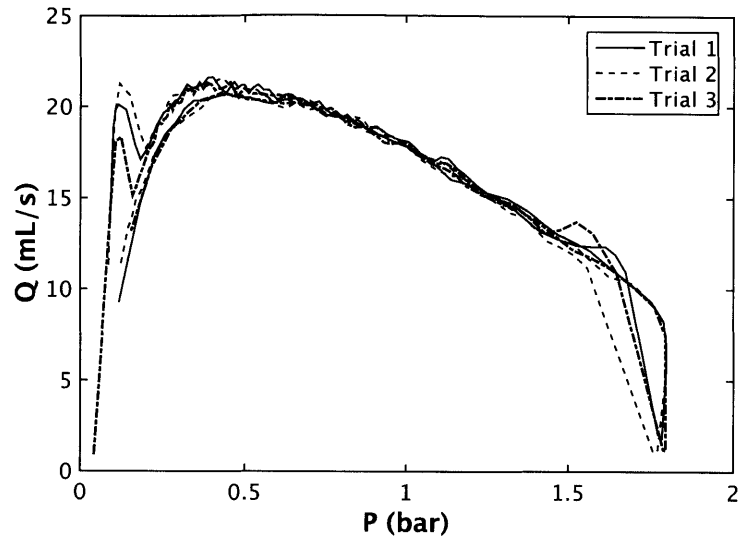


Figure A-45: 1/2" inner diameter, 1' total length dripper, tested 3 times at six turns.

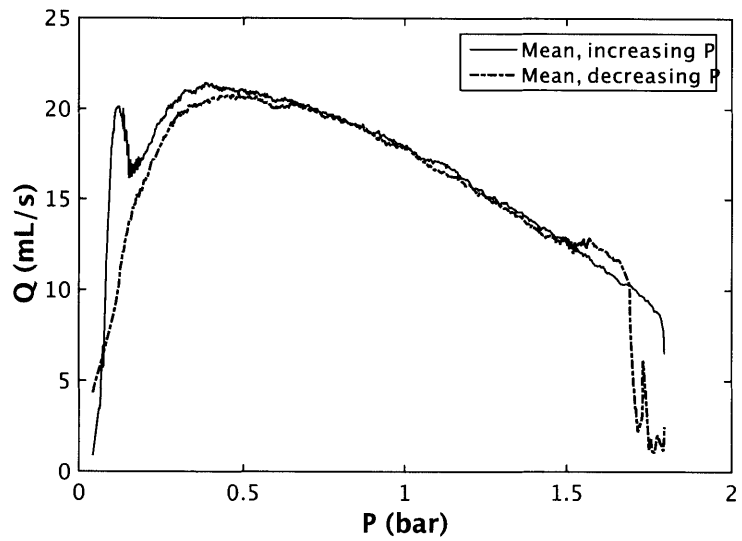


Figure A-46: 1/2" inner diameter, 1' total length dripper, tested 3 times at six turns. The three trials performed were averaged.

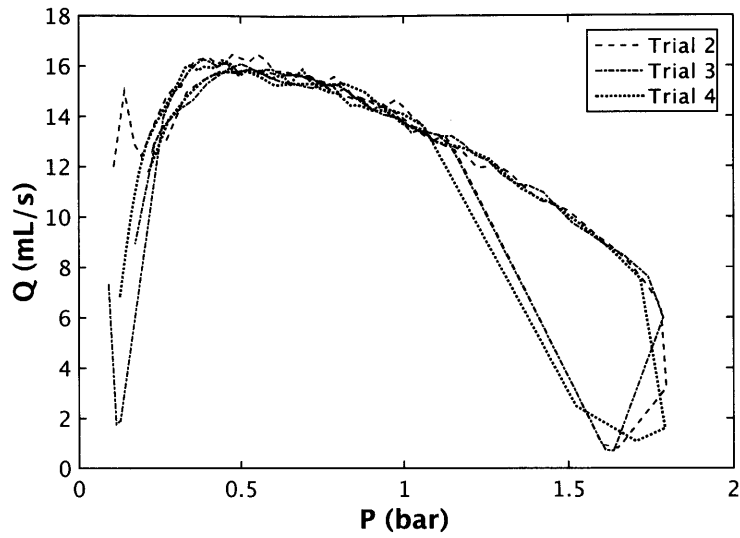


Figure A-47: 1/2" inner diameter, 1' total length dripper, tested 3 times at seven turns.

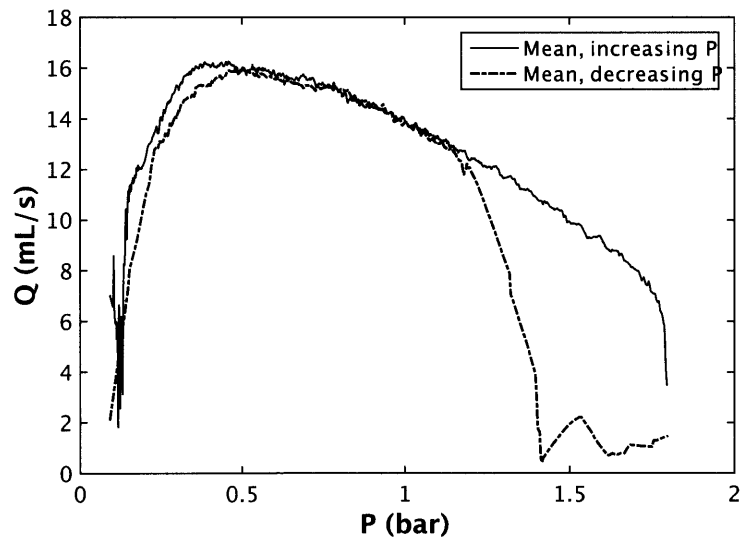


Figure A-48: 1/2" inner diameter, 1' total length dripper, tested 3 times at seven turns. The three trials performed were averaged.

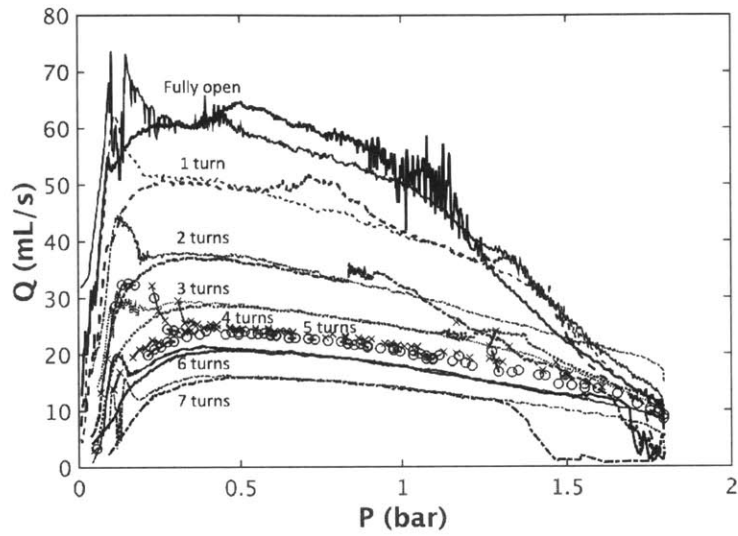


Figure A-49: 1/2" inner diameter, 1' total length dripper, tested from 0 to 7 turns. Each curve shows the average of the trials in a particular test.

## A.7 1/2", 1.25', Needle Valve 2



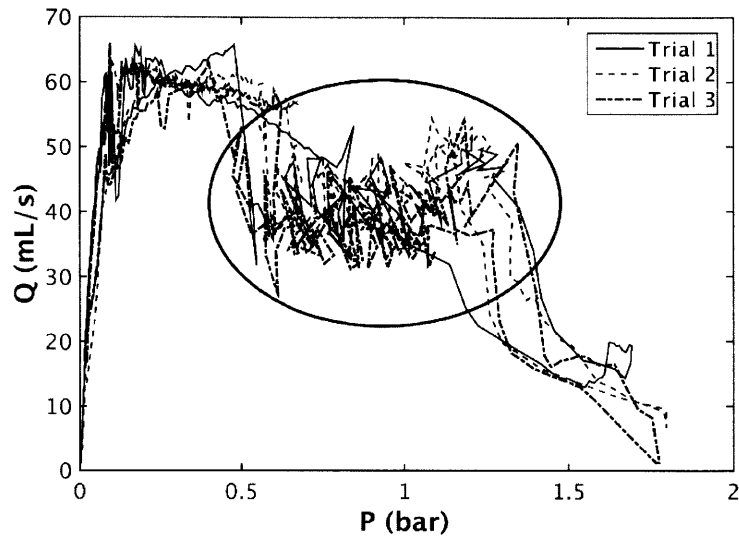


Figure A-50: 1/2" inner diameter, 1.25' total length dripper, tested 3 times at fully open.

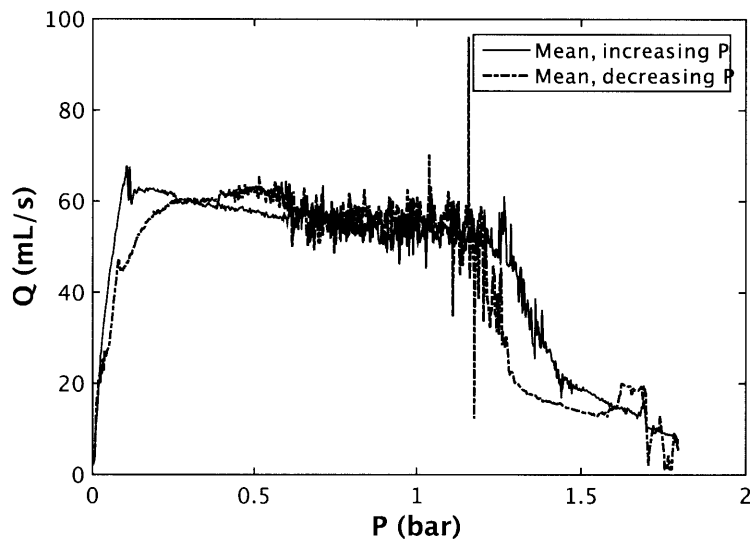


Figure A-51: 1/2" inner diameter, 1.25' total length dripper, tested 3 times at fully open. The three trials performed were averaged.

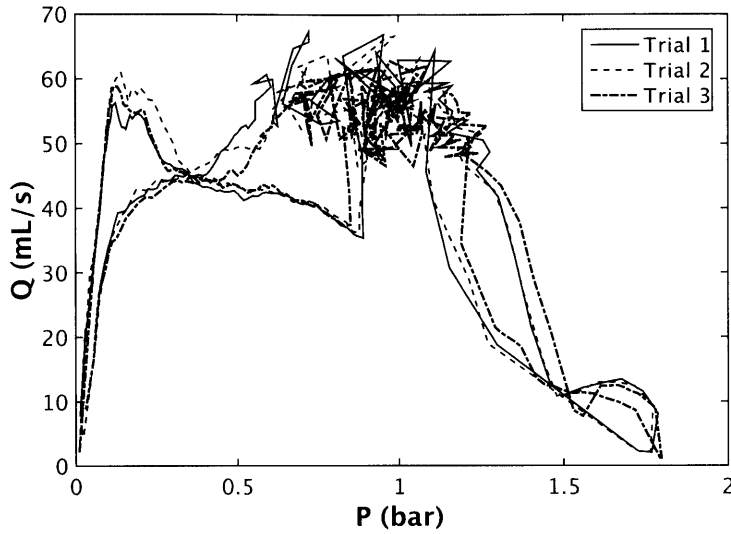


Figure A-52: 1/2" inner diameter, 1.25' total length dripper, tested 3 times at one turn.

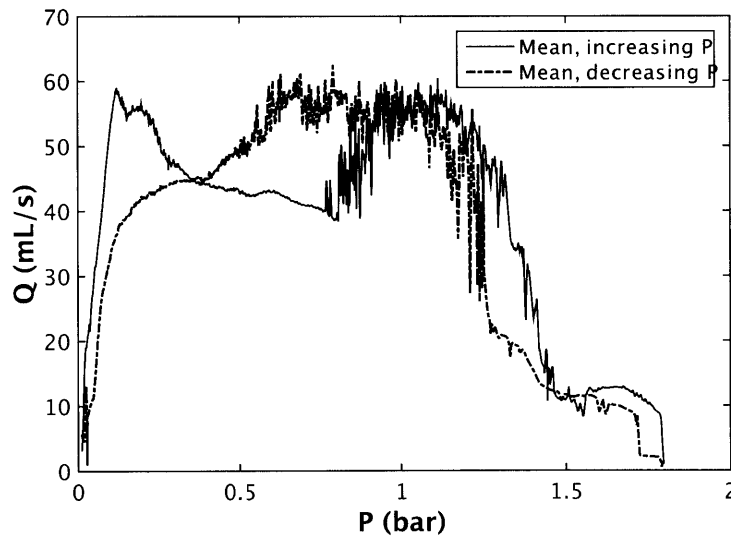


Figure A-53: 1/2" inner diameter, 1.25' total length dripper, tested 3 times at one turn. The three trials performed were averaged.

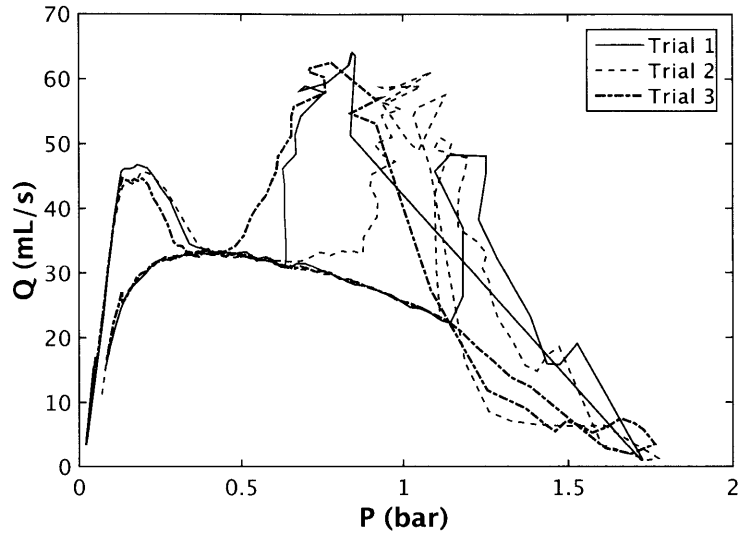


Figure A-54: 1/2" inner diameter, 1.25' total length dripper, tested 3 times at two turns.

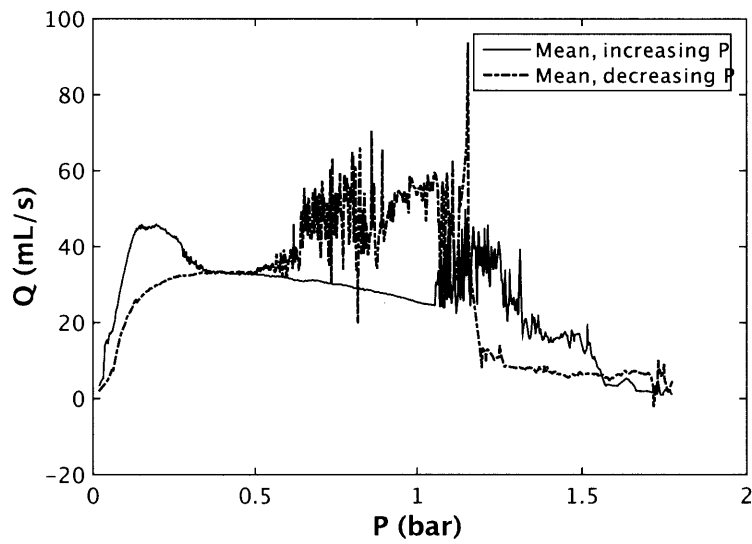


Figure A-55: 1/2" inner diameter, 1.25' total length dripper, tested 3 times at two turns. The three trials performed were averaged.

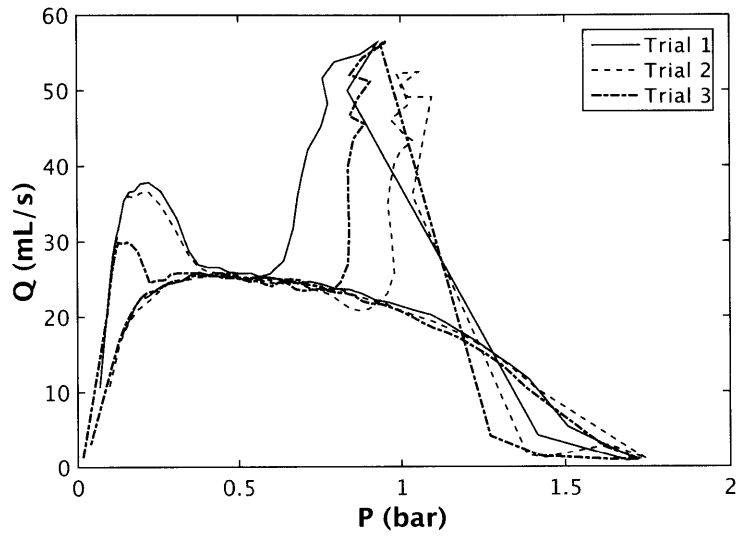


Figure A-56: 1/2" inner diameter, 1.25' total length dripper, tested 3 times at three turns.

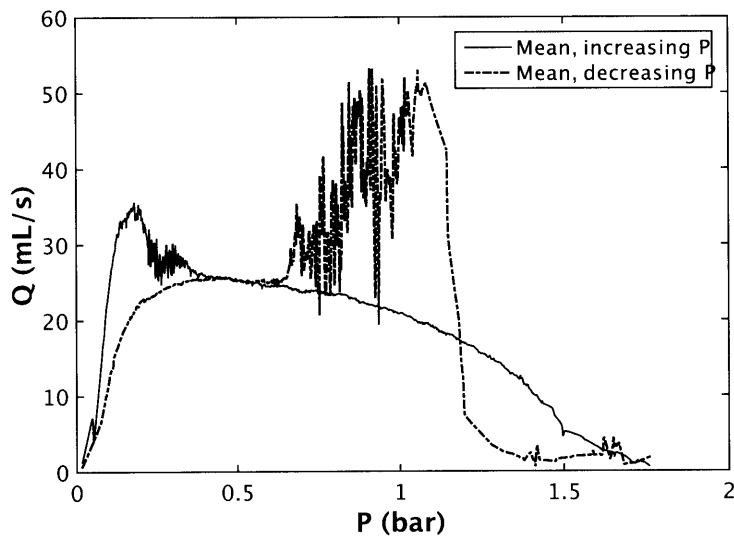


Figure A-57: 1/2" inner diameter, 1.25' total length dripper, tested 3 times at three turns. The three trials performed were averaged.

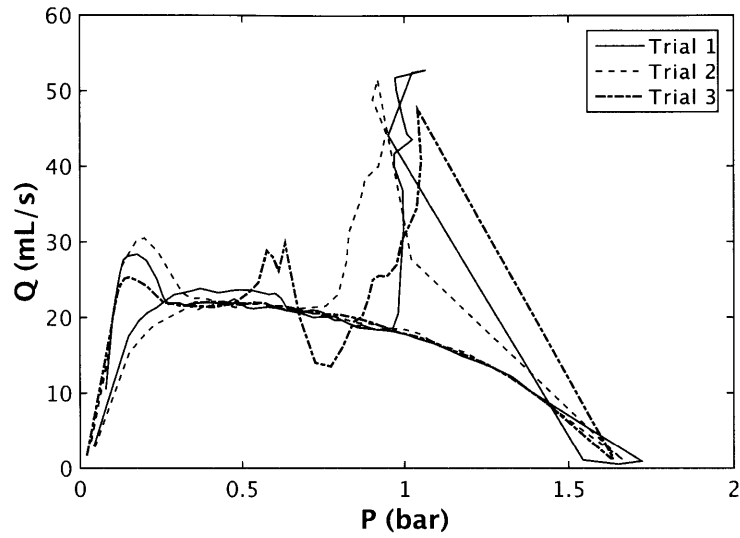


Figure A-58: 1/2" inner diameter, 1.25' total length dripper, tested 3 times at four turns.

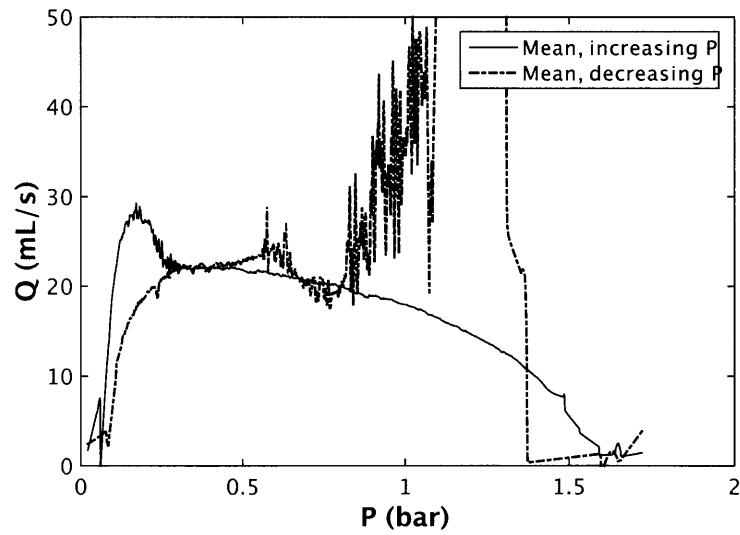


Figure A-59: 1/2" inner diameter, 1.25' total length dripper, tested 3 times at four turns. The three trials performed were averaged.

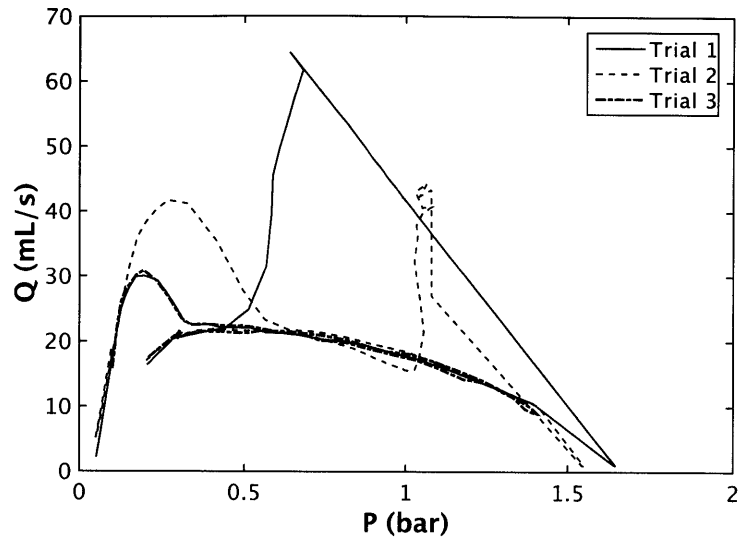


Figure A-60: 1/2" inner diameter, 1.25' total length dripper, tested 3 times at five turns.

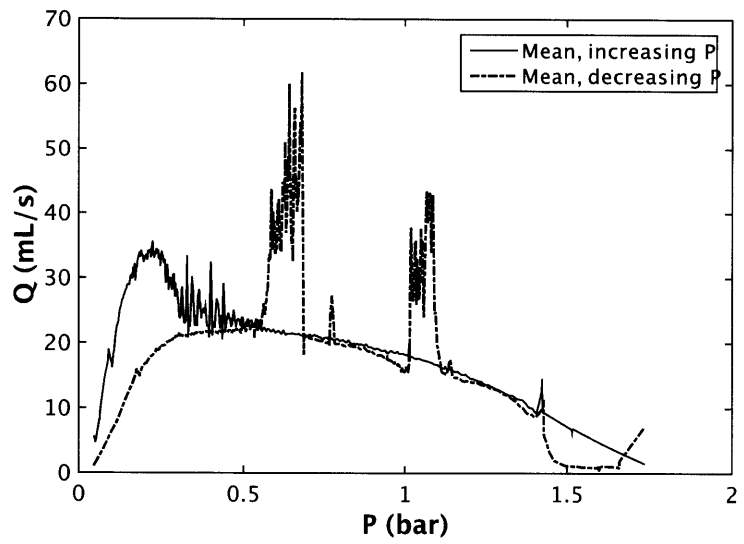


Figure A-61: 1/2" inner diameter, 1.25' total length dripper, tested 3 times at five turns. The three trials performed were averaged.

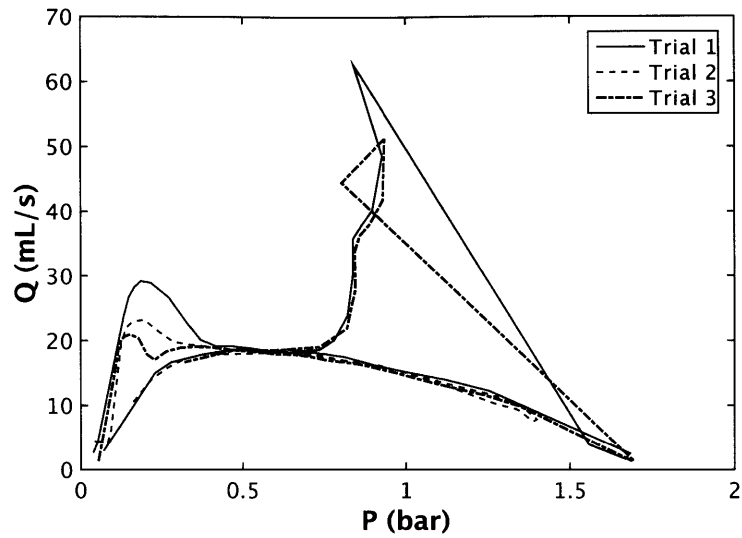


Figure A-62: 1/2" inner diameter, 1.25' total length dripper, tested 3 times at six turns.

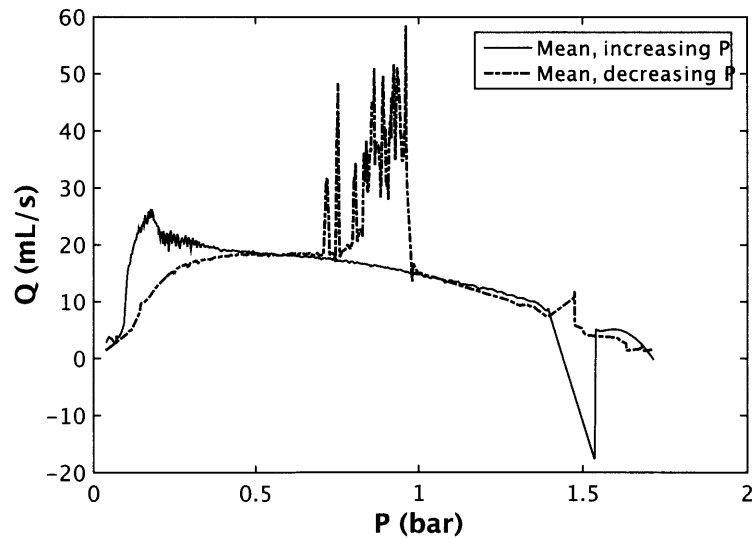


Figure A-63: 1/2" inner diameter, 1.25' total length dripper, tested 3 times at six turns. The three trials performed were averaged.

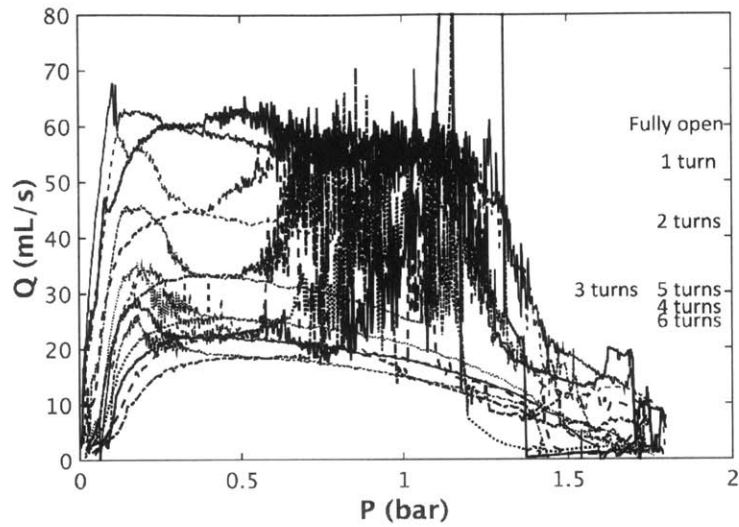


Figure A-64: 1/2" inner diameter, 1.25' total length dripper, tested from 0 to 6 turns. Each curve shows the average of the trials in a particular test.

## A.8 Effect of Total Length



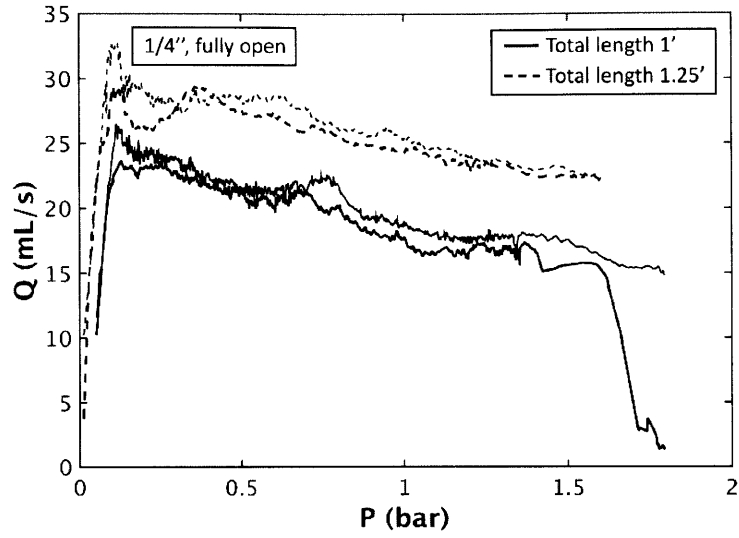


Figure A-65: Comparison of 1' and 1.25' drippers, each with 1/4" inner diameter, tested with a fully open valve.

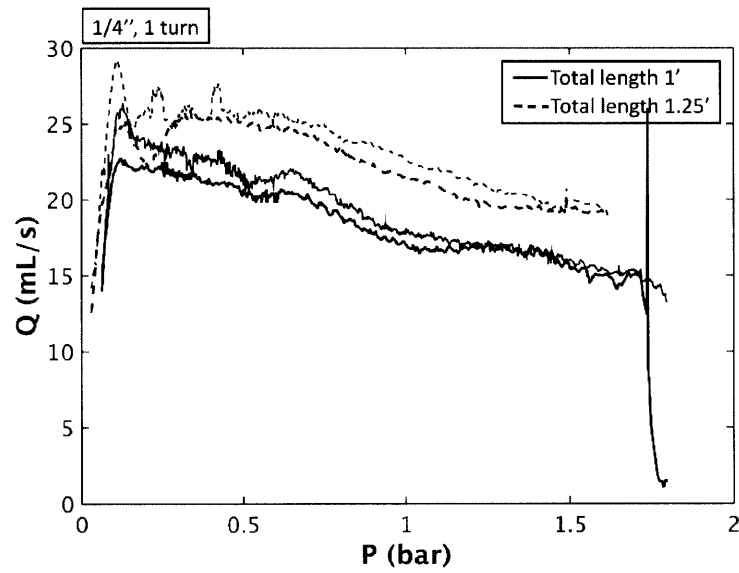


Figure A-66: Comparison of 1' and 1.25' drippers, each with 1/4" inner diameter, tested at one turn.

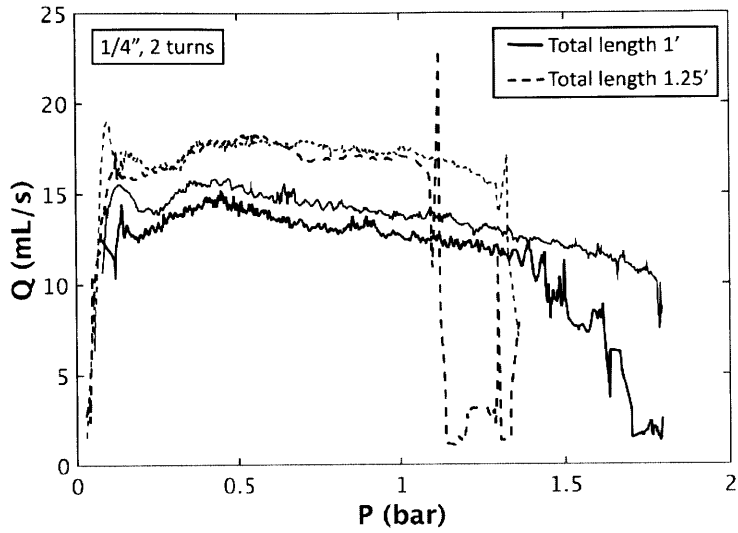


Figure A-67: Comparison of 1' and 1.25' drippers, each with 1/4" inner diameter, tested at two turns.

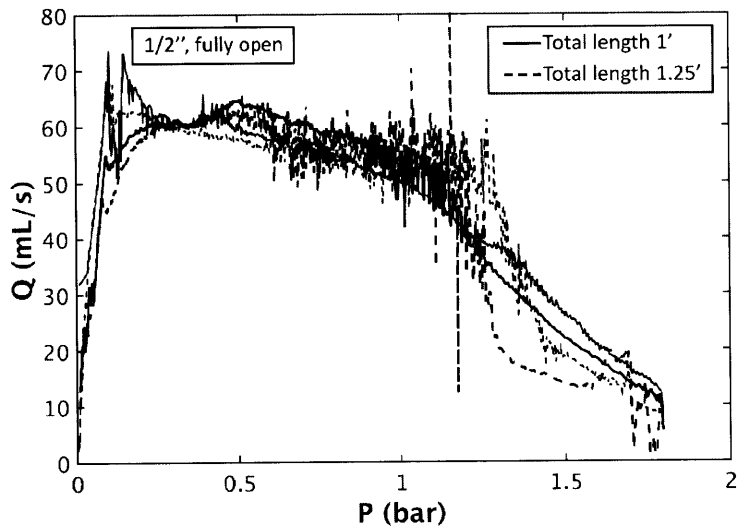


Figure A-68: Comparison of 1' and 1.25' drippers, each with 1/2" inner diameter, tested with at fully open.

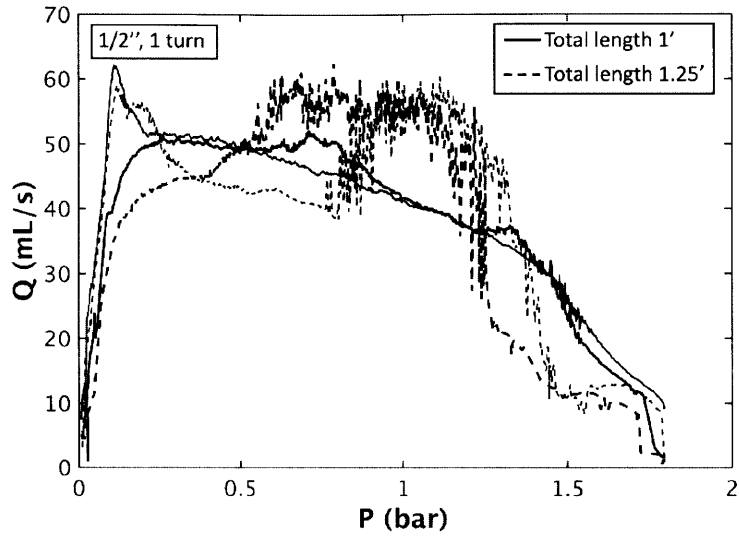


Figure A-69: Comparison of 1' and 1.25' drippers, each with 1/2" inner diameter, tested with at one turn.

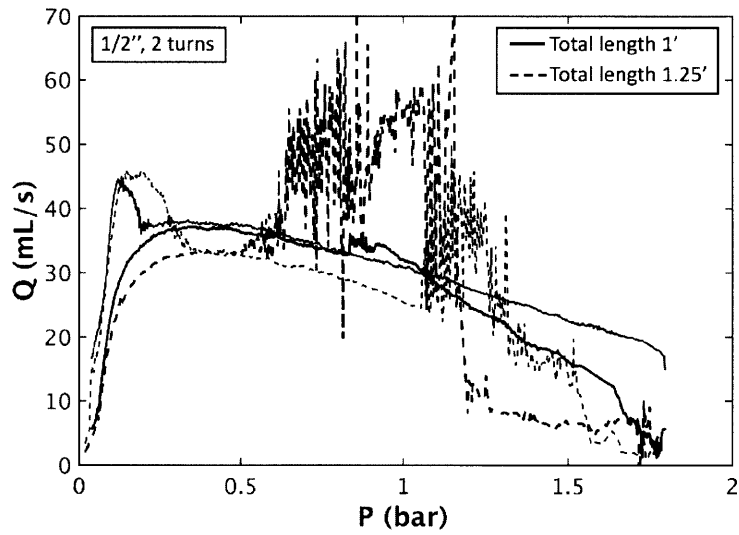


Figure A-70: Comparison of 1' and 1.25' drippers, each with 1/2" inner diameter, tested with at two turns.

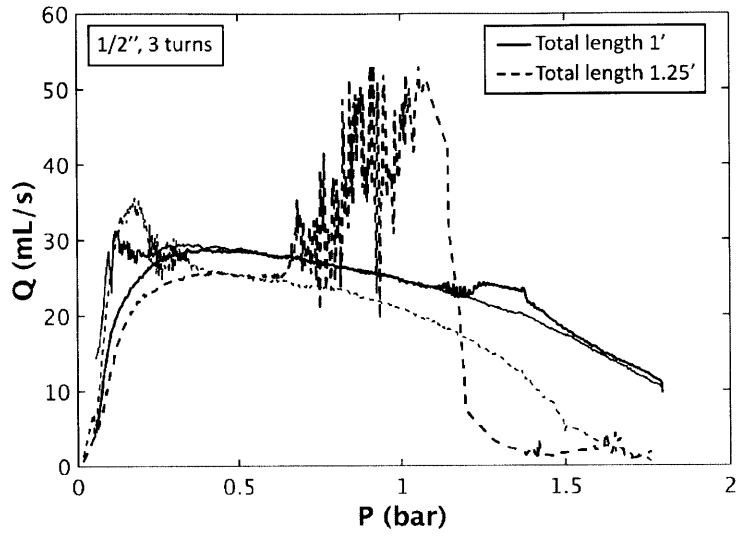


Figure A-71: Comparison of 1' and 1.25' drippers, each with 1/2" inner diameter, tested with at three turns.

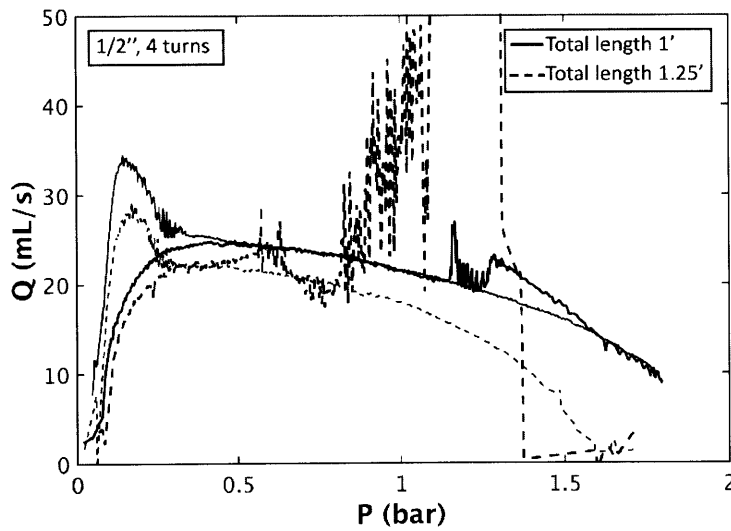


Figure A-72: Comparison of 1' and 1.25' drippers, each with 1/2" inner diameter, tested with at four turns.

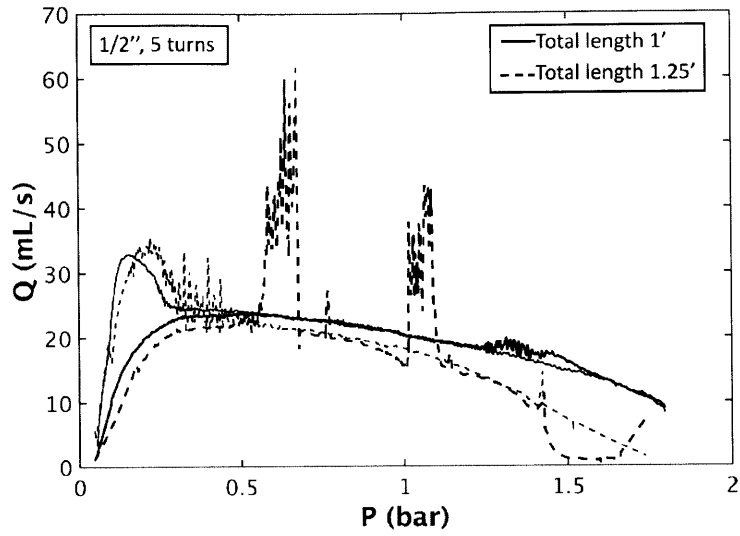


Figure A-73: Comparison of 1' and 1.25' drippers, each with 1/2" inner diameter, tested with at five turns.

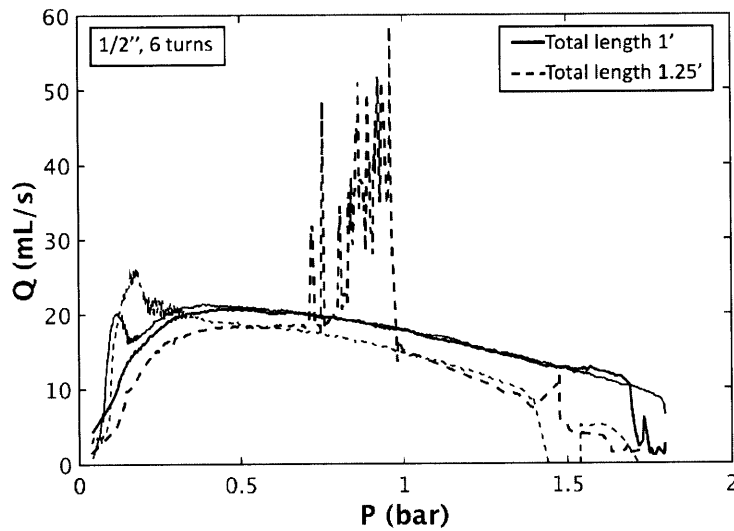


Figure A-74: Comparison of 1' and 1.25' drippers, each with 1/2" inner diameter, tested with at six turns.

## A.9 Effect of Inner Diameter

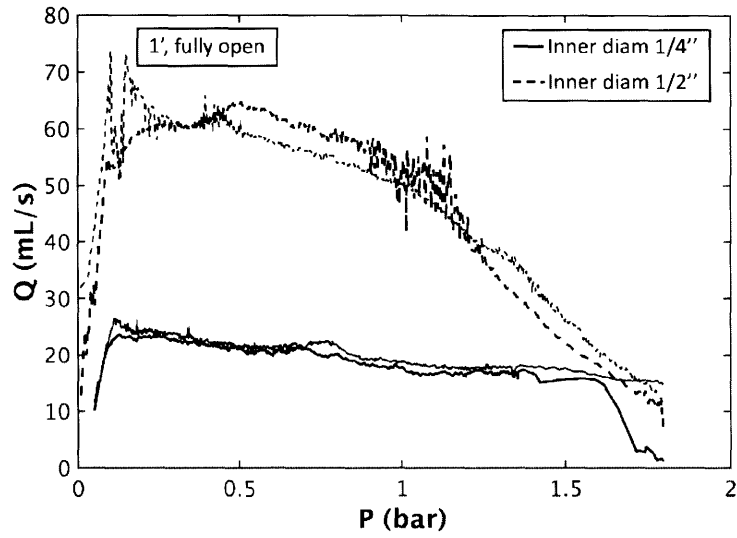


Figure A-75: Comparison of 1/2" and 1/4" drippers, each 1' long, tested with a fully open valve.

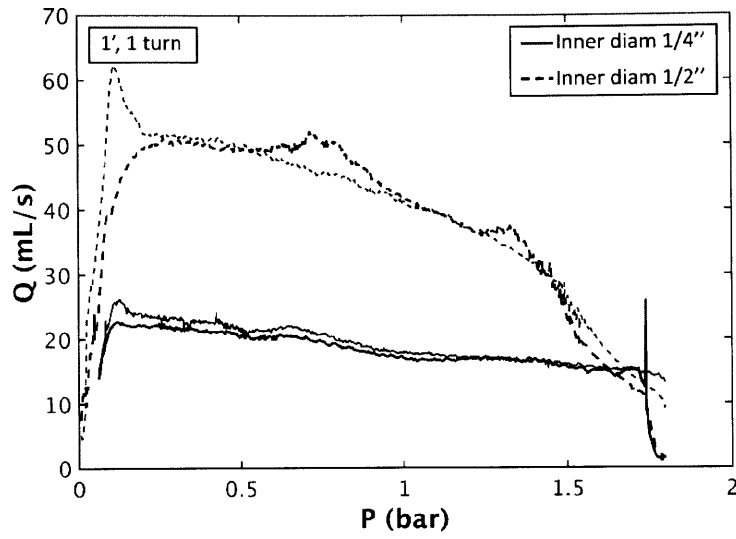


Figure A-76: Comparison of 1/2" and 1/4" drippers, each 1' long, tested with at one turn.

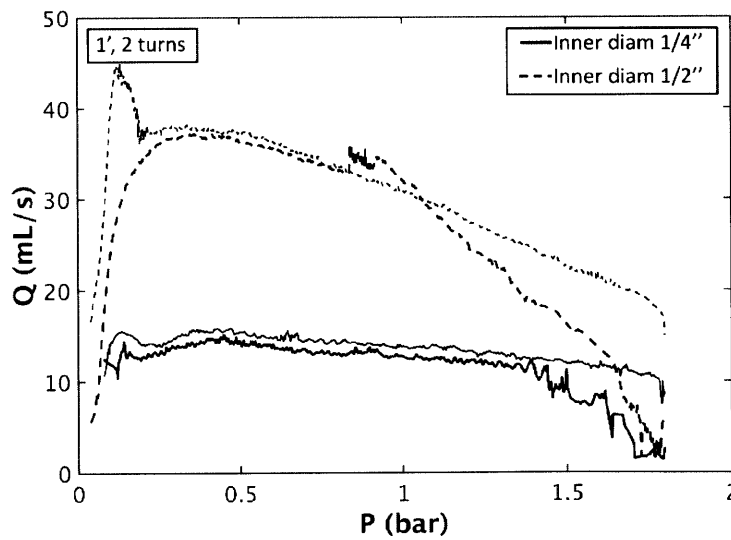


Figure A-77: Comparison of 1/2" and 1/4" drippers, each 1' long, tested with at two turns.

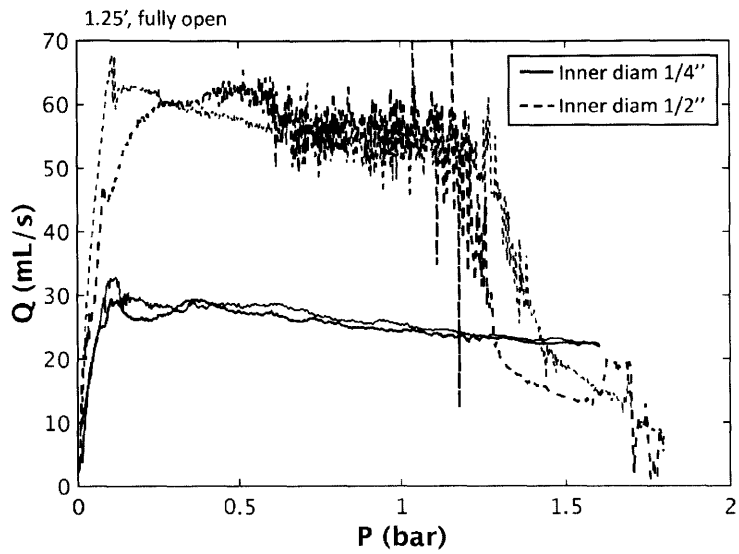


Figure A-78: Comparison of 1/2" and 1/4" drippers, each 1.25' long, tested with a fully open valve.

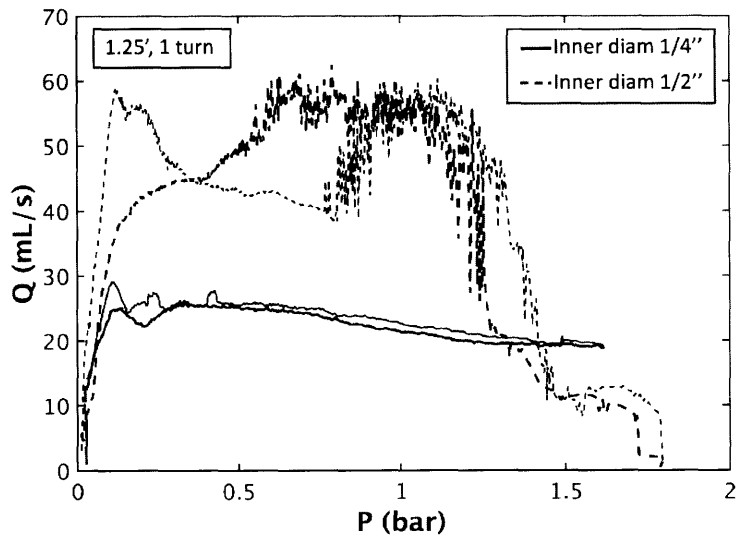


Figure A-79: Comparison of 1/2" and 1/4" drippers, each 1.25' long, tested with at one turn.



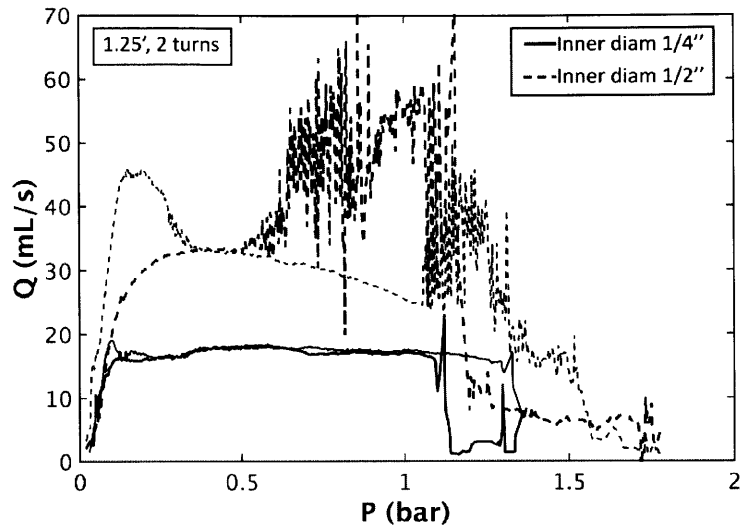


Figure A-80: Comparison of 1/2" and 1/4" drippers, each 1.25' long, tested with at two turns.

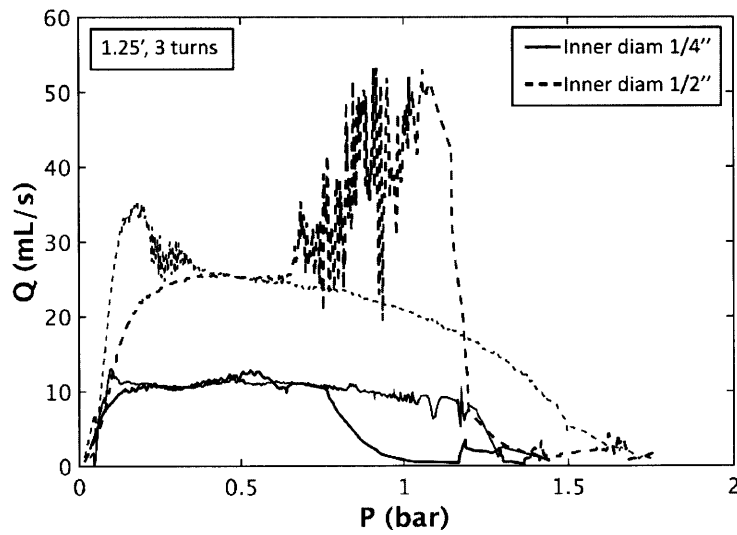


Figure A-81: Comparison of 1/2" and 1/4" drippers, each 1.25' long, tested with at three turns.

# Appendix B

## Data Analysis Script (Matlab)

The following Matlab script was used to analyze the data collected. It is by default set to analyze 3 trials of each test, but tests can be added or subtracted depending on how many trials were run or need to be analyzed.

```
clear;
dirname='./D0p25_L1p25-needlebigtop/';
namelist=dir([dirname '/V3turn_L1p25_H1s32_D0p25*']);

fullname1=namelist(1).name;
fid1=fopen([dirname fullname1]);
fgetl(fid1);
C1=textscan(fid1,'%s %s %f %s %s %f');
fgetl(fid1);
fclose(fid1);

fullname2=namelist(2).name;
fid2=fopen([dirname fullname2]);
fgetl(fid2);
C2=textscan(fid2,'%s %s %f %s %s %f');
```

```

fgetl(fid2);
fclose(fid2);

fullname3=namelist(3).name;
fid3=fopen([dirname fullname3]);
fgetl(fid3);
C3=textscan(fid3,'%s %s %f %s %s %f');
fgetl(fid3);
fclose(fid3);

** data processing
D=0.01016*2^(-1/3);
A=2*pi*D^2/4;
Q_unit=3.785e-3/1547;
% m^3 of water detected for each pulse, characteristic of flow meter
dt=1/2000;

P1=(C1{3}-0.5)/4*25*6.8948*0.01;      %bar
P2=(C2{3}-0.5)/4*25*6.8948*0.01;      %bar
P3=(C3{3}-0.5)/4*25*6.8948*0.01;      %bar
%P4=(C4{3}-0.5)/4*25*6.8948*0.01;      %bar

%P readings are voltage readings from 0.5 to 4.5 V
%0.5 V corresponds to 0 Psi
%4.5 V corresponds to 25 Psi

Q_raw1=C1{6};
Q_raw2=C2{6};
Q_raw3=C3{6};
%Q_raw4=C4{6};

x=20;

```

```

[Q_pulse1,Q_i1]=findpeaks(Q_raw1,'MinPeakWidth',x);
[Q_pulse2,Q_i2]=findpeaks(Q_raw2,'MinPeakWidth',x);
[Q_pulse3,Q_i3]=findpeaks(Q_raw3,'MinPeakWidth',x);
%[Q_pulse4,Q_i4]=findpeaks(Q_raw4,'MinPeakWidth',x);
%Q_i1 is index of peak
%Q_pulse1 is value of peak

% debug for Q
%   figure(1);
%   plot(Q_raw1);
%   hold all; %hold plot for next plot
%   plot(Q_i1,Q_pulse1,'ro');

Q1=zeros(1,length(Q_raw1));
Q2=zeros(1,length(Q_raw2));
Q3=zeros(1,length(Q_raw3));
%Q4=zeros(1,length(Q_raw4));
Q_grad1=Q_unit./gradient(Q_i1)/dt;
Q_grad2=Q_unit./gradient(Q_i2)/dt;
Q_grad3=Q_unit./gradient(Q_i3)/dt;
%Q_grad4=Q_unit./gradient(Q_i4)/dt;

s=10; %averaging every s signals
ii=1;
for i=1:length(Q_i1)-s
    Q_1(ii)=1E6*s*Q_unit/dt/(Q_i1(i+s)-Q_i1(i));
    P_1(ii)=mean(P1(Q_i1(i):Q_i1(i+s)));
    ii=ii+1;
end
ii=1;
for i=1:length(Q_i2)-s
    Q_2(ii)=1E6*s*Q_unit/dt/(Q_i2(i+s)-Q_i2(i));

```

```

    P_2(ii)=mean(P2(Q_i2(i):Q_i2(i+s)));
    ii=ii+1;
end
ii=1;
for i=1:length(Q_i3)-s
    Q_3(ii)=1E6*s*Q_unit/dt/(Q_i3(i+s)-Q_i3(i));
    P_3(ii)=mean(P3(Q_i3(i):Q_i3(i+s)));
    ii=ii+1;
end
% ii=1;
% for i=1:length(Q_i4)-s
%     Q_4(ii)=1E6*s*Q_unit/dt/(Q_i4(i+s)-Q_i4(i));
%     P_4(ii)=mean(P4(Q_i4(i):Q_i4(i+s)));
%     ii=ii+1;
% end

hold all;

%% Set up some constants for changing font sizes, etc
AxisFontSize=14;
TextFontSize=10;

%% Redraw and format the figure
% h=plot(x,y1,'-o',x,y2,'--');
box on
h=plot(P_1(1:5:end),Q_1(1:5:end),'-', 'color','black');
h=plot(P_2(1:5:end),Q_2(1:5:end),'--', 'color','black');
h=plot(P_3(1:5:end),Q_3(1:5:end),'-.', 'color','black');
%h=plot(P_4(1:5:end),Q_4(1:5:end),':', 'color','black');

% set the figure size and position; gcf means current figure handle
set(gcf,'PaperPosition',[0 0 4 4]);

```

```

% set some properties; gca means current axis handle
set(gca,'fontsize',AxisFontSize,'xgrid','off','ygrid','off',...
'fontweight','normal','fontname','Computer Modern Roman')
% set the position of the axes in the figure
set(gca,'Position',[0.15 0.19 0.75 0.7])
% set the linewidth for all lines
set(h,'linewidth',1.5);

xlabel('P (bar)', 'fontsize', 17, 'fontweight', 'bold');
ylabel('Q (mL/s)', 'fontsize', 17, 'fontweight', 'bold');
labels={['Trial 1'},{'Trial 2'},{'Trial 3'}];
legend(labels,'fontsize',13);

%% Saving
fstart=1;
fend=find(fullname1=='.',1,'last');
%finds the last . in the name and makes that the end
% saveas(gcf,[fullname(1:fend-1),'.png']);

rez=600; %resolution (dpi) of final graphic
f=gcf; %f is the handle of the figure you want to export
figpos=getpixelposition(f);
resolution=get(0,'ScreenPixelsPerInch');
set(f,'paperunits','inches','papersize',figpos(3:4)/resolution,...
'paperposition',[0 0 figpos(3:4)/resolution]);
path='/Users/tlin15/Dropbox (MIT)/GEAR Lab/Tube_data/2015_04/Figures';
name=[fullname1(1:fend-3),'.png'];
print(f,fullfile(path,name),'-dpng',['-r',num2str(rez)],'-opengl')
savefig([fullname1(1:fend-3)]);

```

# Appendix C

## Averaging Script (Matlab)

The following Matlab script was used to average the trials for each test. Again, it is by default set to analyze 3 trials of each test, but tests can be added or subtracted depending on how many trials were run or need to be analyzed.

```
clear;
dirname='./D0p25_L1p25_needlebigtop/';
namelist=dir([dirname '/V3turn_L1p25_H1s32_D0p25*']);

fullname1=namelist(1).name;
fid1=fopen([dirname fullname1]);
fgetl(fid1);
C1=textscan(fid1,'%s %s %f %s %s %f');
fgetl(fid1);
fclose(fid1);

fullname2=namelist(2).name;
fid2=fopen([dirname fullname2]);
fgetl(fid2);
C2=textscan(fid2,'%s %s %f %s %s %f');
```

```

fgetl(fid2);
fclose(fid2);

fullname3=namelist(3).name;
fid3=fopen([dirname fullname3]);
fgetl(fid3);
C3=textscan(fid3,'%s %s %f %s %s %f');
fgetl(fid3);
fclose(fid3);

** data processing
D=0.01016*2^(-1/3);
A=2*pi*D^2/4;
Q_unit=3.785e-3/1547;
dt=1/2000;

P1=(C1{3}-0.5)/4*25*6.8948*0.01;      %bar
P2=(C2{3}-0.5)/4*25*6.8948*0.01;      %bar
P3=(C3{3}-0.5)/4*25*6.8948*0.01;      %bar

Q_raw1=C1{6};
Q_raw2=C2{6};
Q_raw3=C3{6};

x=20;
[Q_pulse1,Q_i1]=findpeaks(Q_raw1,'MinPeakWidth',x);
[Q_pulse2,Q_i2]=findpeaks(Q_raw2,'MinPeakWidth',x);
[Q_pulse3,Q_i3]=findpeaks(Q_raw3,'MinPeakWidth',x);

Q1=zeros(1,length(Q_raw1));
Q2=zeros(1,length(Q_raw2));
Q3=zeros(1,length(Q_raw3));

```



```

Q-grad1=Q_unit./gradient(Q_i1)/dt;
Q-grad2=Q_unit./gradient(Q_i2)/dt;
Q-grad3=Q_unit./gradient(Q_i3)/dt;

s=10;
ii=1;
for i=1:length(Q_i1)-s
    Q_1(ii)=1E6*s*Q_unit/dt/(Q_i1(i+s)-Q_i1(i));
    P_1(ii)=mean(P1(Q_i1(i):Q_i1(i+s)));
    ii=ii+1;
end
ii=1;
for i=1:length(Q_i2)-s
    Q_2(ii)=1E6*s*Q_unit/dt/(Q_i2(i+s)-Q_i2(i));
    P_2(ii)=mean(P2(Q_i2(i):Q_i2(i+s)));
    ii=ii+1;
end
ii=1;
for i=1:length(Q_i3)-s
    Q_3(ii)=1E6*s*Q_unit/dt/(Q_i3(i+s)-Q_i3(i));
    P_3(ii)=mean(P3(Q_i3(i):Q_i3(i+s)));
    ii=ii+1;
end

hold all;

%% Averaging (default 3 inputs)
P_tot=[P_1 P_2 P_3];
maxP=max(P_tot);
minP=min(P_tot);

```

```

[M1, I1]=max(P_1);
[M2, I2]=max(P_2);
[M3, I3]=max(P_3);

P_11=P_1(1:I1);           %increasing segment of P_1
P_12=P_1(I1:length(P_1)); %decreasing segment of P_1
P_21=P_2(1:I2);
P_22=P_2(I2:length(P_2));
P_31=P_3(1:I3);
P_32=P_3(I3:length(P_3));

k=0.001;
P_avg=[];
Q_avg=[];
L=[];
U=[];
for i=minP:k:(maxP-k)    %increasing P
    if (i+k)<=maxP
        P_avg=[P_avg 0.5*(2*i+k)];

        I_11=find(P_11>=i & P_11<(i+k));
        Q_11=Q_1(I_11);
        I_21=find(P_21>=i & P_21<(i+k));
        Q_21=Q_2(I_21);
        I_31=find(P_31>=i & P_31<(i+k));
        Q_31=Q_3(I_31);

        Q_avg=[Q_avg mean([Q_11 Q_21 Q_31])];
        L=[L (max([Q_11 Q_21 Q_31])-mean([Q_11 Q_21 Q_31]))];
        U=[U (mean([Q_11 Q_21 Q_31])-min([Q_11 Q_21 Q_31]))];
    end

```

```

if (i+k)>maxP
    r=0.5*(i+maxP);
    P_avg=[P_avg r];

    I_11=find(P_11>=i & P_11<maxP);
    Q_11=Q_1(I_11);
    I_21=find(P_21>=i & P_21<maxP);
    Q_21=Q_2(I_21);
    I_31=find(P_31>=i & P_31<maxP);
    Q_31=Q_3(I_31);

    Q_avg=[Q_avg mean([Q_11 Q_21 Q_31])];
    L=[L (max([Q_11 Q_21 Q_31])-mean([Q_11 Q_21 Q_31]))];
    U=[U (mean([Q_11 Q_21 Q_31])-min([Q_11 Q_21 Q_31]))];

end
end

P_avg2=[];
Q_avg2=[];
L2=[];
U2=[];
for i=minP:k:(maxP-k)      %decreasing P
    if (i+k)<=maxP
        P_avg2=[P_avg2 0.5*(2*i+k)];

        I_12=find(P_12>=i & P_12<(i+k));
        Q_12=Q_1(I_12+I1-1);
        I_22=find(P_22>=i & P_22<(i+k));
        Q_22=Q_2(I_22+I2-1);
        I_32=find(P_32>=i & P_32<(i+k));
        Q_32=Q_3(I_32+I3-1);
    end

```

```

    Q_avg2=[Q_avg2 mean([Q_12 Q_22 Q_32])];
    L2=[L2 (max([Q_12 Q_22 Q_32])-mean([Q_12 Q_22 Q_32]))];
    U2=[U2 (mean([Q_12 Q_22 Q_32])-min([Q_12 Q_22 Q_32]))];
end

if (i+k)>maxP
    r=0.5*(i+maxP);
    P_avg=[P_avg r];

    I_12=find(P_12>=i & P_12<maxP);
    Q_12=Q_1(I_12+I1-1);
    I_22=find(P_22>=i & P_22<maxP);
    Q_22=Q_2(I_22+I2-1);
    I_32=find(P_32>=i & P_32<maxP);
    Q_32=Q_3(I_32+I3-1);

    Q_avg=[Q_avg mean([Q_12 Q_22 Q_32])];
    L2=[L2 (max([Q_12 Q_22 Q_32])-mean([Q_12 Q_22 Q_32]))];
    U2=[U2 (mean([Q_12 Q_22 Q_32])-min([Q_12 Q_22 Q_32]))];
end
end

AxisFontSize=14;
TextFontSize=10;
box on

h=plot(P_avg,smooth(Q_avg),'-','color','black');
h=plot(P_avg2,smooth(Q_avg2),'-.','color','black');

set(gcf,'PaperPosition',[0 0 4 4]);
set(gca,'fontsize',AxisFontSize,'xgrid','off','ygrid','off',...
'fontweight','normal','fontname','Computer Modern Roman')

```

```

set(gca, 'Position', [0.15 0.19 0.75 0.7])
set(h, 'linewidth', 1.5);
xlabel('P (bar)', 'fontsize', 17, 'fontweight', 'bold');
ylabel('Q (mL/s)', 'fontsize', 17, 'fontweight', 'bold');
labels=[{'Mean, increasing P'}, {'Mean, decreasing P'}];
legend(labels, 'fontsize', 13);

%% Saving
fstart=1;
fend=find(fullname1=='.', 1, 'last');
rez=600;
f=gcf;
figpos=getpixelposition(f);
resolution=get(0, 'ScreenPixelsPerInch');
set(f, 'paperunits', 'inches', 'papersize', figpos(3:4)/resolution, ...
'paperposition', [0 0 figpos(3:4)/resolution]);
path='/Users/tlin15/Dropbox (MIT)/GEAR Lab/Tube_data/2015_04/Figures';
name=[fullname1(1:fend-3), '_avg.png'];
print(f, fullfile(path, name), '-dpng', ['-r', num2str(rez)], '-opengl')
savefig([fullname1(1:fend-3), '_avg']);

```

# Appendix D

## Determining Ranges of Constant Flow Rate

In this study, flow rates are defined as constant if it stays within 5% above and below the "average" flow rate. The flow rate at the end of a constant region (approximated) is the bottom limit of the range (denoted  $x$ ) and is used to calculate the upper limit of the range (denoted  $y$ ) in the following manner:

$$y - \frac{y + x}{2} = 0.05\left(\frac{y + x}{2}\right) \quad (\text{D.1})$$

$$y = \frac{21}{19}x \quad (\text{D.2})$$

The region of constant flow rate is therefore  $[y,x]$ . The pressures that bound this region can be determined from the Matlab figures.

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