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MEASUREMENT AND ANALYSIS OF PRESSURE PROFILE WITHIN BIG AREA ADDITIVE MANUFACTURING SINGLE SCREW EXTRUDER

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Abstract

Pressure distributions within a single screw extruder are dependent on several factors, namely, processing parameters and flow geometry. The Big Area Additive Manufacturing (BAAM) system involves a complex flow geometry with multiple flow zones following the screw extruder. This study utilized experimental data and a one-dimensional (1-D) analytical model to compare pressures at specific areas of interest in the BAAM system. Initial results show a need for further two-dimensional (2-D) and three-dimensional (3-D) simulation and modeling of the BAAM extruder with more accurate underlying assumptions. The results of this work will allow for further study of BAAM input parameters for optimal print quality, material properties, and print head geometric design.

Background

Big area additive manufacturing is a large scale AM system that utilizes a single-screw extruder (SSE) to transform plastic pellets into a melt flow and ultimately a printed part. The screw within the SSE is run at a range of rotations per minute (RPMs) to accommodate a range of machine output. As a result, pressure within the BAAM extruder varies significantly across RPMs and the flow path of the melt. Characterizing this pressure profile allows for a deeper understanding of the system to validate print output predictions and simulation.

Additionally, this work serves as a lead into the printability model developed by Duty et al [1]. The first fundamental condition for printability states: “pressure driven extrusion must occur through a given diameter nozzle at a specified flow rate” while operating at a pressure below the system limit. The concept proposed by this printability model directly lead to the experimental creation of a “pressure map” detailing the machine’s behavior over a range of screw RPMs.

The BAAM extruder has been split into subsections for clarity, consisting of the hopper, single screw extruder, end cap, and nozzle. In the BAAM extruder’s case, there is several inches of melt flow in the end cap (**Figure 1**) containing a melt thermocouple, pressure transmitter, burst disc, and back pressure screw. The melt thermocouple, pressure transmitter, and burst disc are non-flow impeding and are treated as having negligible impact on the melt’s behavior. The back-pressure screw, however, is intentionally designed to adjust pressure within the machine. Turning

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the back-pressure screw into the machine impedes the flow and increases max pressure within the single screw extruder and, subsequently, the final extrusion pressure.

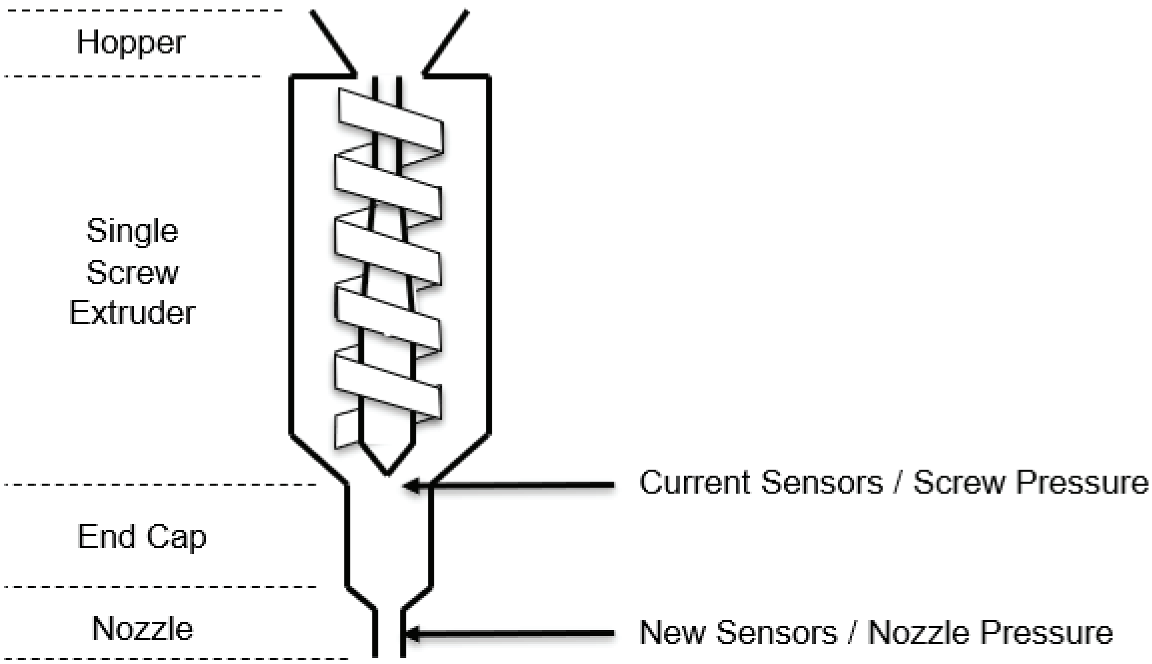

Figure 1: BAAM extruder subsections with sensor locations.

Two areas of interest were chosen in the BAAM system for pressure measurement as shown in **Figure 1**. The first location is at the end of the screw. This is a common standard in single screw extruder theory and defined as the screw pressure [2]. Furthermore, all geometry following the screw is referred to as the die. The BAAM is already actively measuring the screw pressure to the machine's operator terminal. The second location is just before the material is extruded and referred to as the nozzle pressure. In order to measure nozzle pressure, the BAAM required some retrofitting. A new nozzle was designed with a sensor port for pressure measurement as shown in **Figure 2**. The new nozzle has the same flow geometry as standard BAAM nozzles to ensure validity in comparison. It features an interchangeable tip to test the range of nozzles used on the BAAM, specifically, 0.2 inch (5.08 mm), 0.3 inch (7.62 mm), and 0.4 inch (10.16 mm) tip sizes. A Dynisco model TPT4634-5M-3/18-SIL2 combo pressure transmitter and melt thermocouple was selected due to its similarity to the current screw pressure sensor, a Dynisco model TPT4624-5M-6/18-SIL2.

Figure 2: New nozzle and sensor attached to BAAM end cap.

Data was captured separately for each sensor. The screw pressure sensor data was logged alongside screw RPMs in the BAAM control computer at its limit of 2 Hz. The nozzle pressure sensor was logged directly to a laptop computer with a Measurement Computing USB-202 DAQ at 50 Hz. It was desired for the nozzle sensor to be logged separately to allow for the higher data capture rate to properly record transient pressures when starting and stopping flow. The screw sensor could not be recorded at a higher rate without sacrificing RPM recording and live operator feedback during testing.

Experimental Procedure

In order to observe pressure fluctuations, a series of BAAM depositions were monitored over a range of RPMs (50, 100, 150, 200, 250, 300, & 350). This experiment was done with the 0.3 inch nozzle and the back pressure screw half way into the machine. For material, 20% carbon fiber acrylonitrile butadiene styrene (ABS) from Techmer was used (Electrafil® J-1200/CF/20). Two single layer 30 inch (762 mm) beads were printed at each RPM. In order to keep a consistent bead geometry of 0.6 inches (15.24 mm) wide and 0.15 inches (3.81 mm) high, print speed scaled linearly with RPM as shown in **Table 1**. After each bead the machine rested for 60 seconds, and the nozzle cleaned of any residual material.

Test RPM	Print Speed (mm/s)
50	39.06
100	78.11
150	117.17
200	156.23
250	195.28
300	234.34
350	278.98

Table 1: Print speed for each RPM test.

Experimental Results & Discussion

The result from a 50 RPM test is shown in **Figure 3** with two characteristic areas defined, steady pressure and peak pressure. Peak pressure is reached at the transient phase of the extrusion start at the start of the bead. Steady pressure is reached when the extrusion observes steady flow. At the end of each bead the pressures return to a resting value, as material remains in the nozzle and screw. As discussed in the background, the flow geometry and back pressure screw create a pressure differential between the two sensors.

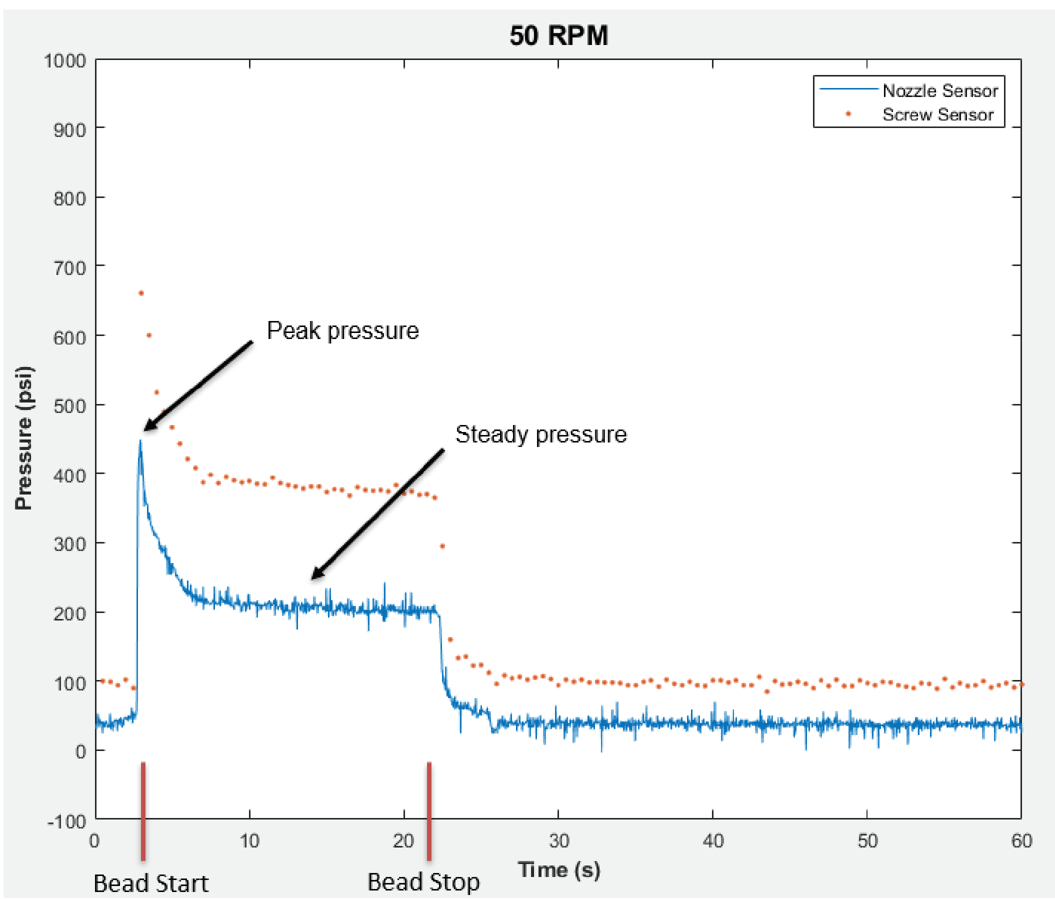

Figure 3: Plot of results for both sensors at 50 RPM with areas of interest labeled.

Nozzle pressure results for all RPMs were combined into one plot as shown in **Figure 4**. All RPMs had similar behavior in initially reaching the peak pressure, however, at higher RPMs a steady pressure was not achieved. It is believed this is due to the time of the print decreasing as RPMs increase. For example, at 350 RPM the bead only took 3 seconds to print. This was not enough time for the machine to reach steady flow.

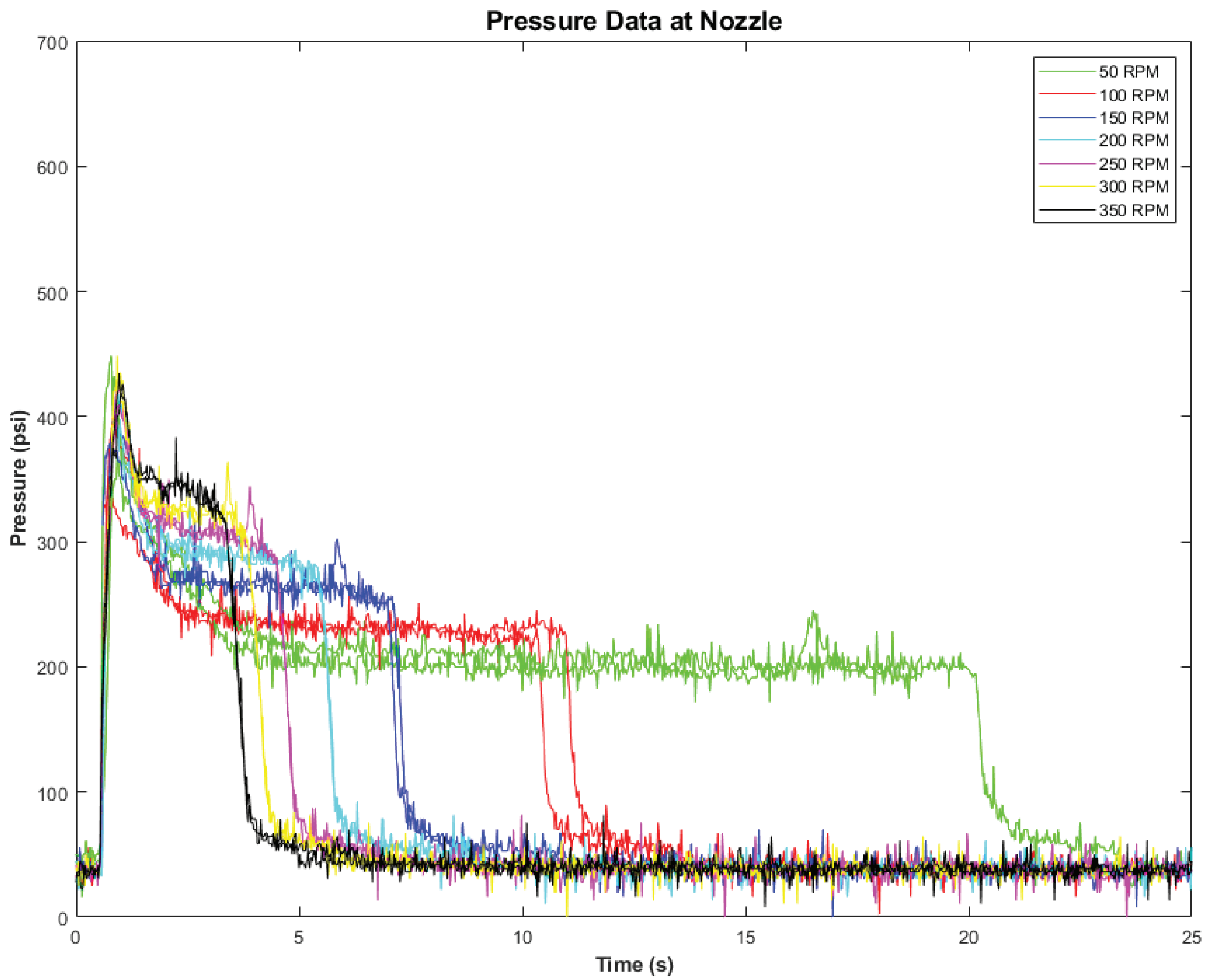

Figure 4: Combined nozzle pressure data at all RPMs tested.

Results for the average steady pressure at both sensors are compared in **Figure 5.** Peak pressure for the nozzle is also included, but not for the screw sensor. It was found that the 2 Hz sampling rate at the screw sensor was not fast enough to capture a true peak; the peak fell within the sampling times. Peak pressure remained relatively constant across all RPM tests. Average steady pressure was found by averaging pressure data after the peak and before the bead stop. As expected, pressure increased linearly with screw RPM. However, it is observed that the average steady pressure between the two sensors widens as RPM increases. This difference is shown in **Figure 6.**

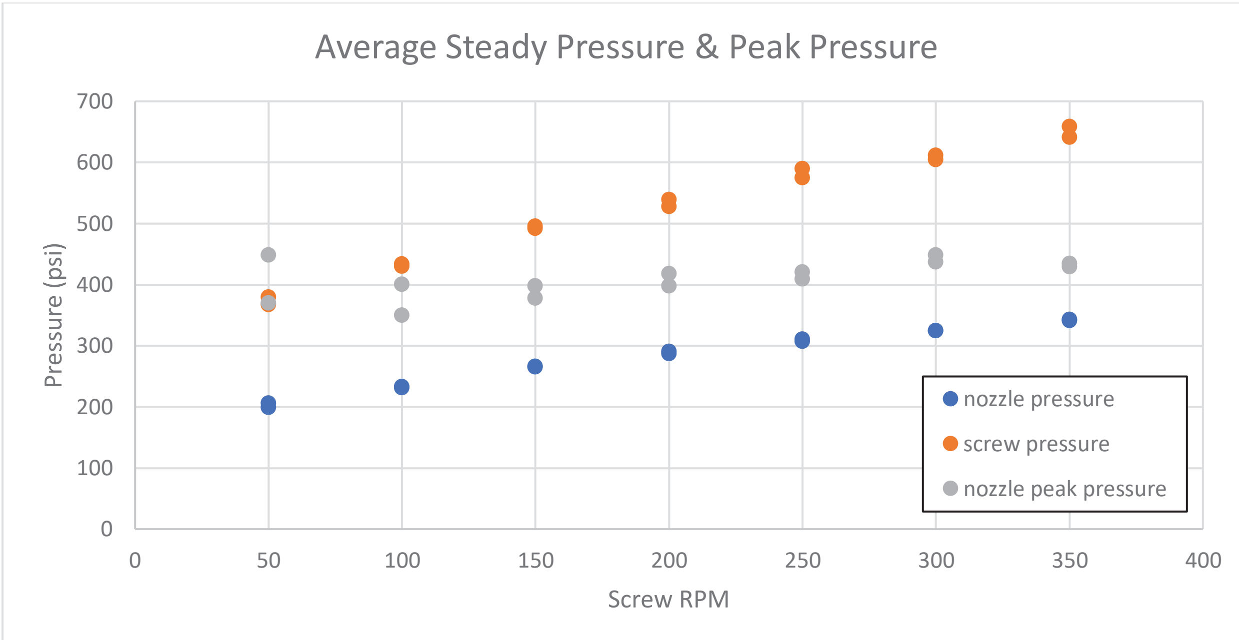

Figure 5: Average steady pressure for both sensors and peak pressures at the nozzle.

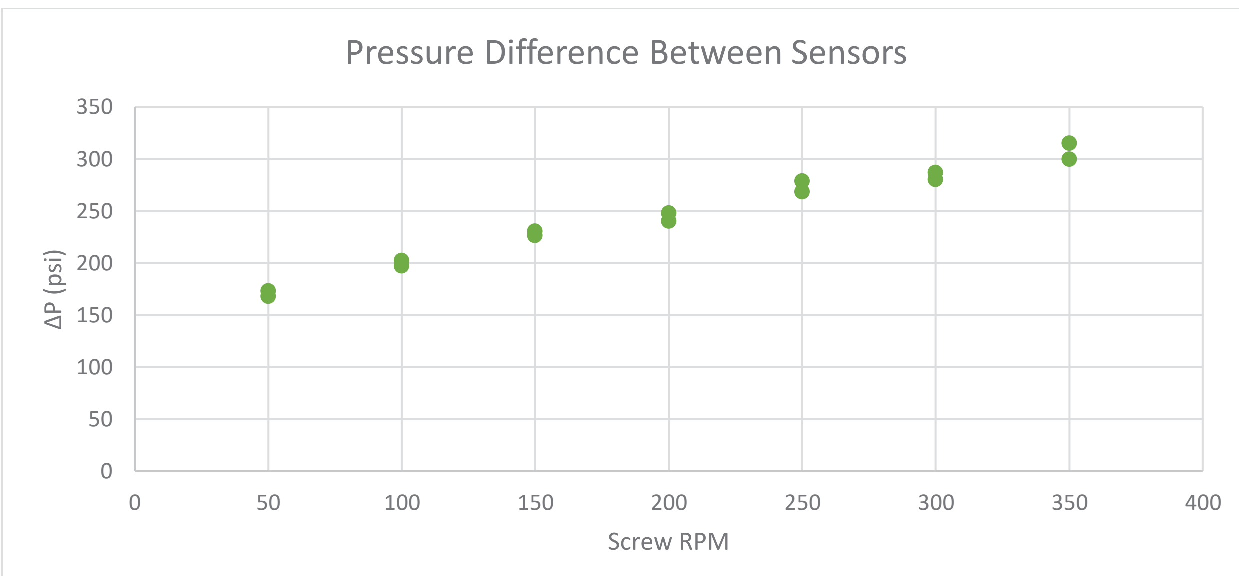

Figure 6: Pressure difference between average steady pressures of the sensors.

Beads were weighed after the experiment to find an average mass flow rate for the entire bead by dividing mass by the known extrusion time. A linear relation between screw RPM and mass flow rate was found as shown in **Figure 7.** The trendline was found to be

$$Q = 0.0925N + 2.7043 \quad (1) \qquad \text{Eq. (1)}$$

where Q is the mass flow rate and N is screw RPM. Data deviated from this trendline up to 15%.

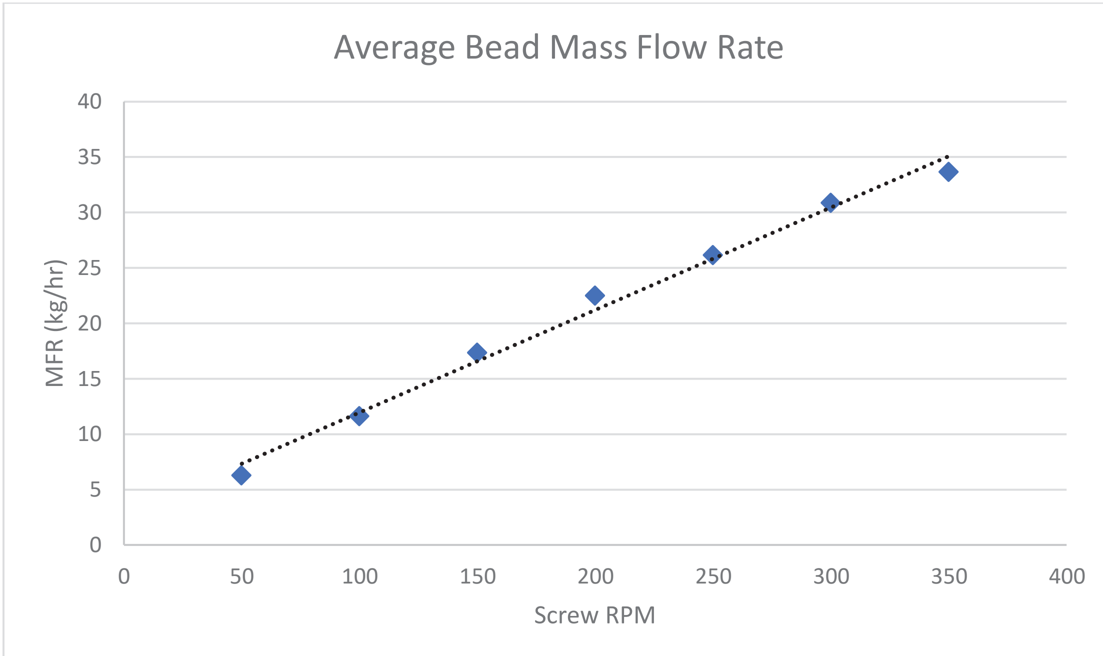

Figure 7: Bead mass flow rates for each RPM test with trendline.

Analytical Approach

Many analytical models for single screw extrusion have been developed with varying assumptions. To serve as a base line this research used a 1-D model by Middleman [2] with the Newtonian and isothermal assumptions, with the intent of progressing through increasingly complex assumptions in future work. Middleman's model treats the extruder as a pump, unwinds the screw channel, and uses simple mass balance to account for all flow. This results in the following analytical equations for output and pressure

$$Q = \frac{Ak}{C+k}N \quad (2)$$ Eq. (2)

$$\Delta P = \frac{\mu A}{C+k}N \quad (3)$$ Eq. (3)

where N is screw RPM, Q is output, ΔP is pressure rise, μ is viscosity, A and C are purely geometric parameters from the screw, and k is the die constant. The die constant is found by treating all flow geometry in the BAAM after the screw as a tubular die with the equation

$$k = \frac{\pi\left(\frac{D}{2}\right)^4}{128L} \quad (4)$$ Eq. (4)

Where D is the diameter of the die and L is the length of the die. The results of this model compared to the experimental results are shown in **Figure 8**. Flow rate provided a good fit to the data until tapering off by 14% at 350 RPM. Pressure, however, is clearly not an accurate fit to the data except at low RPM (50 RPM). This is due to the incorrect Newtonian assumption and the viscosity term in **Equation 3**. The large viscosity of the carbon fiber ABS causes the analytical result to deviate away from actual rapidly.

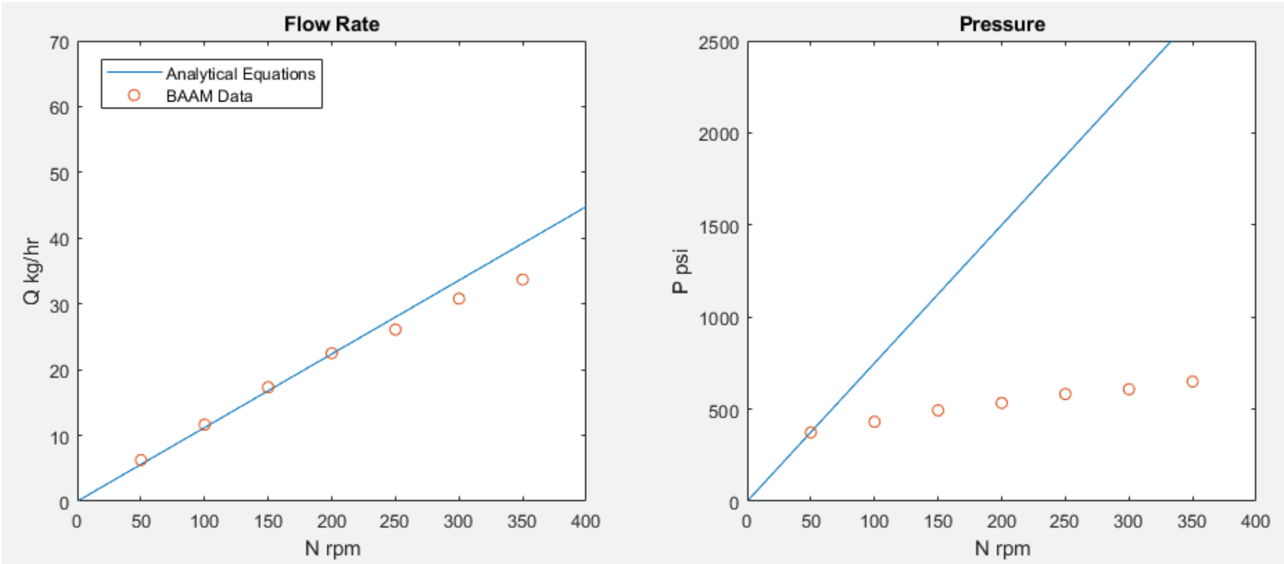

Figure 8: 1-D Analytical results compared to experimental data.

Conclusions & Next Steps

A new pressure monitoring sensor has been added to the BAAM system. From experimental data, it has been demonstrated that there is a linear relation between RPM, pressure throughout the BAAM melt flow, and mass flow rate. There is a distinct, characteristic, pressure drop between the two BAAM sensors at the nozzle and at the end of the screw. As RPMs increase it is increasingly difficult to achieve steady pressure in the system. The 1-D model with Newtonian and isothermal assumptions proved to be relatively accurate in predicting flow rate of the BAAM within 14% error, but not at all accurate in predicting pressure due to the incorrect Newtonian assumption.

Experimentally, next steps will consist of more variations on print settings such as back pressure screw, screw type, nozzle size, and increasing bead length. Analytically, next steps will explore 2-D and 3-D solvers with more complex assumptions (Non-Newtonian, adiabatic) until experimental results and analytical results coincide.

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