A Study of Single-Phase Flow Through Irregular Miniature Channel Cross-Sectional Geometry and Porous Media

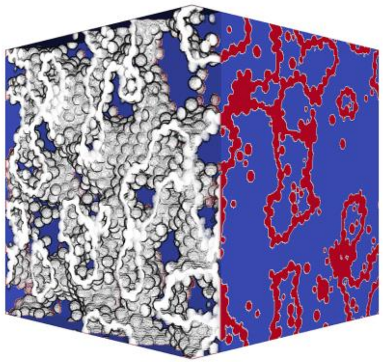
By: Daniel Berg

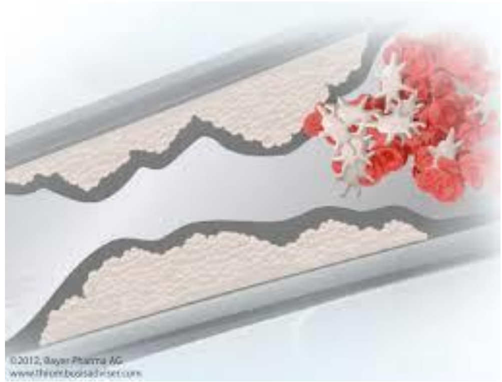
Project Overview

- Designed, built, and calibrated an experimental setup to support a wide variety of geometries and fluid experiments.
- Current study focused primarily on single-phase flow through rectangular miniature channels with Newtonian distilled water.
- Studying effects of flow through sudden cross-sectional area expansion and contraction in miniature channels and comparing results to flow through porous media.

Possible Applications of Research

- Porous media heat exchangers (high surface area to volume ratio)
- Pathological blood flow when accumulations of fatty plaques of cholesterol and blood clots increase in the cavity of the coronary artery [1]
- Optimizing pumping efficiency and thermal processes in space applications

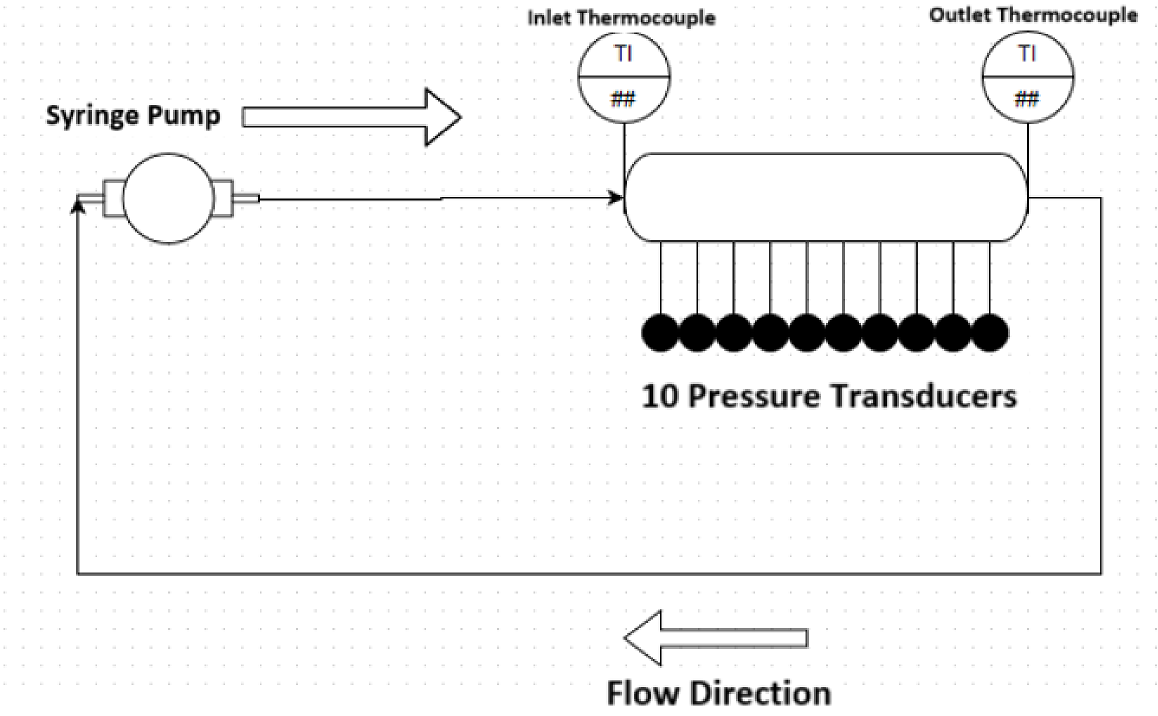




Experimental Setup

- Major Equipment:

1) Syringe pump
2) Test section
3) 10 pressure transducers
4) 2 thermocouples
5) Data acquisition device
6) Microscope with high speed digital camera



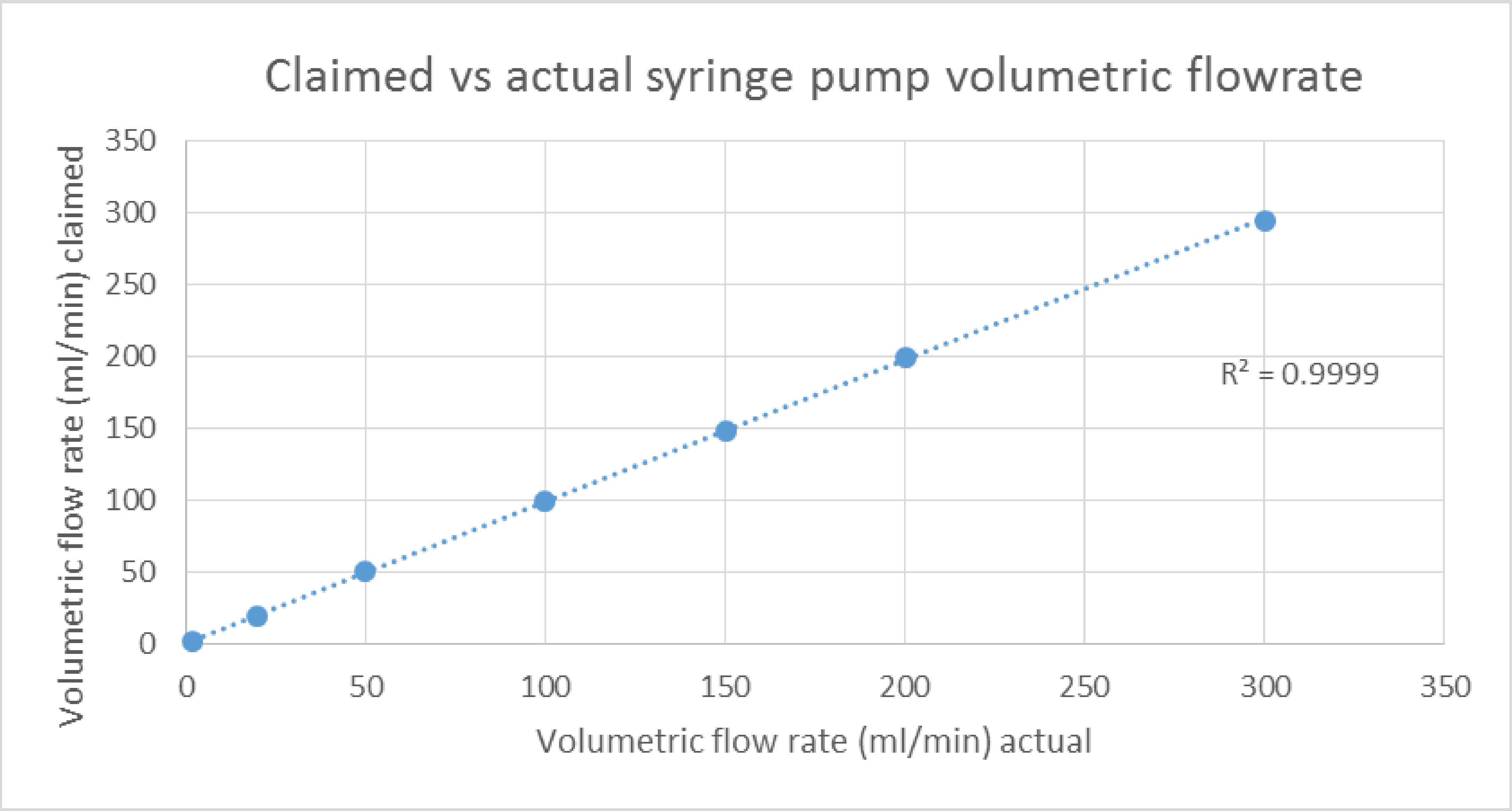
Syringe Pump

- Allows testing of complex fluids such as nanofluids
- Flow rates ranging from < 1 nanoliter/min to 300 ml/min
- Push-pull setup with one way valves allow constant flow

Syringe Pump Calibration

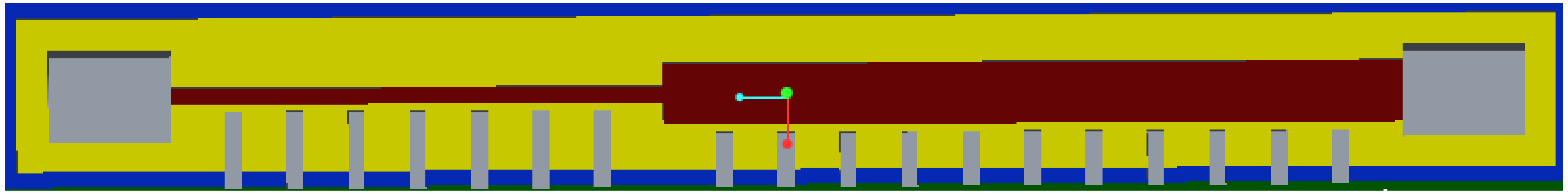
- 7 independent flow rates measured each repeated 5 times
- Mean and standard deviation were compiled for all 7 flow rates
- Using a t-distribution table and $\Delta = \sigma\, t_{95} / N^{0.5}$
- Volumetric flow rate = mean ± Δ = 200 ± 1.47 ml/min
- Including graduated cylinder and syringe pump uncertainties of ± 0.5 and ± 0.0035 ml/min respectively yields a total error of ± 1.70 ml/min using total error = $(x^2+y^2+z^2)^{0.5}$
- The maximum volumetric flow rate total uncertainty will be ± 1.17% with a 95% confidence level. [2]

Syringe Pump Calibration

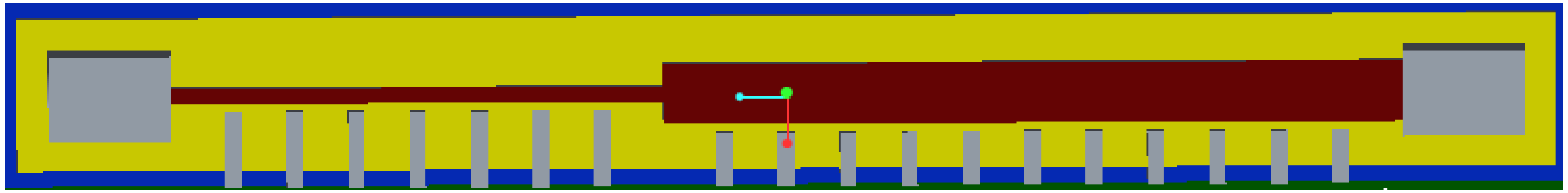


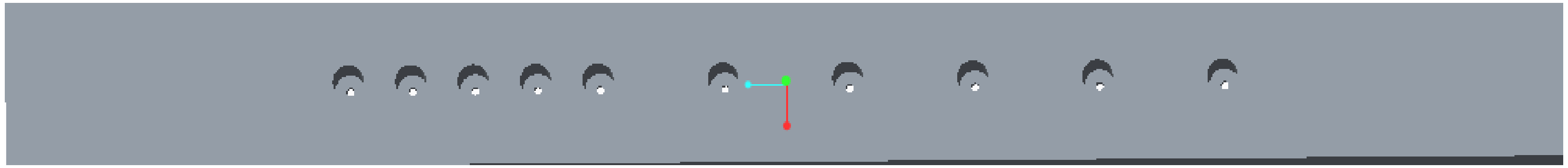
Expansion/Contraction Test Section

- Total length of 88.9 mm
- Cross-sectional area of 1.59 x 1.59 mm over first 31.75 mm
- Cross-sectional area of 1.59 x 6.35 mm over last 57.15 mm
- Area ratio of 4 / 1
- 10 pressure taps connected to pressure transducers
- Thermocouples at entrance and exit monitor temperature



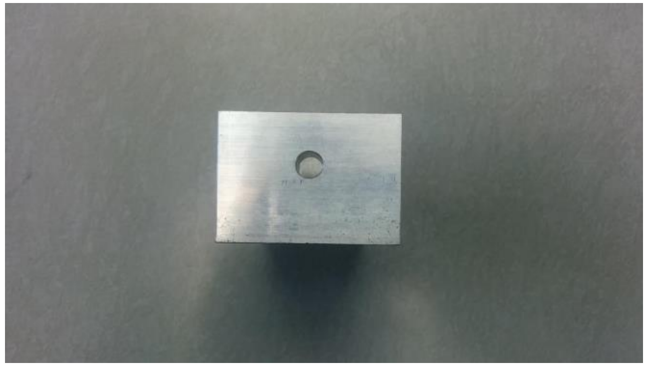
Expansion/Contraction Test Section

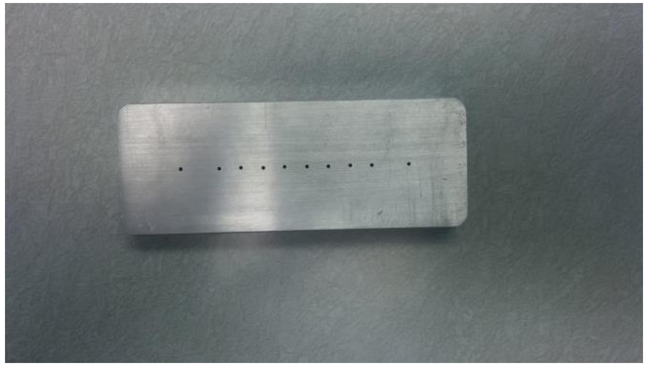


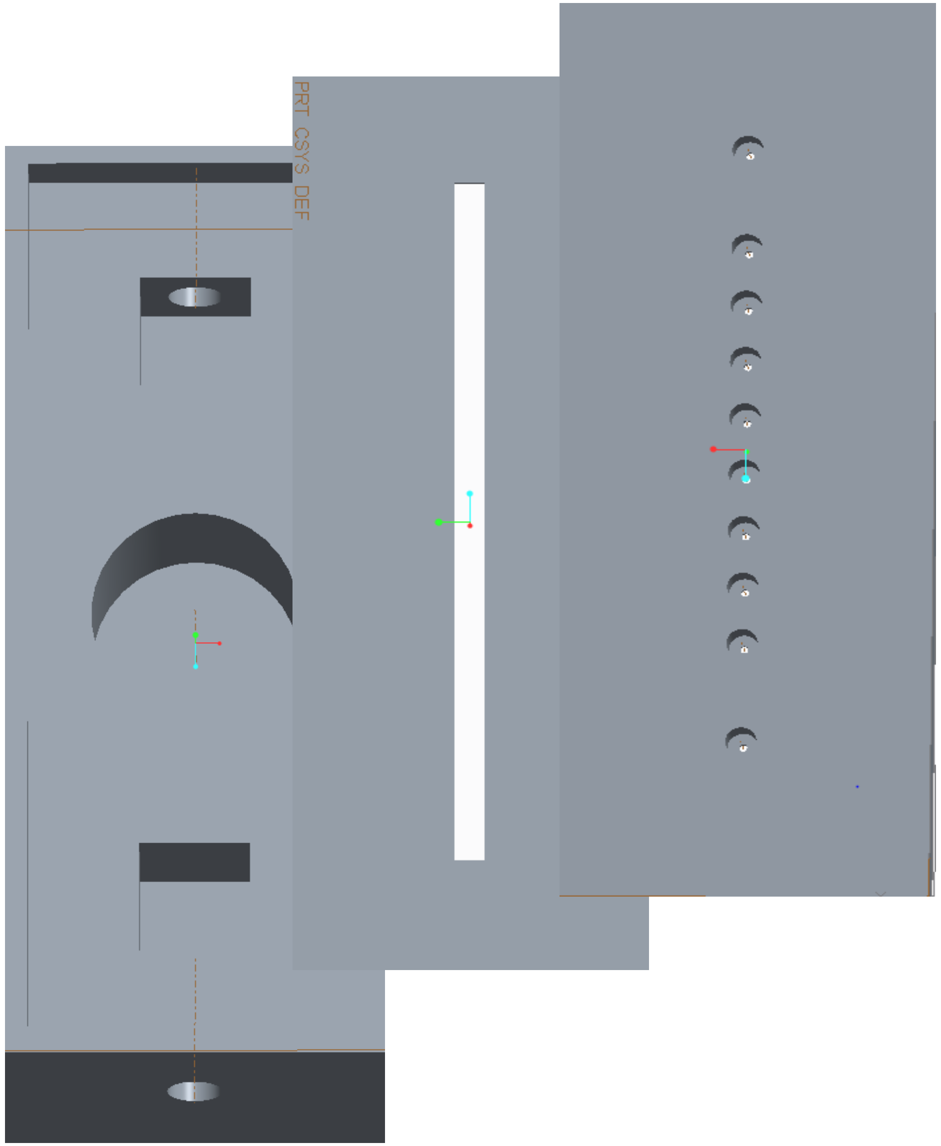


Porous Media Test Section

- Allows test material to be changed
- 10 pressure transducers
- Thermocouple at inlet and outlet
- Reservoirs located before and after channel
- Channel size can be customized
- 101.6 mm long
- 1.59 x 3.175 mm cross-sectional area






PRT_CSYS_DEF

Pressure Transducers

- 10 Honeywell pressure transducers
- Six Sigma manufacturing process
- Minimum life span of 10 million cycles
- 10 local static pressure measurements on both test sections
- Calibrated with a Fluke pressure calibrator

Keysight Data Acquisition Device

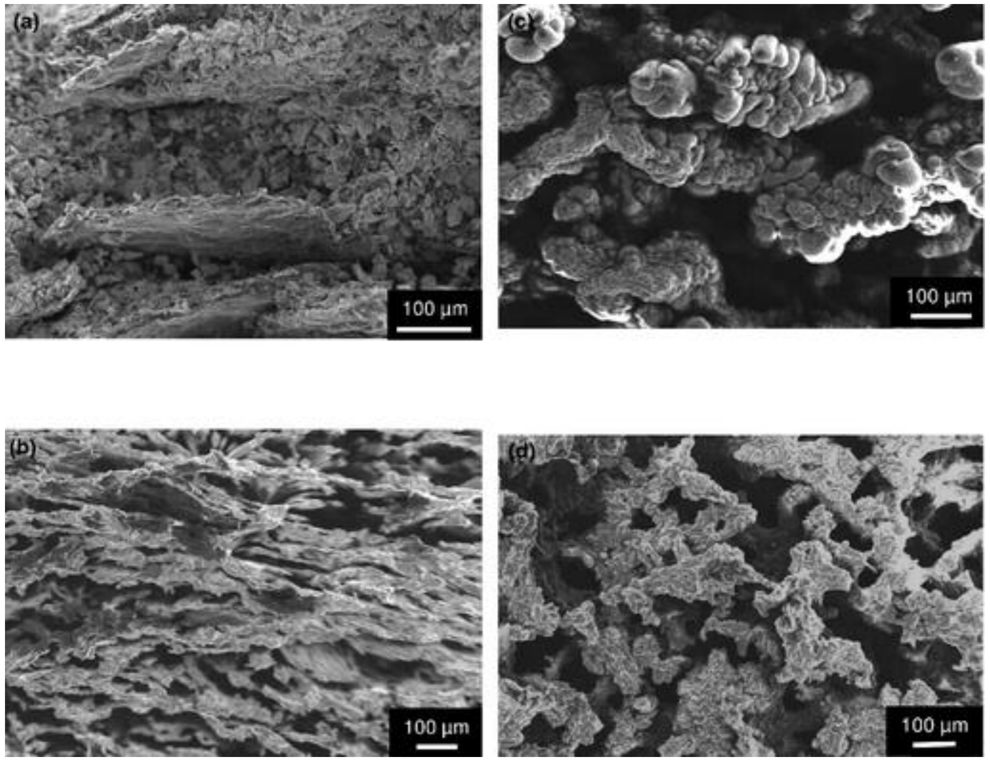
- 2 data points per second collected from pressure transducers and thermocouples
- Over 400 independent test runs
- Data from each run collected and averaged
- Over 260,000 total data points collected

Amscope Microscope

- 225X magnification
- Allows digital pictures of porous samples
- Will be utilized to analyze two-phase flow in future experiments

Porous Media

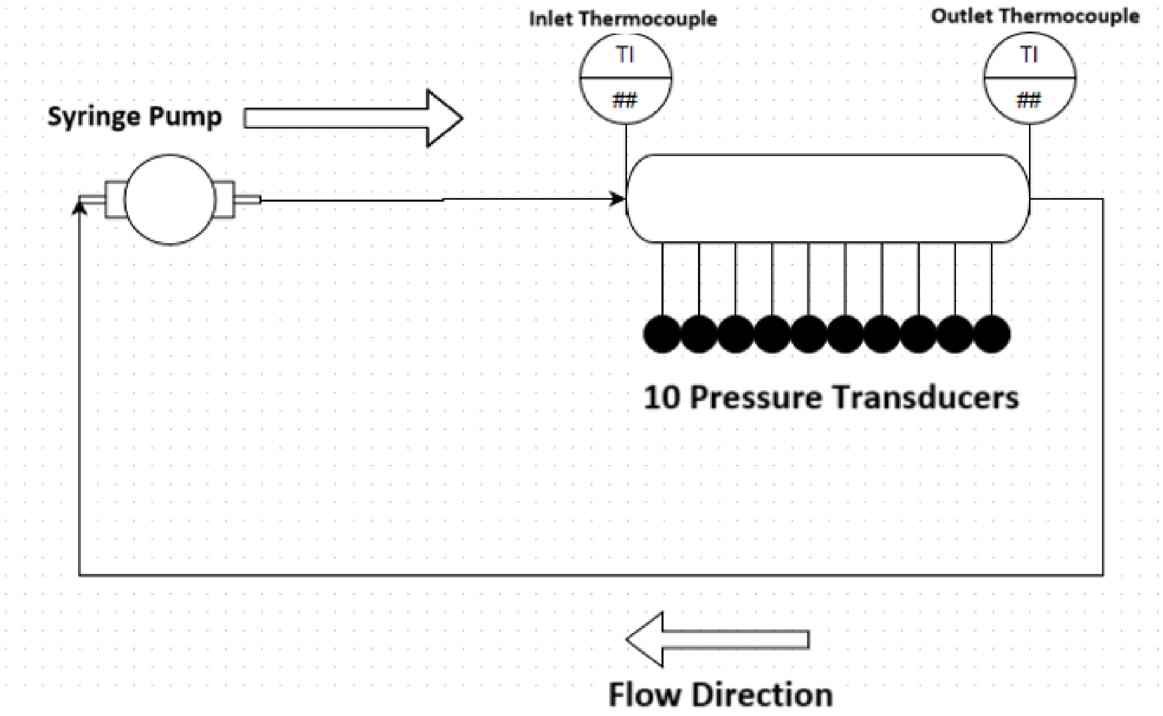
- Titanium oxide porous ceramics synthesized by Dr. Surojit Gupta



SEM micrographs of (a) fractured surface of the cross section of the green body of Composition C (Table 1), (b) fractured surface of the cross section of Composition C, (c) fractured surface of the cross section of Composition E (Table 1), and (d) top surface of the composition E after heat treatment at 1450 °C for 4 hours (Gupta & Riyad, 2014).

Data Acquisition Methodology

- Steady-state flow measured for 30 seconds at set volumetric flow rate
- Average taken of all 60 pressure measurements
- Procedure repeated at many flow rates



Porous Media Equations

- Darcy's Law: $\Delta P/L = (\mu/K) U$
- Works well for viscous drag dominated flow [3]
- Hazen-Dupuit-Darcy (HDD) model: $\Delta P/L = (\mu/K)*U + C*\rho*U^2$
- Works well for viscous and form drag dominated flow [3]
- K = permeability (m^2)
- C = form-coefficient (1/m)

Permeability (K) and Form (C) Values

- Using 2 independent runs and the HDD model allow K and C to be solved.
- Higher K value is more permeable and less resistive to flow [3]
- Higher C value correlates to higher form drag and more resistive to flow
- $K = 5.28 \times 10^{-9}\ m^2$
- $C = 236\ m^{-1}$

Viscous Versus Form Drag in Porous Material Internal Flow

Viscous Drag

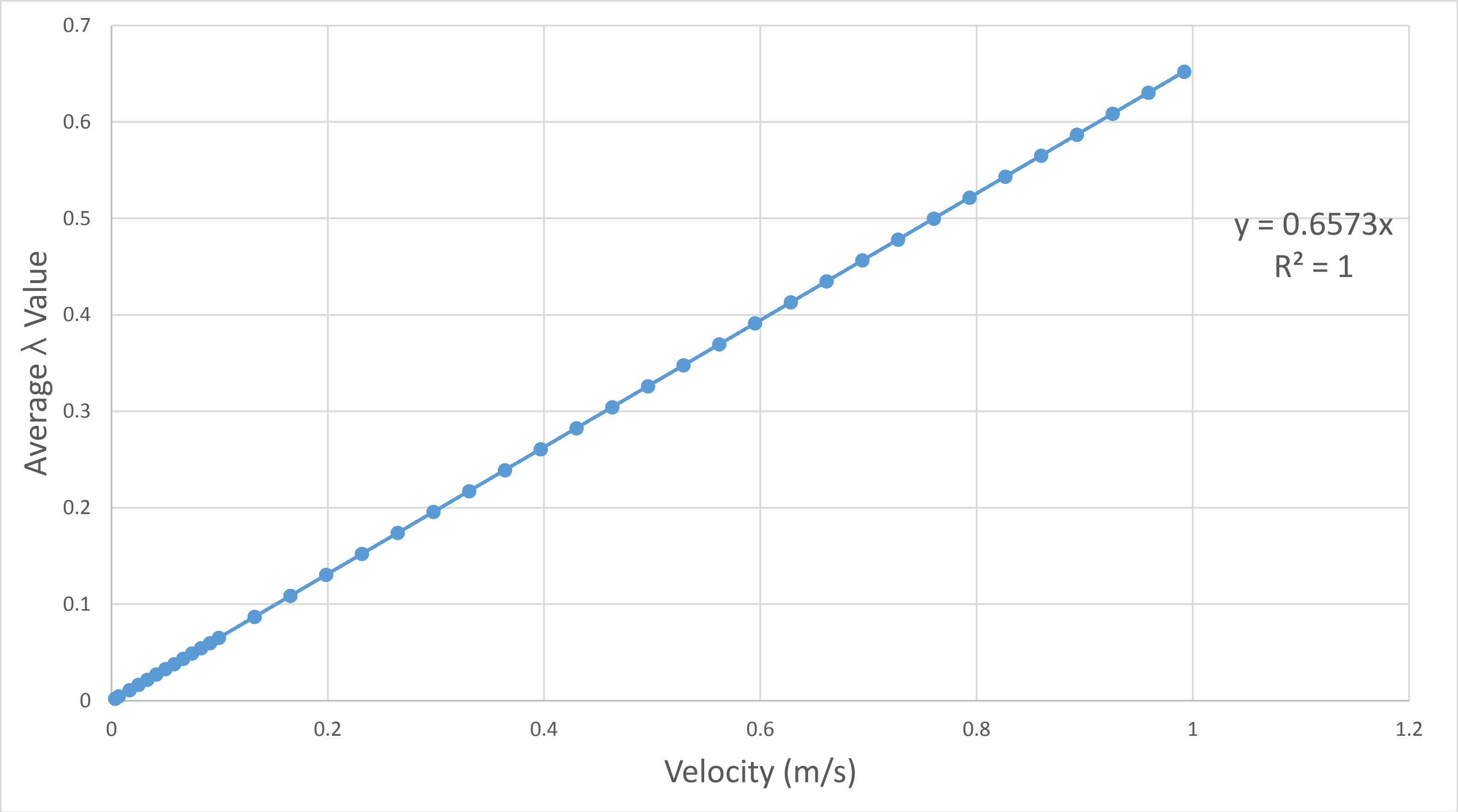
- Linear increase with average velocity
- Permeability (K) dictates flow

Form Drag

- Parabolic increase with average velocity
- Increased or decreased depending on the physical shape of the object impeding the flow
- Form coefficient (C) dictates flow

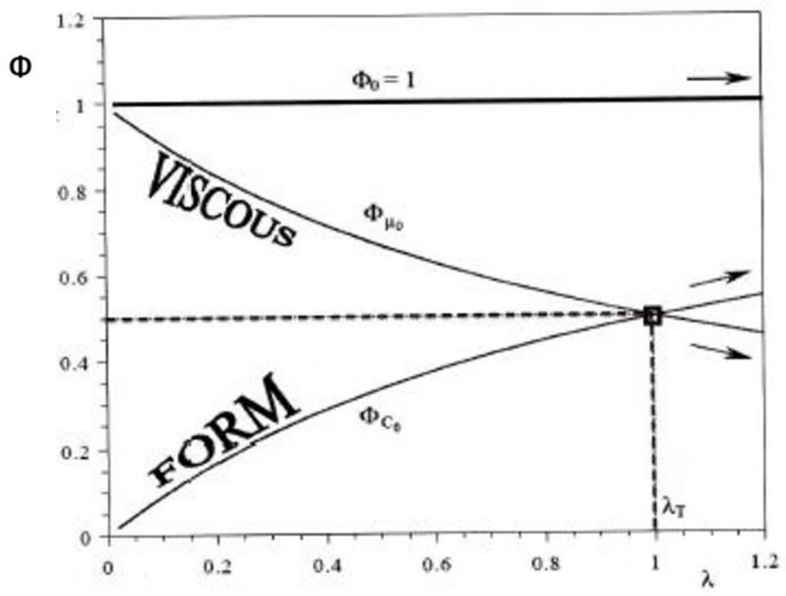
Determining a Reynolds Number for Flow Through Porous Materials

- Reynolds number (λ) based on Permeability and Form Coefficients
- $\lambda = (\rho * C_0 * K_0 / \mu_0) * U$

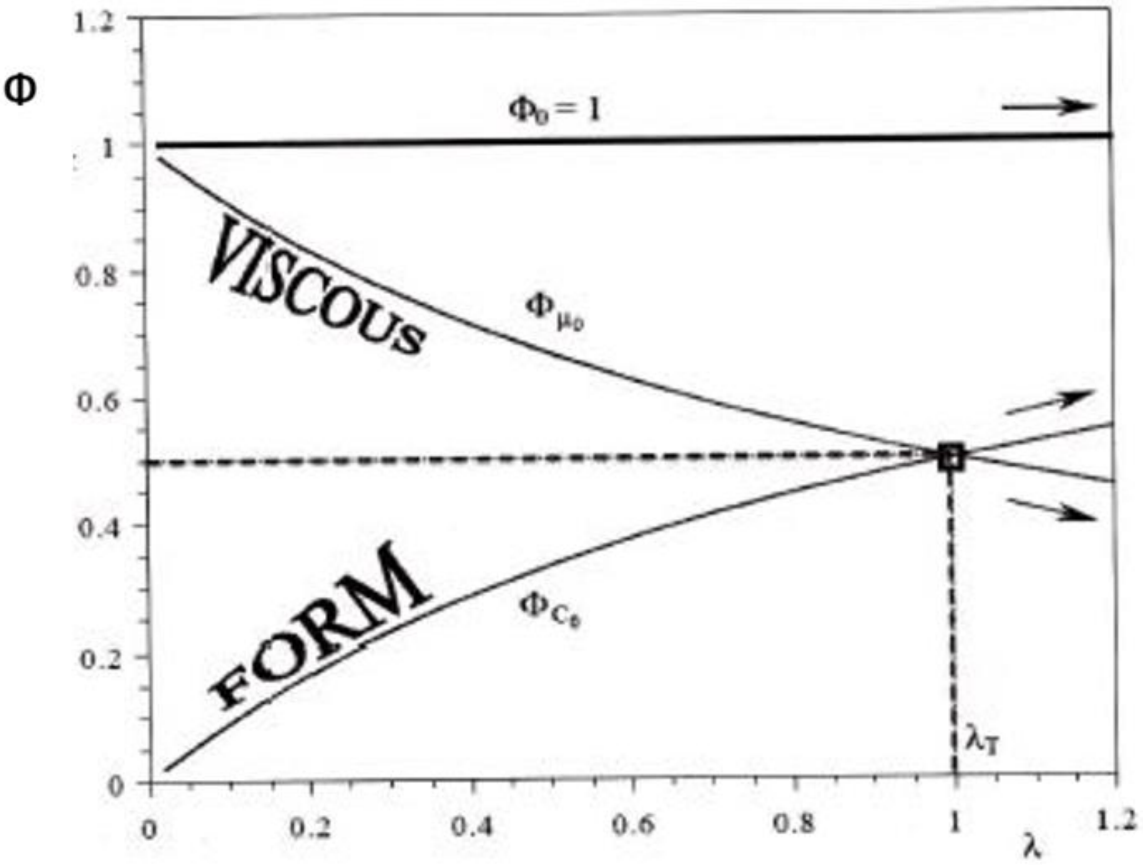


Determining the Dominate Drag

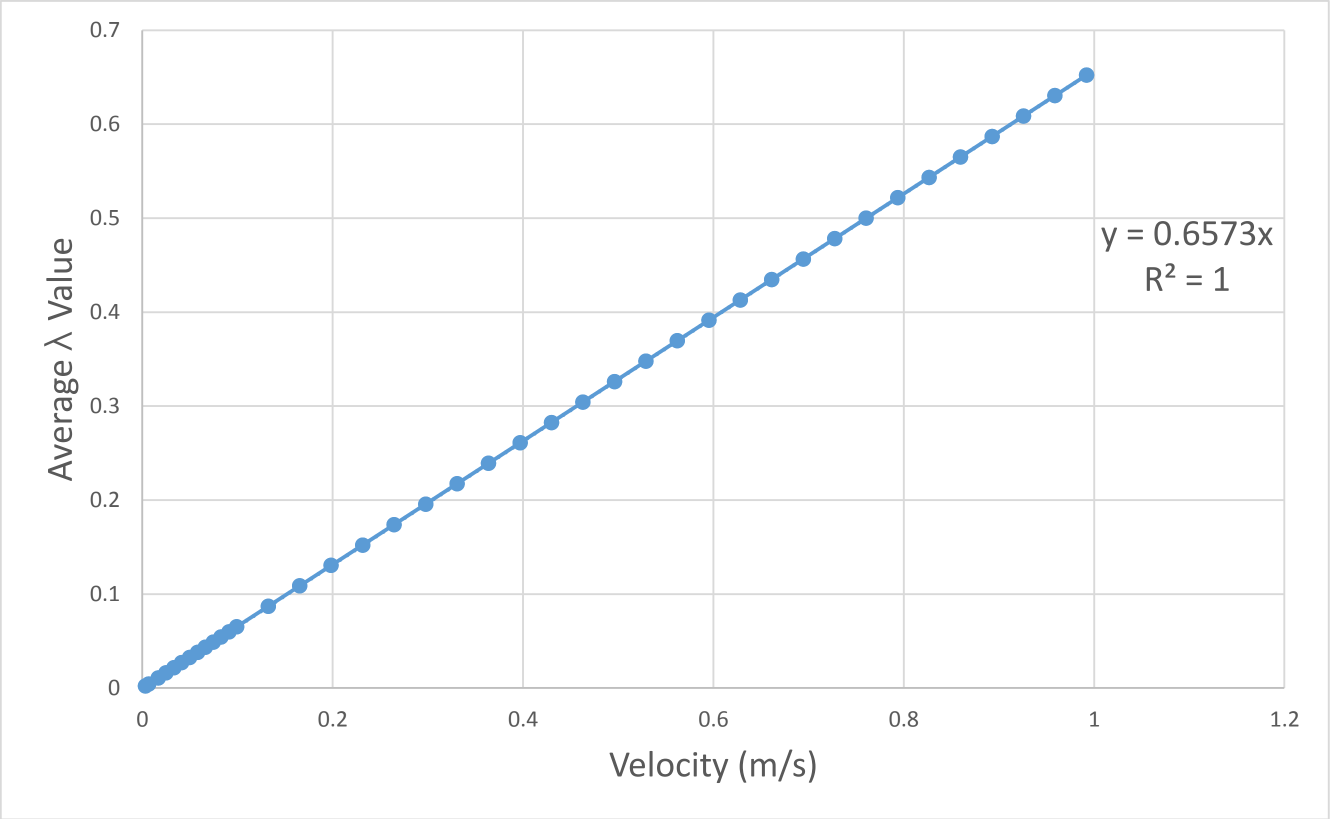
- Using: $\lambda = (\rho * C_0 * K_0 / \mu_0) * U$ [3]
- When $\lambda > 1$, flow has departed from Darcy flow and is form dominated [3]
- When $\lambda < 1$, flow is viscous dominated [3]
- When $\lambda = 1$, flow is affected equally by form and viscous drag.



…Continued



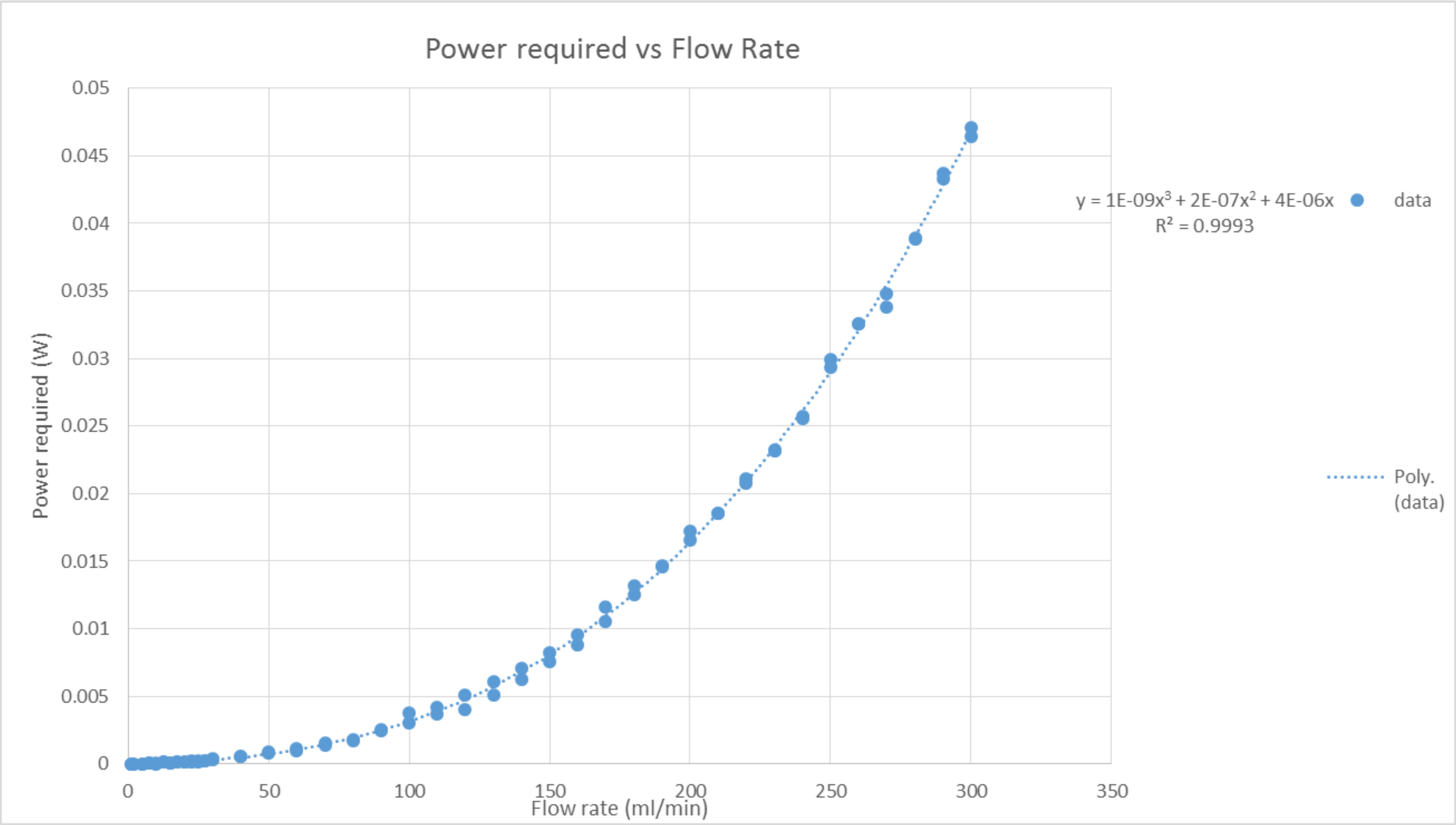
Φ
λ
$\Phi_0 = 1$
VISCOUS
Φ_{μ_0}
FORM
Φ_{C_0}
λ_T
0
0.2
0.4
0.6
0.8
1
1.2



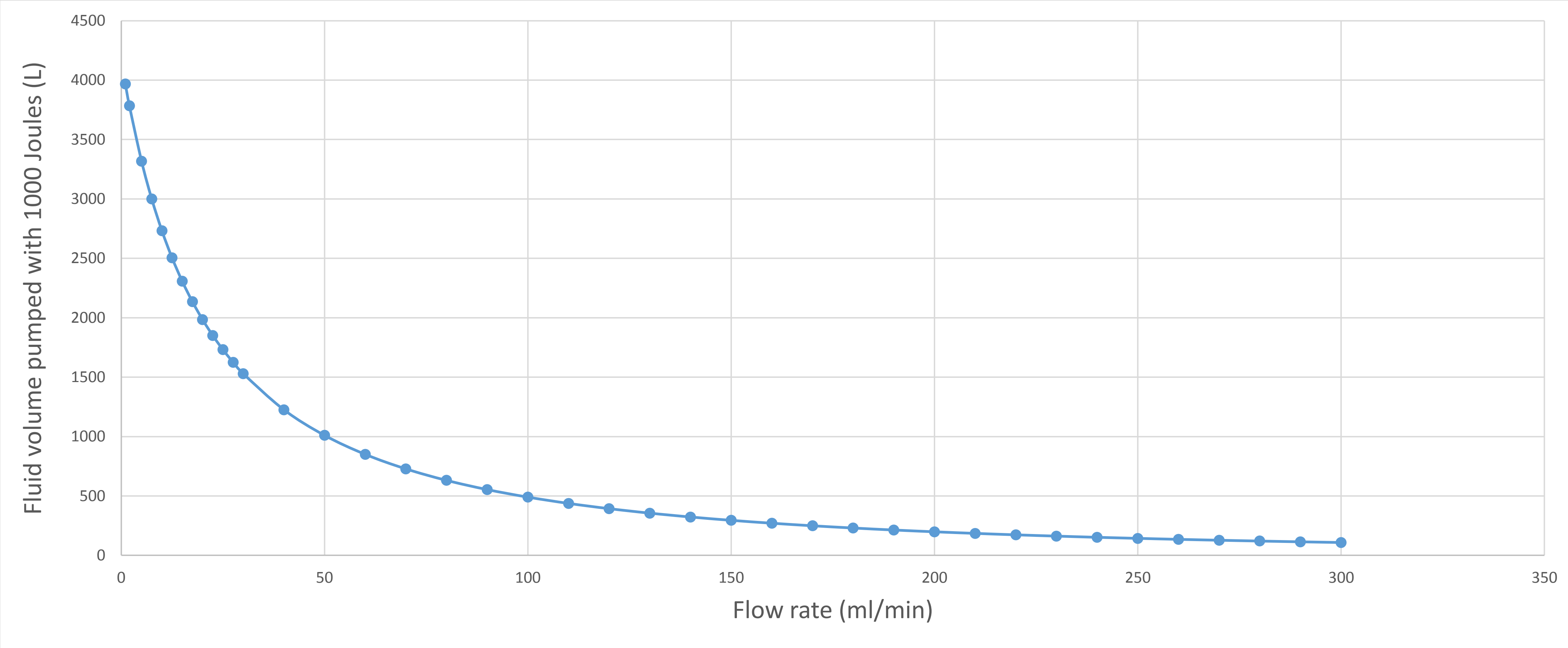
Average λ Value
Velocity (m/s)
y = 0.6573x
$R^2 = 1$
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.2
0.4
0.6
0.8
1
1.2

Power Required for Flow Through Porous Media

- Power (W) = ΔP * Volumetric flow rate [4]

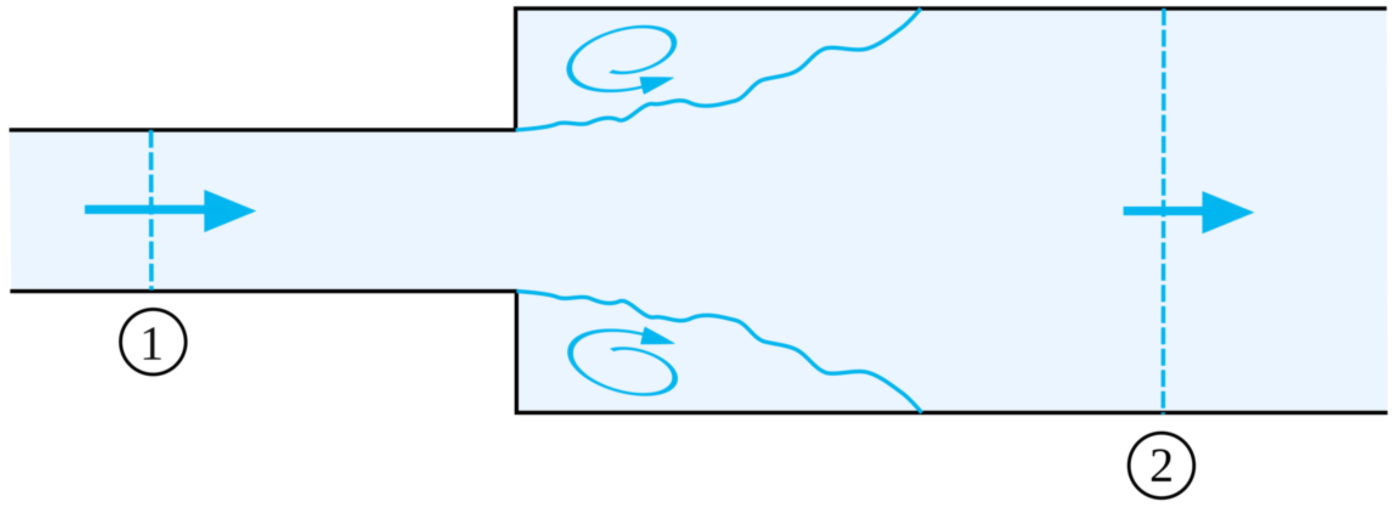


Fluid Volume Pumped vs. Flow Rate

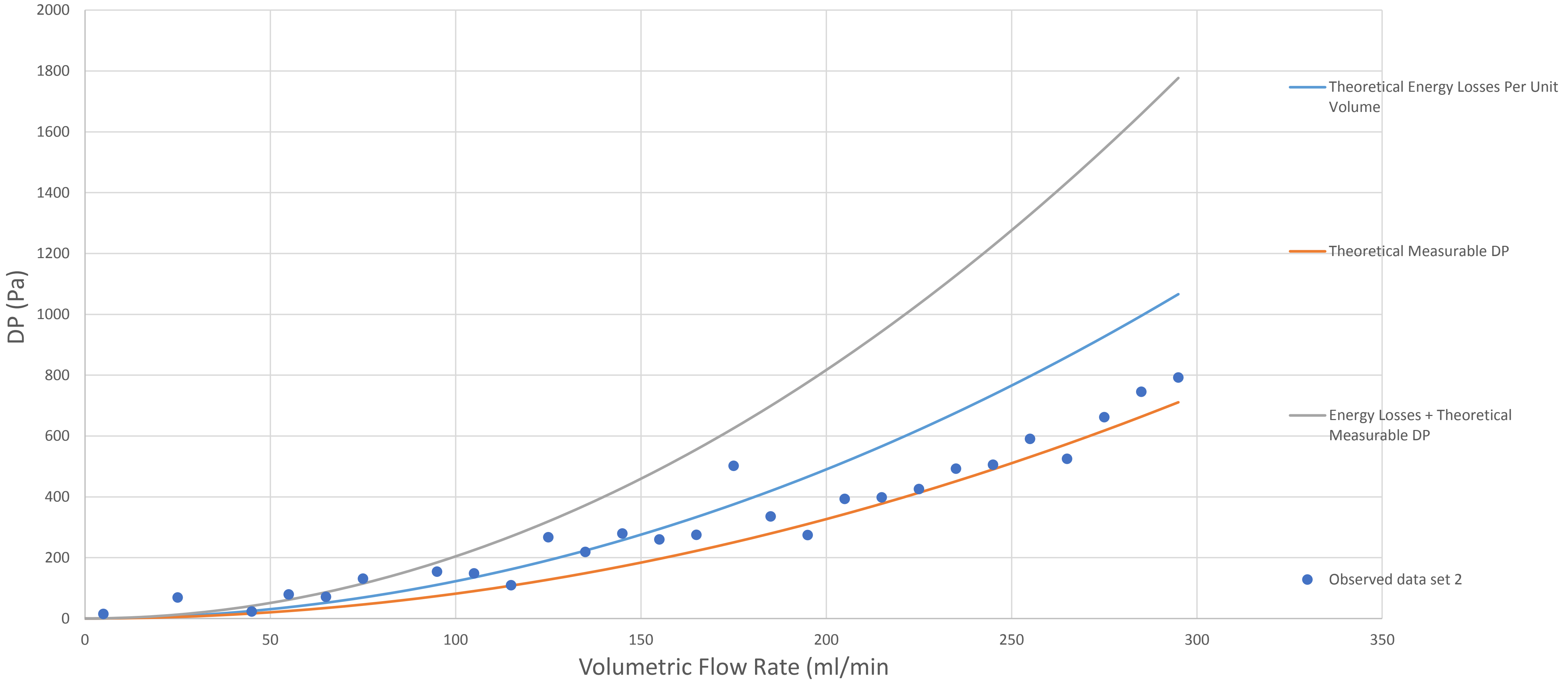


Expansion Test Section

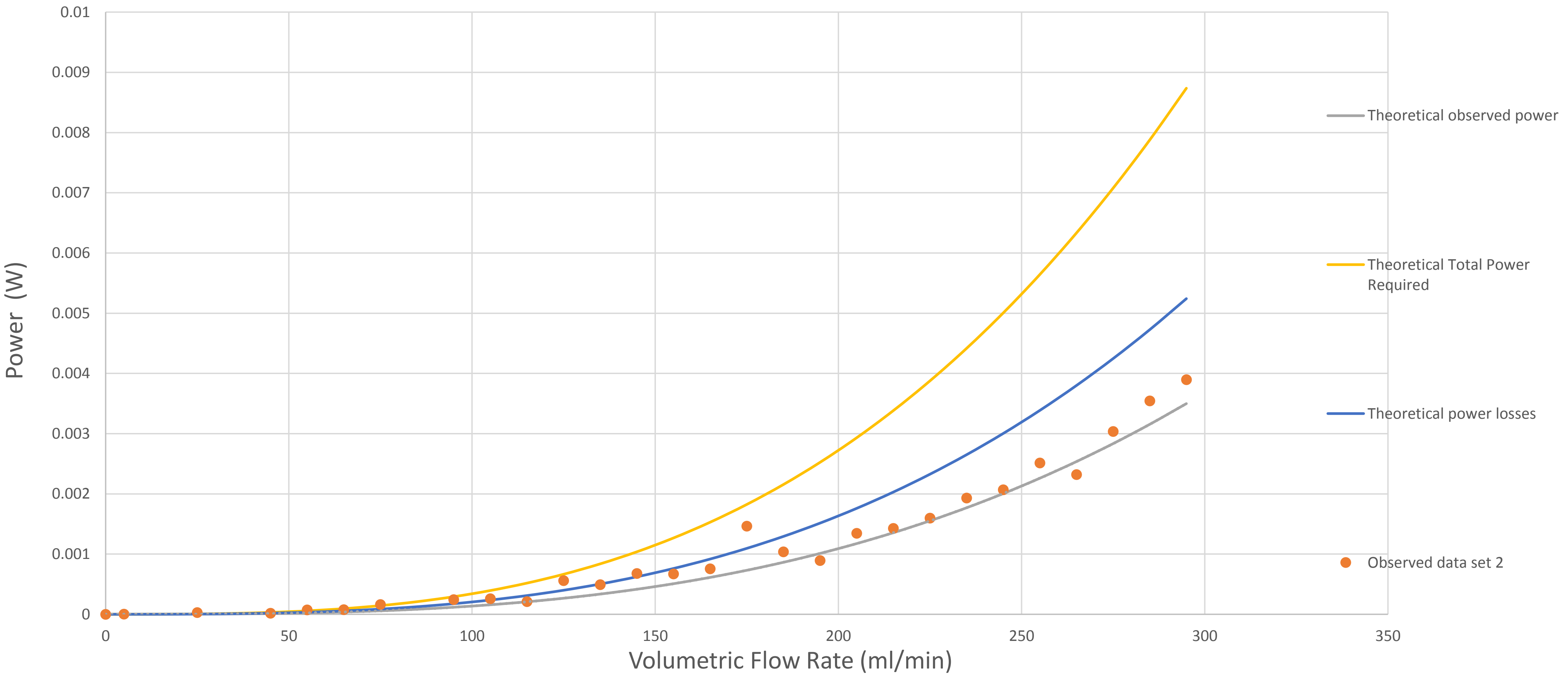
- Expansion area ratio of 1 to 4
- Borda–Carnot equation
- Energy loss per unit volume: $\Delta E_{e\ loss} = 0.5*\rho*(1-(A_1/A_2))*U_1^2$
- Theoretical measurable : $\Delta P_{e\ measured} = (A_1/A_2)*(1-(A_1/A_2))*\rho*U_1^2$
- Total needed to move liquid: $\Delta P_{e\ measured} + \Delta E_{e\ loss} = 0.5*\rho*(U_1^2-U_2^2)$



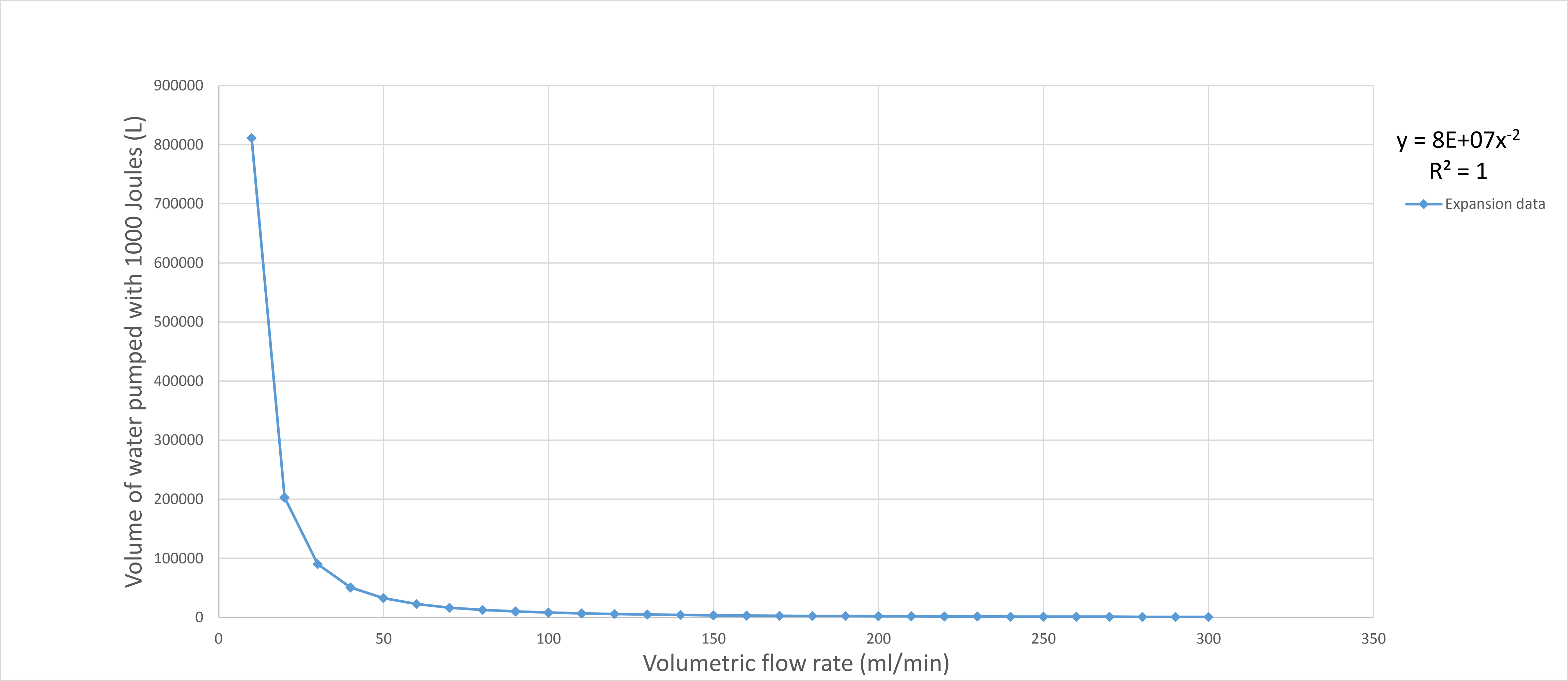
Expansion Differential Pressure vs. Flow Rate



Expansion Power Required vs. Flow Rate



Expansion Total Volume Moved With 1000 Joules



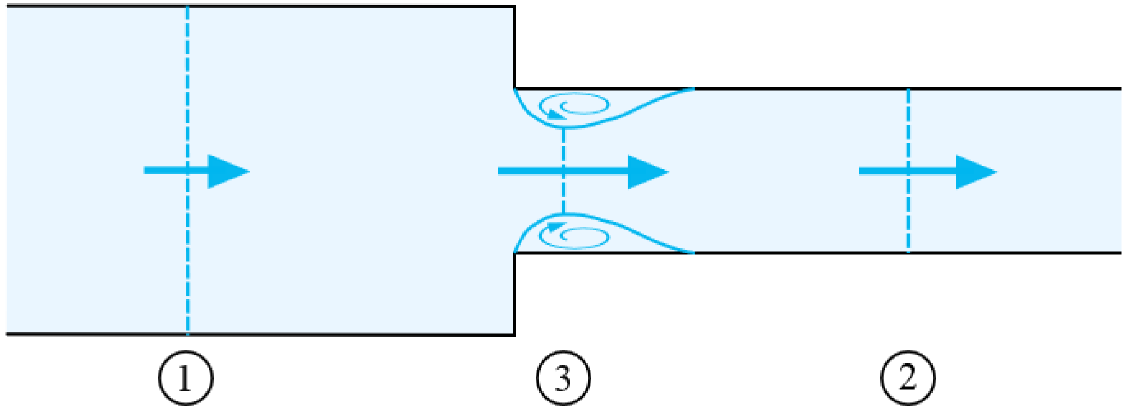
Contraction Test Section

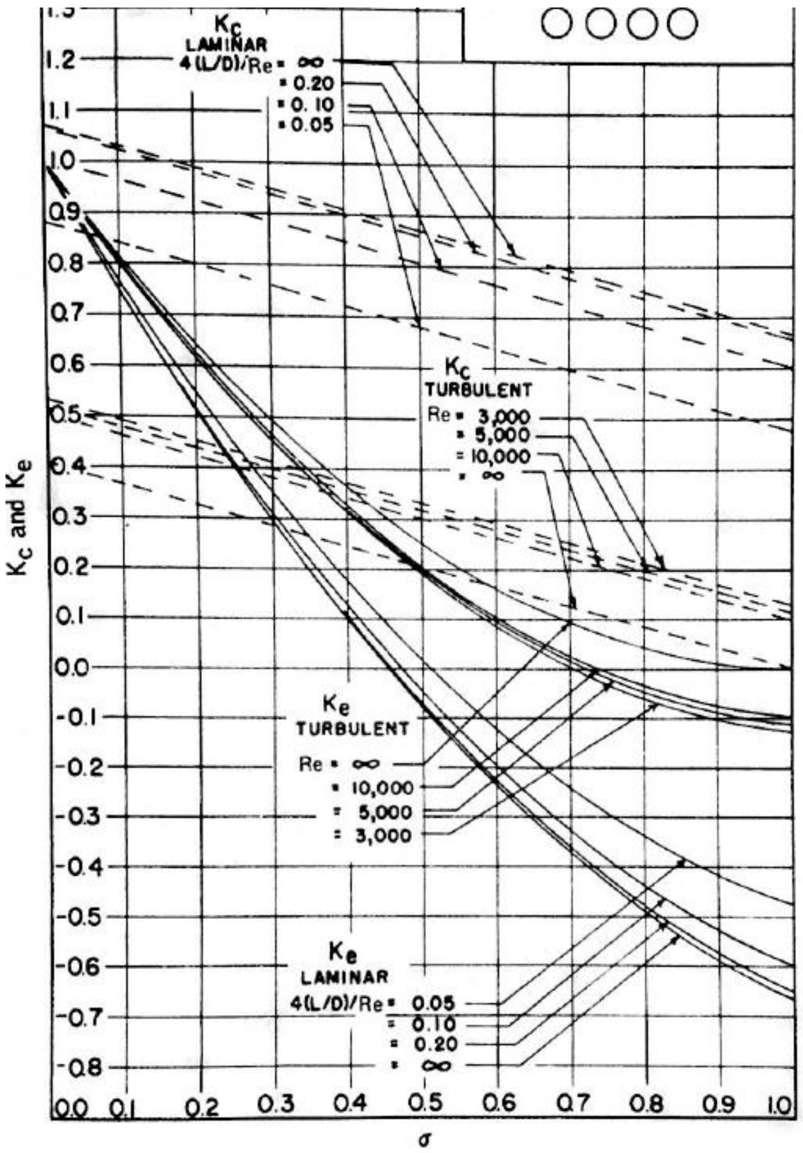
- Contraction area ratio of 4 to 1
- Theoretical measured ΔP calculated with:
- $\Delta P = (0.5\rho V^2)[(1-\sigma^2)+K_c]$, [5]

where: $\sigma = 0.25$

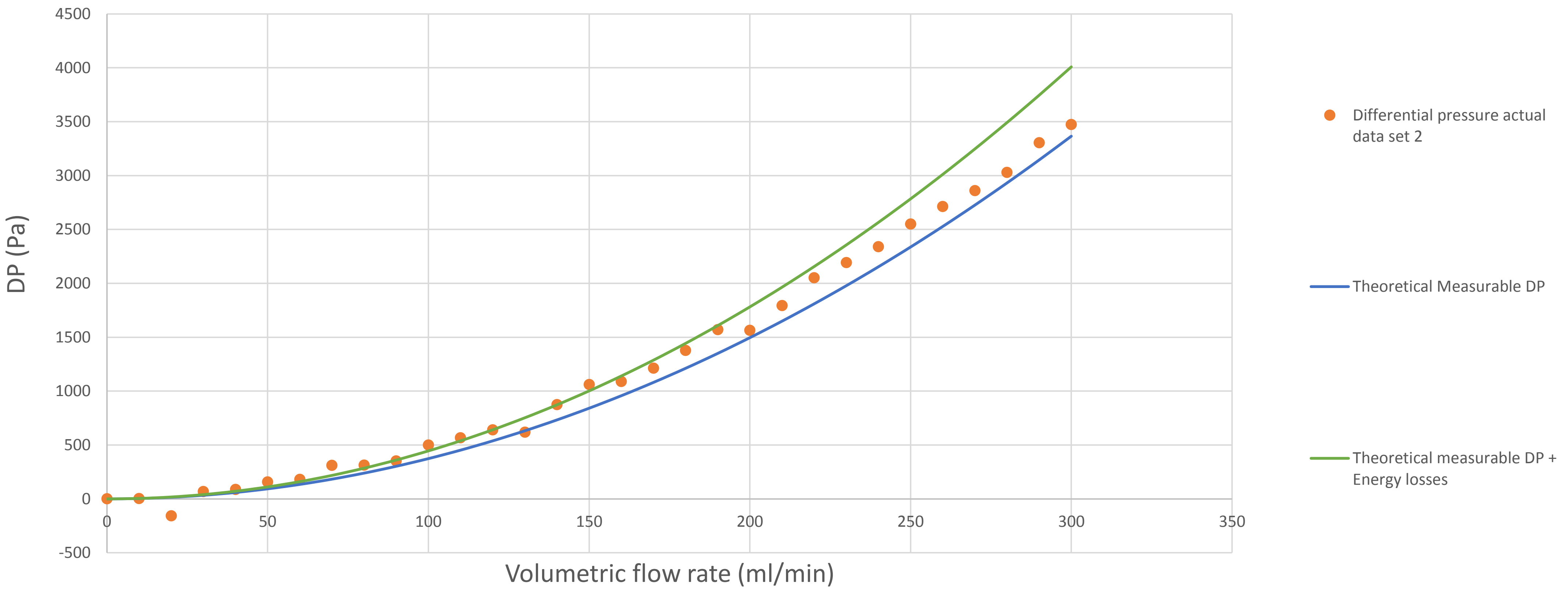
- $\Delta E_c = 0.5*\rho*[(1/a)-1]^2*U^2$

where: $a = 0.63 = 0.37*(A_2/A_1)^3$

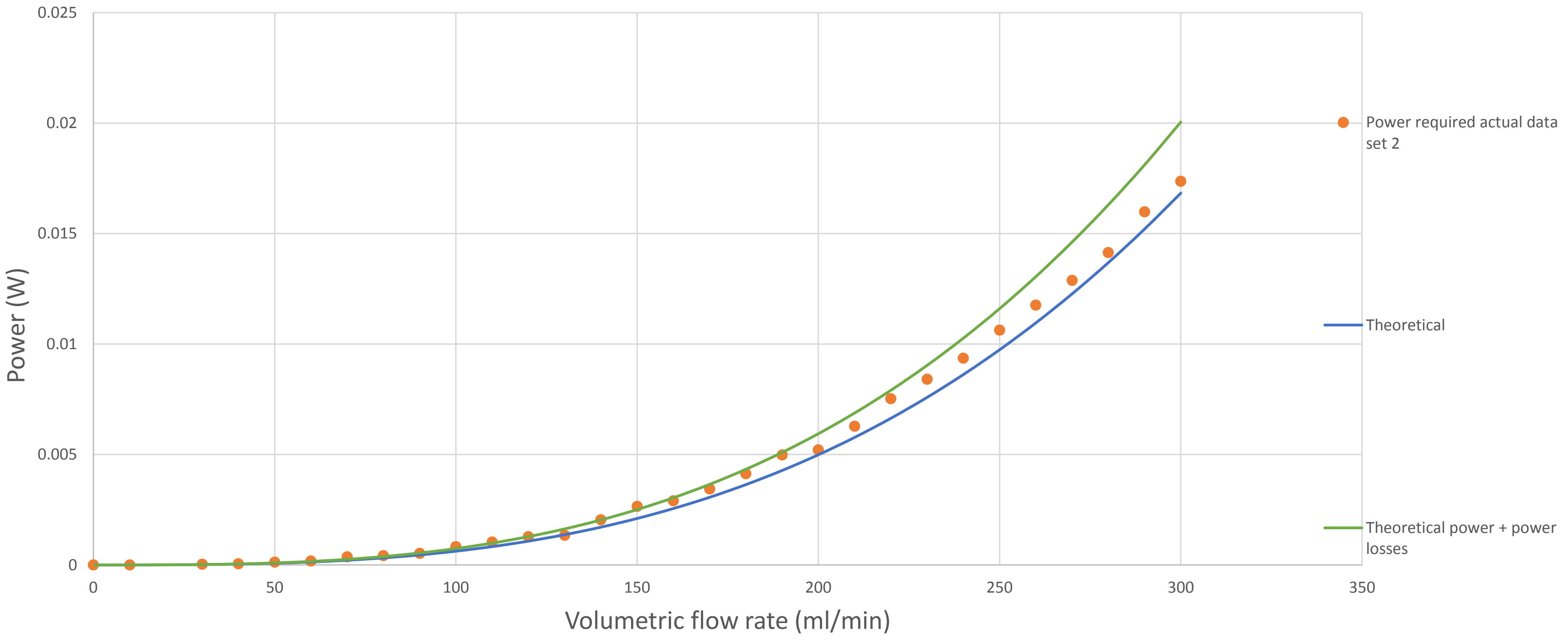




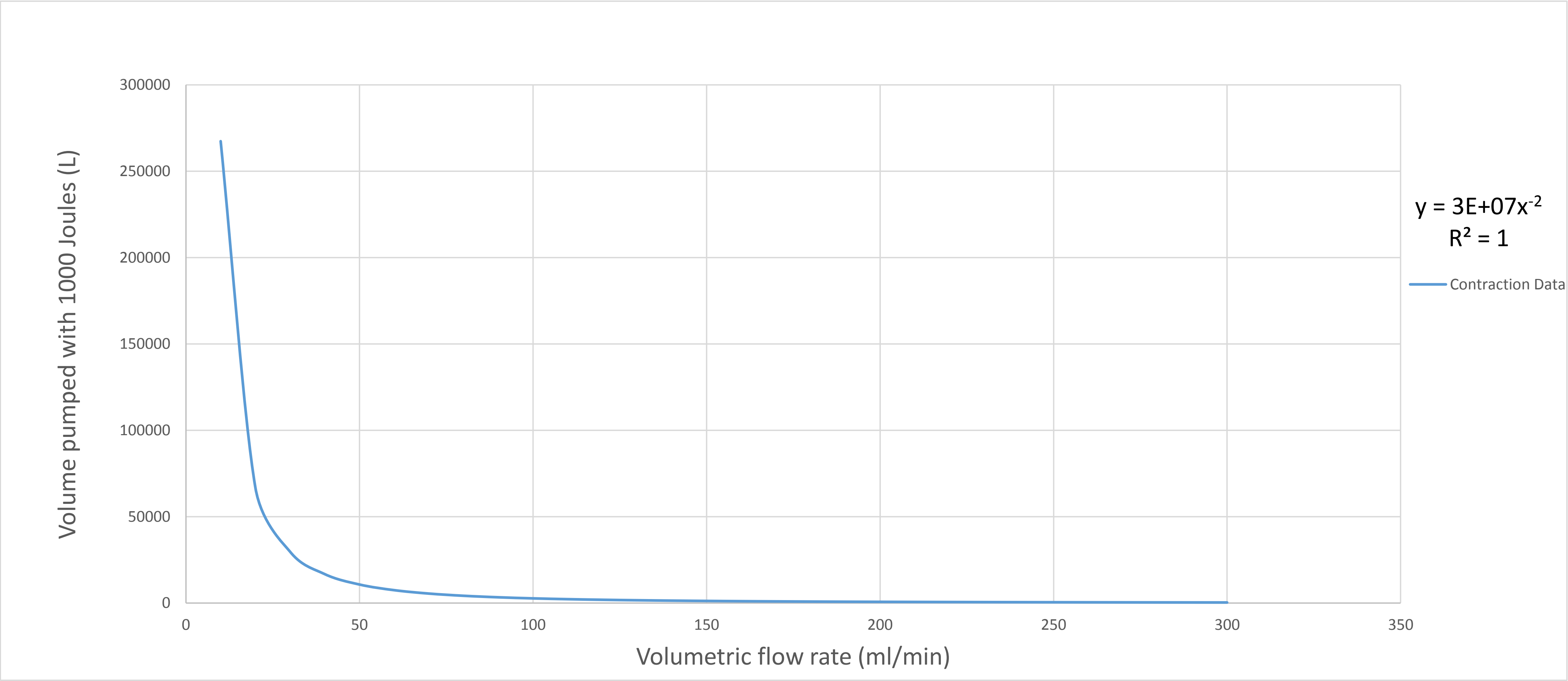
Contraction DP Using U = 1.98 m/s and Laminar Assumptions K_c=0.78 Including Losses



Contraction Required Power Using U = 1.98 m/s and Laminar Assumptions K_c=0.78 Including Losses

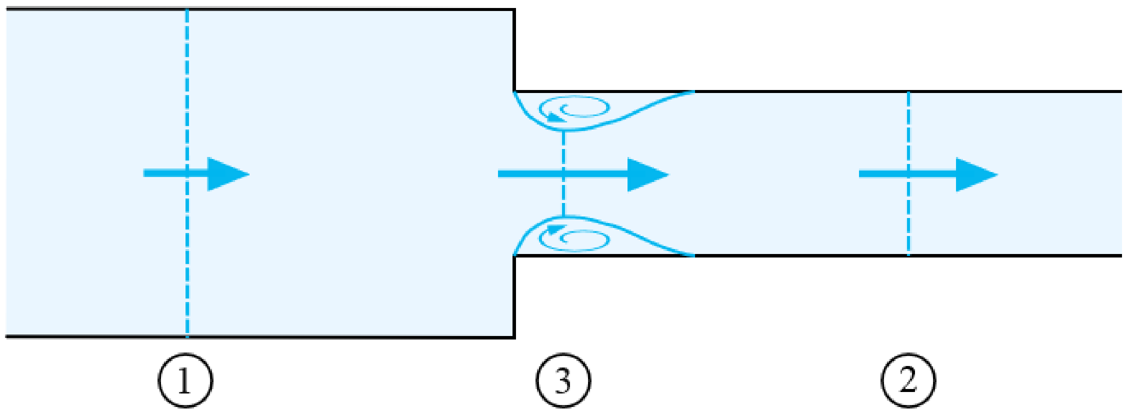


Contraction Volume Pumped with 1000 Joules



Contraction Conclusions

- Using the higher velocity (1.98 m/s) and laminar ($K_c = 0.78$) aligned best with the empirical data.
- To achieve a fully turbulent environment (Re = 10,000), a velocity of 5.7 m/s is needed, which is 288% higher than the maximum rate available with the current syringe pump and test section.



Simplified Differential Pressure Equations

- ΔP_{porous} = (L)*[(1.9*10^8 m^{-2})*μ*U + 236 m^{-1}*ρ*U^2]
- ΔP_e = (0.47)*ρ* U^2
- ΔP_c = (1.02)*ρ* U^2

Simplified Required Energy Equations

- $E_{porous} = (L)*\Lambda*[(1.9*10^8\ m^{-2})*\mu*U + 236\ m^{-1}*\rho*U^2]$

- $E_e = \Lambda*(0.47)*\rho*\ U^2$

- $E_c = \Lambda*(1.02)*\rho*\ U^2$

Simplified Required Power Equations

- $\delta E/\delta t_{porous}$ = (L)*[961*μ*U^2 + 0.0012 m*ρ*U^3]

- $\delta E/\delta t_e$ = (1.2*10^{-6} m^2)* (ρ)* U^3

- $\delta E/\delta t_c$ = (2.6*10^{-6} m^2)* (ρ) * U^3

Final Conclusions

- A system was designed, built, and calibrated to test a wide variety of fluids and conditions.
- 2.2 times more power, energy, and ΔP are required to flow through the contraction than the expansion.
- Minimizing flow rate minimized ΔP, energy and power needed to flow the liquid.
- Maximizing flow rate maximized ΔP, energy and power needed to flow the liquid.
- ΔP_{porous} is a function of $(U + U^2)$. ΔP_e and ΔP_c are functions of U^2.
- $\delta E/\delta t_{porous}$ is a function of $(U^2 + U^3)$. $\delta E/\delta t_e$ and $\delta E/\delta t_c$ are functions of U^3.

Thank You!

- NASA North Dakota Space Grant Consortium
- NASA ND EPSCoR
- UND Mechanical Engineering Department
- Dr. Clement Tang
- Dr. Surojit Gupta
- Dr. Nanak Grewal

References

- [1] Khaled and Vafai, 2003
- [2] Tang, 2014
- [3] Narasimhan, 2013
- [4] Bergman et al, 2011
- [5] Kays and London, 1998

Any Questions??