Mobile Phone Application For Compressor Performance

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Project Sponsor
Russell Wilburn, *Industry Advisor*
General Electric Oil & Gas

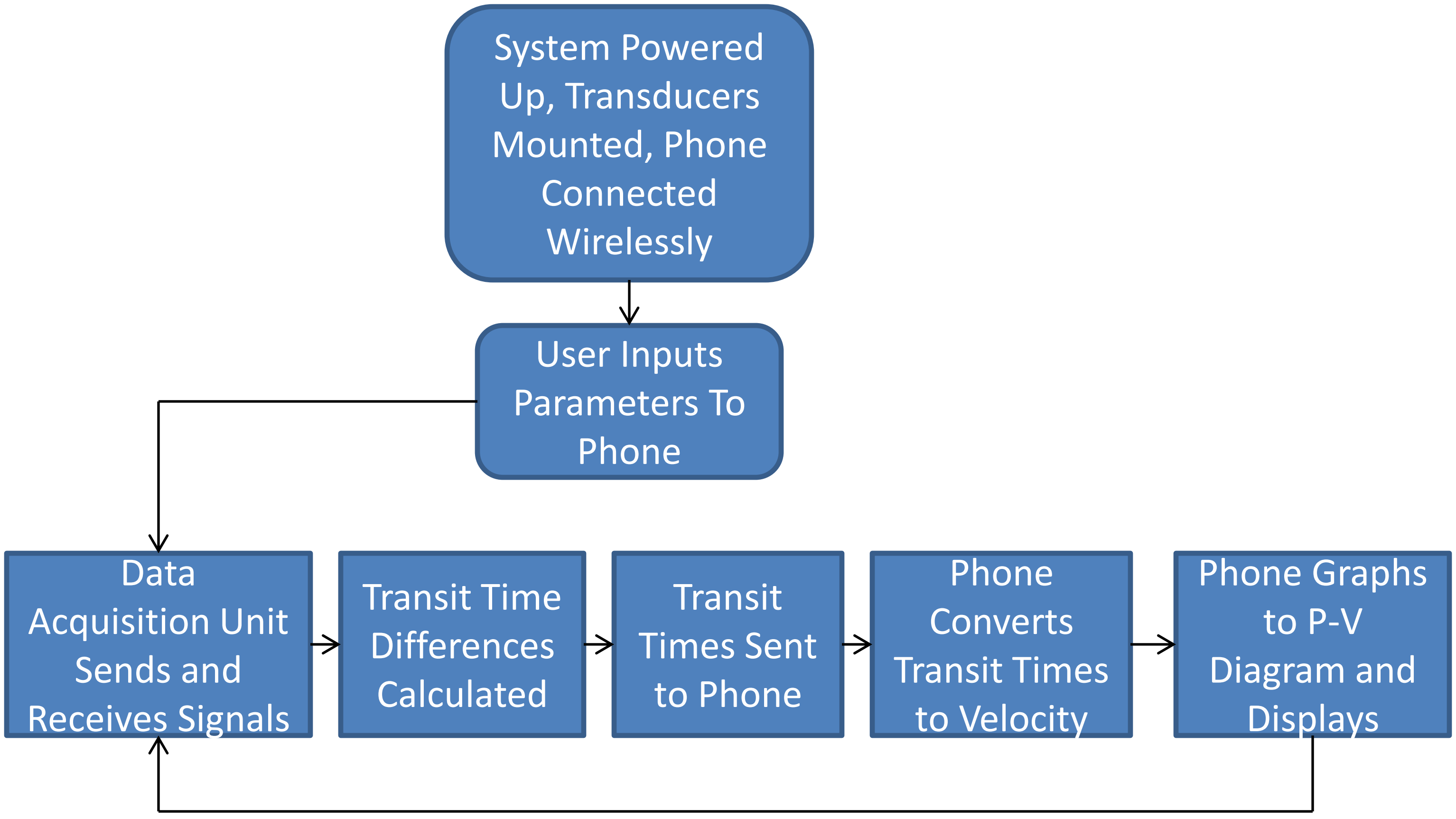
Scope of Project

- Diagnostic tools are already being used by GE for compressor performance, but they…
  - Are too expensive
  - Are time consuming
  - Require customer to power down compressor
- Create a non-intrusive flow velocity measurement system to interface with an Android mobile phone application

Scope of Project

- Customer Needs
  - No modifications to pipes; non-intrusive method
  - Transfer data wirelessly to an Android phone
  - Software must collect, store and display data
  - Assembly time less than 5 minutes
  - Working demo

Functional Diagram



What Are Ultrasonic Transducers?

- Generate frequencies ~18 kHz and above by turning electrical signals into sound via piezoelectric crystals

- Slowing of the ultrasonic signal is dictated by the properties of the medium, including its motion
- This slowing can be calculated using several methods
- Fulfills design spec. of unintrusive measurement

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Functional Diagram
Sensor Selection
Processing and Communication
Theoretical Rationale
Mobile Application
Mounting and Housing Unit
Test Apparatus
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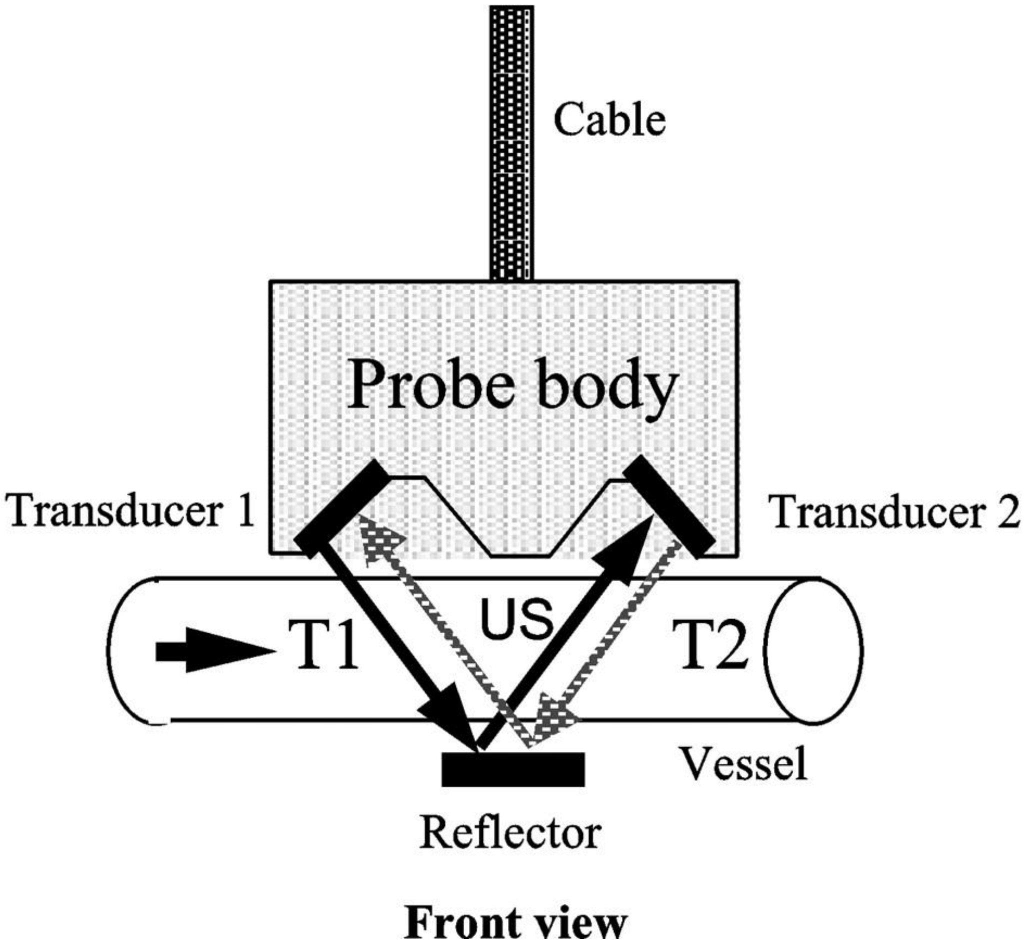
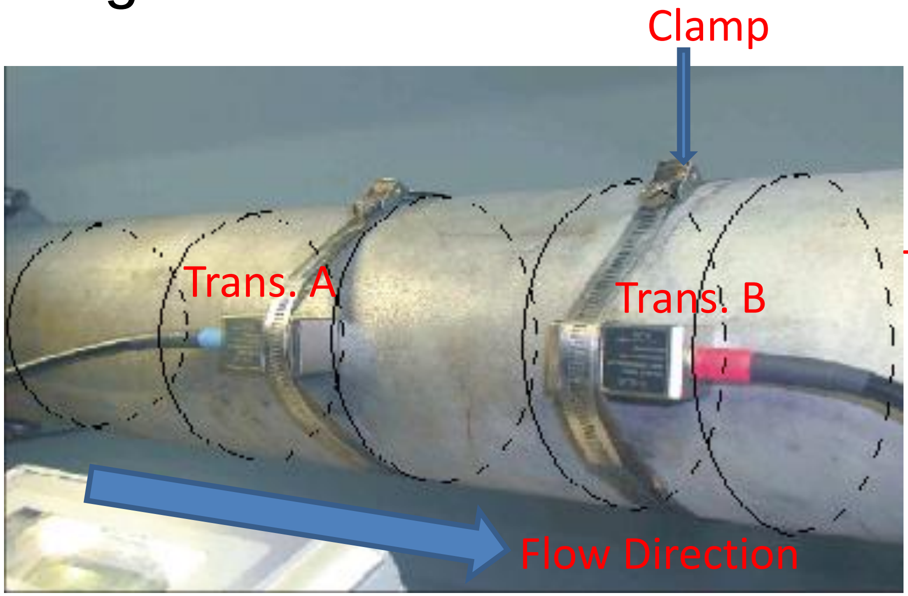
Conclusion

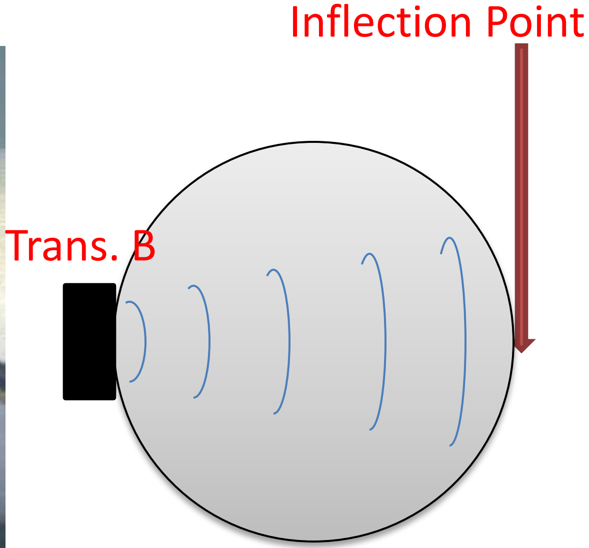
Transit-Time Flow Concept



Transit-Time Flow Concept

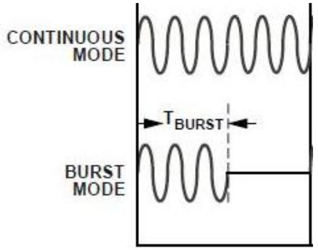
- Ultrasonic waves exit emitter A and are reflected off the inflection point into emitter B
- Signal is slowed based on fluid properties and velocity of flow
- Signal will flow faster in the direction of the flow





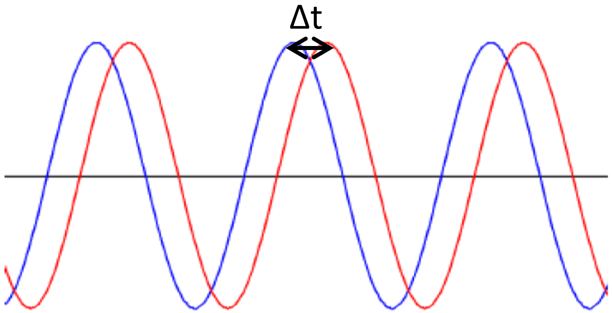
Signal Burst Method

- Bursts of signal can be sent through transducers with the microprocessor waiting for input



- Used on Fuji Portaflow X ultrasonic flow meter

Cross Correlation Method

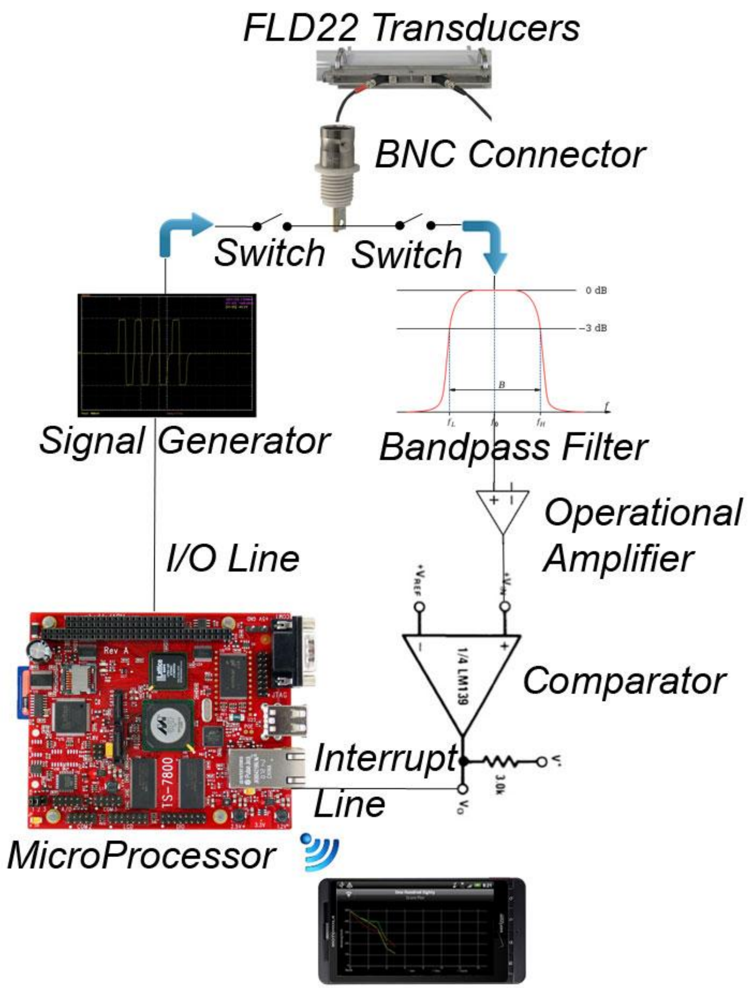


- Shannon-Nyquist Theorem
- Reproduce the signal (red) and compare to initial signal (blue)

Concepts for Data Acquisition Unit

- Single-board PC or Microcontroller Unit?
  - Single-board PC contains a Field Programmable Gate Array
  - More time to setup operating system on Single-board PC
- Wi-Fi or Bluetooth?
  - Wi-Fi has greater range
  - Added security with Wi-Fi

System Level Diagram



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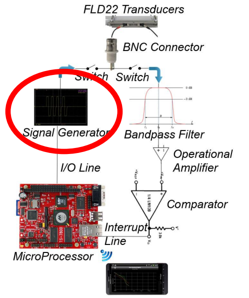
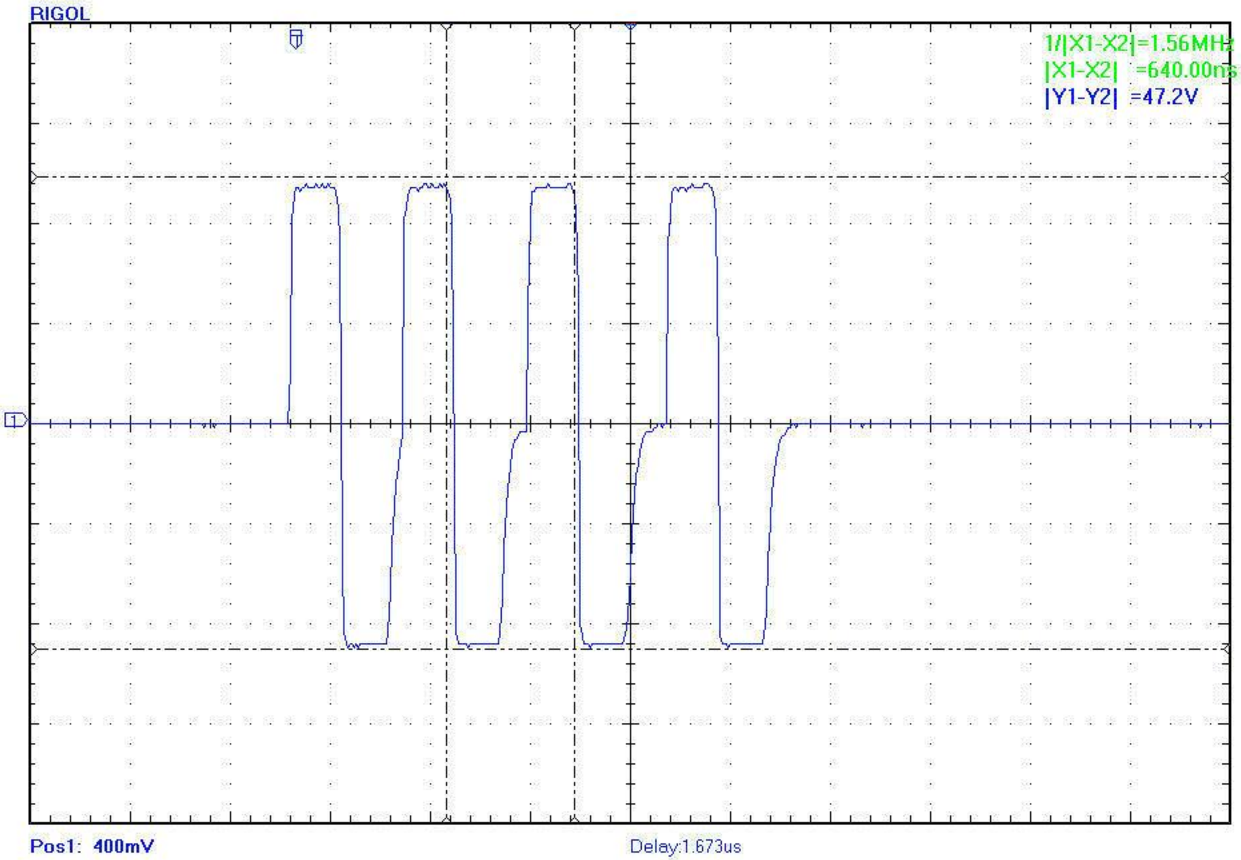
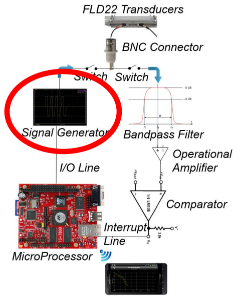
Signal Generation



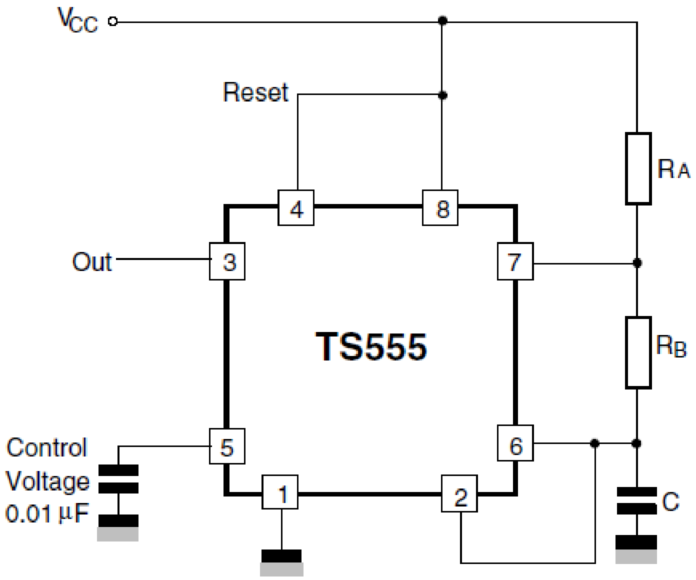


- Signal sent from Fuji Portaflow X data acquisition unit
- To be reproduced on our custom unit

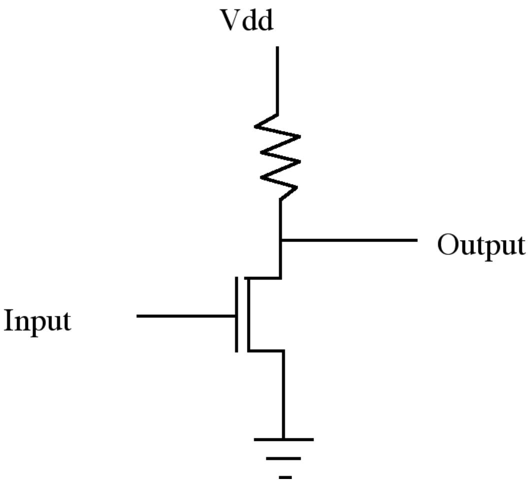
Signal Generation



555 Oscillator



NMOS Inverter Amplifier



- TS555 generates 2 MHz square wave
- Output from pin 3 is amplified to 50V by NMOS inverter amplifier

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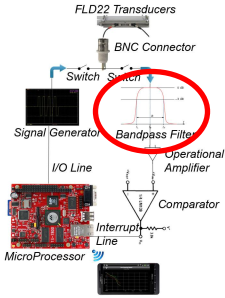
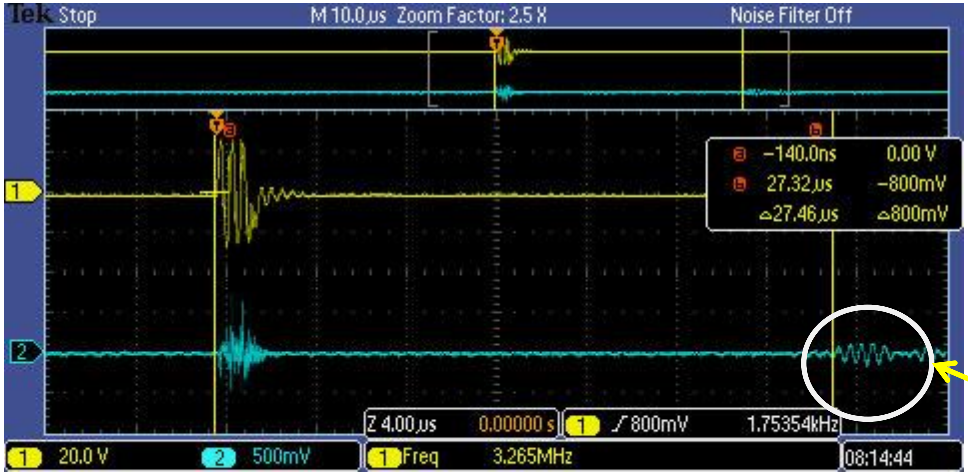
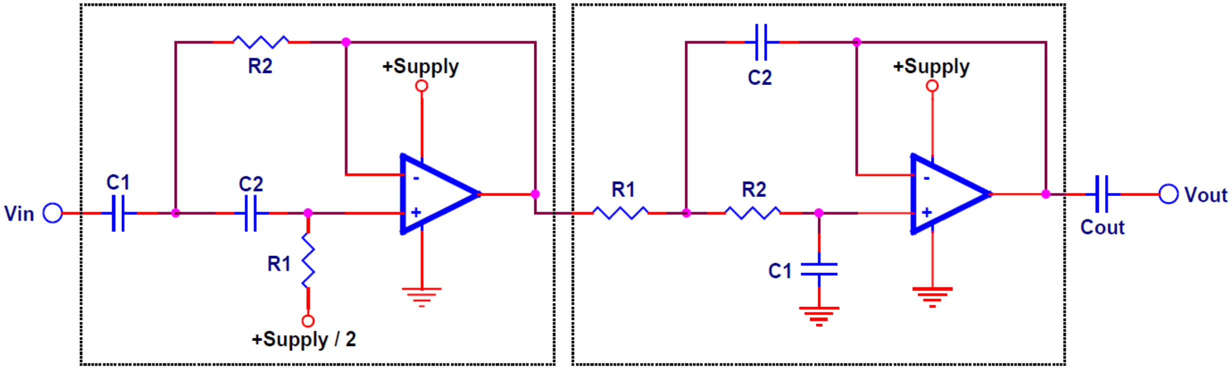
Signal Detection





Signal circled that needs to be detected

Band Pass Filter For 1.5Mhz-2.5Mhz



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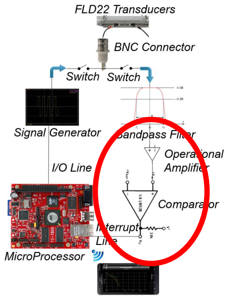
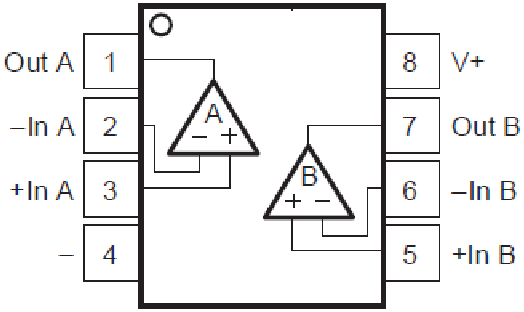


Operational Amplifier

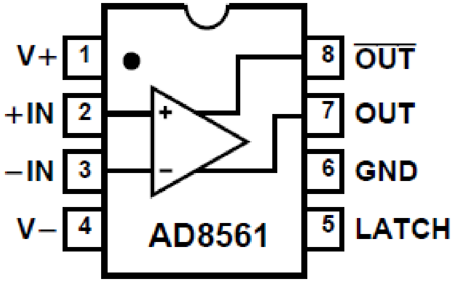
OPA2350



DIP–8, SO–8, MSOP–8

- Wide Bandwidth: 38MHz

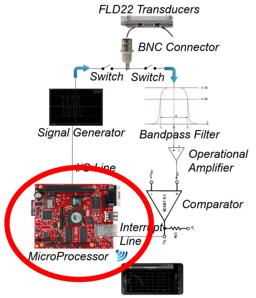
Comparator

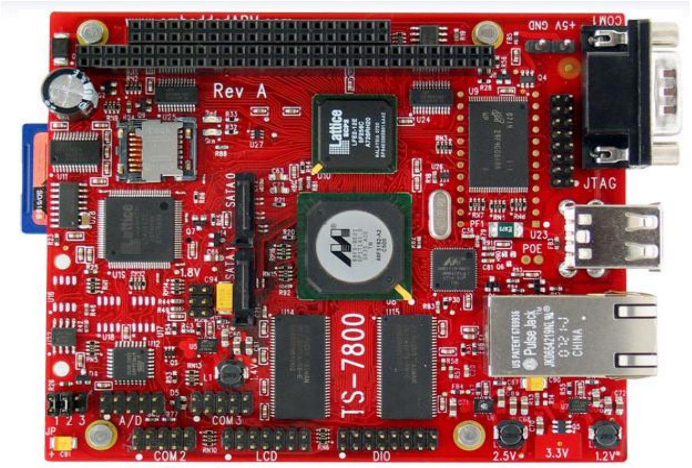


- 7 ns Propagation Delay at 5V
- Single Supply Operation: 3V to 10V

- Simple non-inverting amplifier configuration used for op amp
- Comparator will be used to set off interrupt on microprocessor

Data Acquisition Unit's Processor





TS-7800 Single Board PC

- 500 MHz ARM9 CPU
- 12,000 LUT programmable FPGA
- Runs Kernel 2.6 and Debian by default

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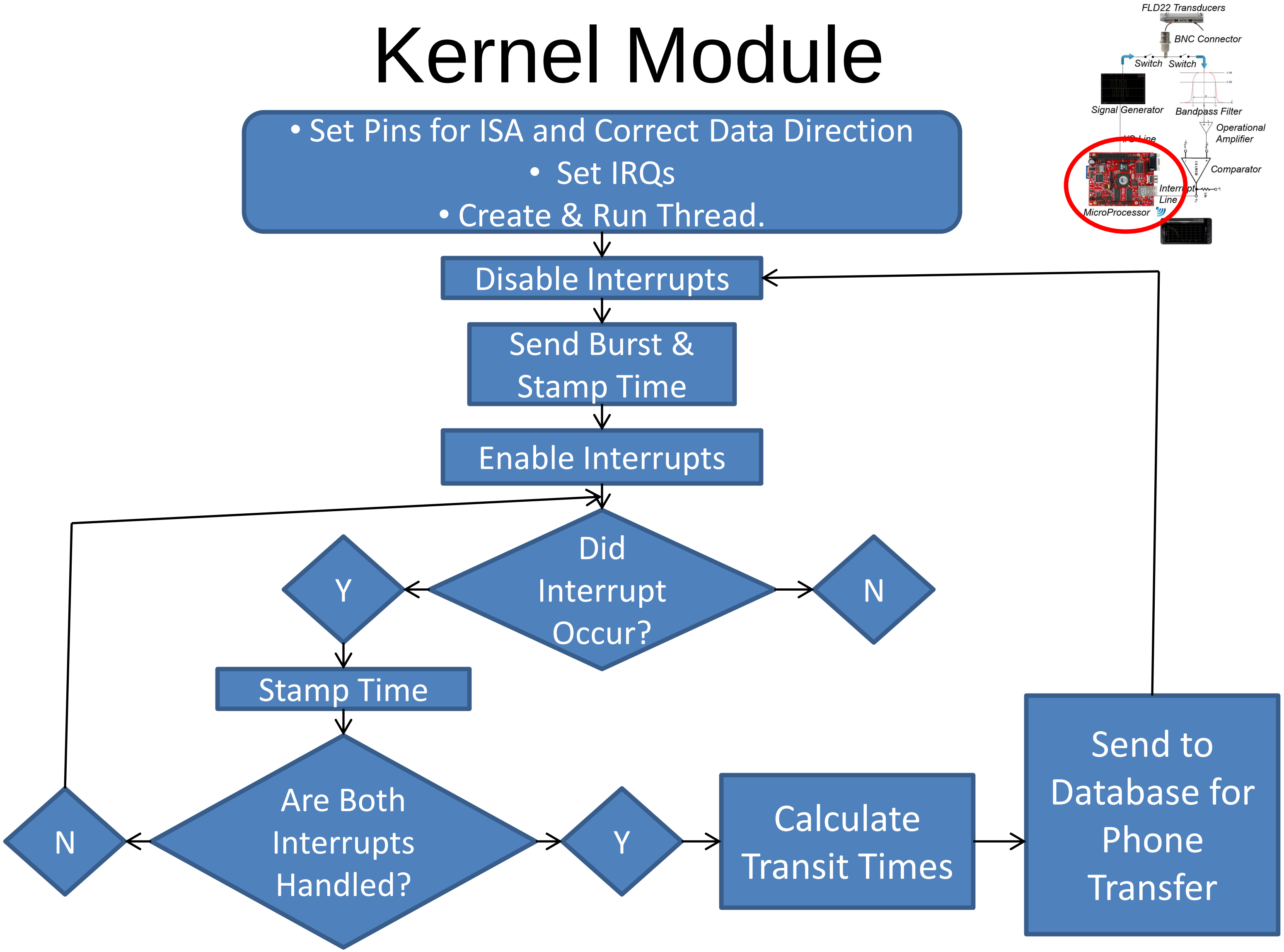
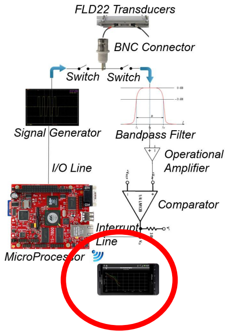
Kernel Module



Communication To Phone



ThinkPenguin Wireless N USB Adapter

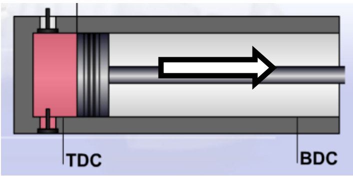
- Data Transfer Rate - Up to 300Mbps
- Security - WEP, WPA. WPA2, WPA-PSK/WPA2-PSK(TKIP/AES)
- Required custom kernel module for 2.6.34
- Driver was cross-compiled for ARM on separate Linux machine

Compressor Flow Characteristics

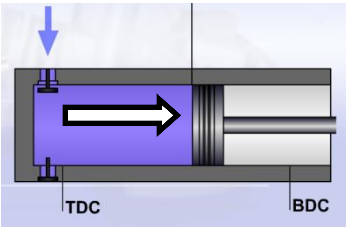
- Need two key parameters
  1. **Volumetric flow rate**
     - Velocity is measured
     - Pipe diameter is known, thus hydraulic cross-section
  2. **P-V Diagram**
     - Needed to begin diagnosis

P-V Diagram

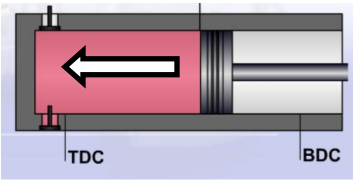
- **A-B:** Re-Expansion



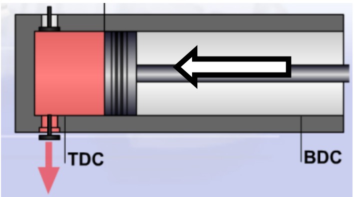
- **B-C:** Gas Intake

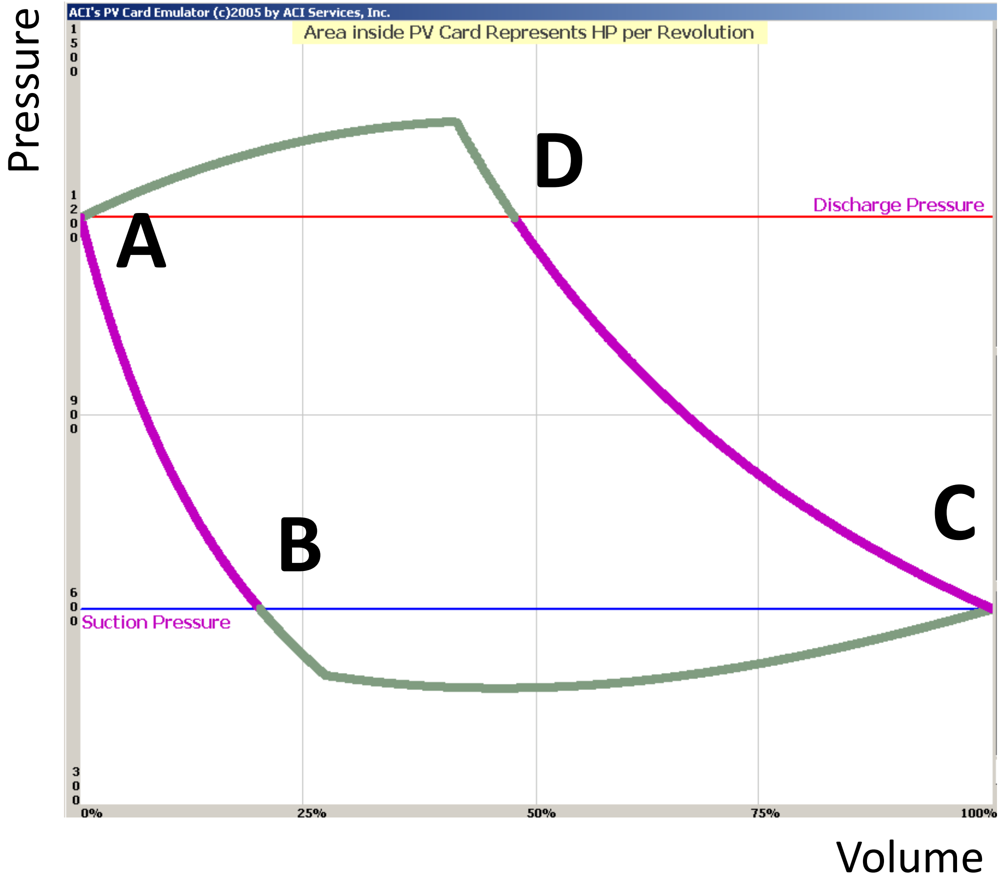


- **C-D:** Compression



- **D-A:** Gas Discharge





Calculating Pressure in Pipe

- Pressure in P-V diagram is static pressure
- Relationship between static pressures and temperatures in compressible fluid:

$$P_d = \frac{P_s}{\left(\frac{T_s}{T_d}\right)^{\frac{\gamma}{\gamma-1}}}$$

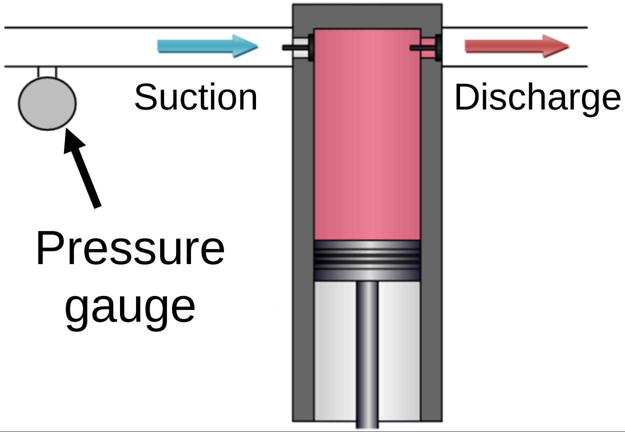
- T_s and P_s: temperature and static pressure in suction pipe near suction valve, respectively
- T_d and P_d: temperature and static pressure in discharge pipe near discharge valve, respectively
- Need ability to measure T_s, T_d and P_s
- Assume compressibility constant, $\gamma = 1.4$ (air)

Pressure Drop in Pipe

- Pressure drop in pipe between valve and pressure gauge:

$$\Delta p = f \cdot \frac{L}{D} \cdot \frac{1}{2} \rho V^2$$

- Where:
  - f = Darcy friction factor
  - L = distance between valve and pressure gauge
  - D = hydraulic diameter of pipe
  - ρ = density of the fluid
  - V = measured velocity of the fluid in the pipe



Pressure Drop in Pipe

- Darcy friction factor dependent on Reynolds Number:

$$Re = \frac{\rho V D}{\mu}$$

- μ = Dynamic viscosity of the fluid
- When considering laminar vs. turbulent flow, difference in pressure drop is small

  - For turbulent cases that are close to laminar
- So assume laminar flow:

$$f = \frac{64}{Re}$$

- No need for Moody charts
  - Preliminary diagnostic tool – no need for high precision
  - Much simpler for operator and App

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Pressure Drop in Pipe

- Pressure drop in pipe resolves to:

$$\Delta p = \frac{8\mu LV}{3D^2}$$

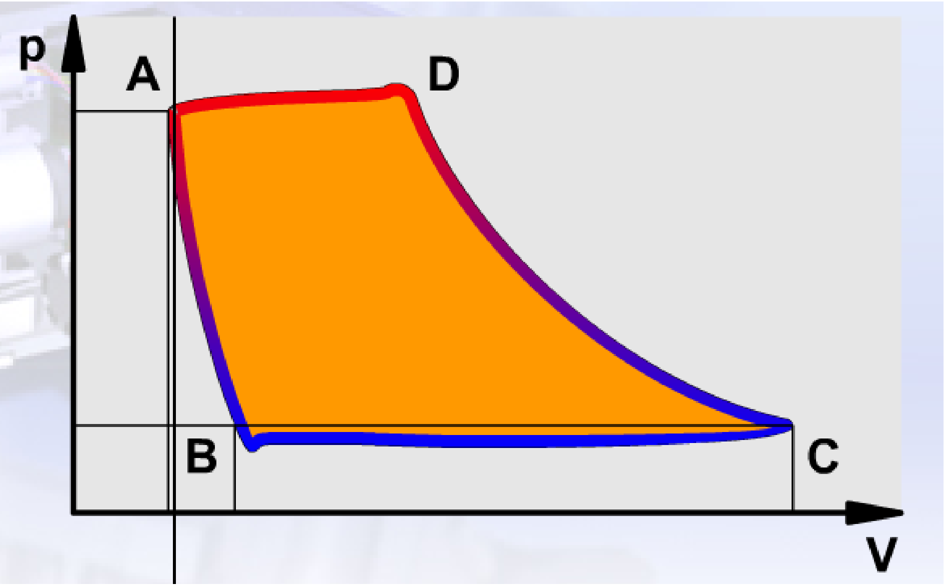
- Using common units:
  - *L* and *D* in inches, *V* in $\frac{ft}{s}$, *μ* in $\frac{lb_f \cdot s}{ft^2}$

- Thus, suction pressure:

$$P_s = P_{measured} + \Delta p$$

$$P_s = P_{0s} + \frac{8\mu LV_{suction}}{3D^2}$$

Generating P-V Curve Volumes



Nomenclature

- B: Bore diameter
- L: Stroke length
- r_c: compression ratio
- ω: rotational speed (RPM)
- TDC: Top Dead Center
- BDC: Bottom Dead Center

Fixed values

A

$$Vol_{TDC} = \frac{\frac{\pi}{4} \cdot B^2 \cdot L}{r_c - 1}$$

C

$$Vol_{BDC} = Vol_{TDC} + \left(\frac{\pi}{4} \cdot B^2 \cdot L\right)$$

Live values

B

$$Vol_B = Vol_{BDC} - \frac{\dot{V}_{suction}}{\omega}$$

D

$$Vol_D = Vol_{TDC} + \frac{\dot{V}_{discharge}}{\omega}$$

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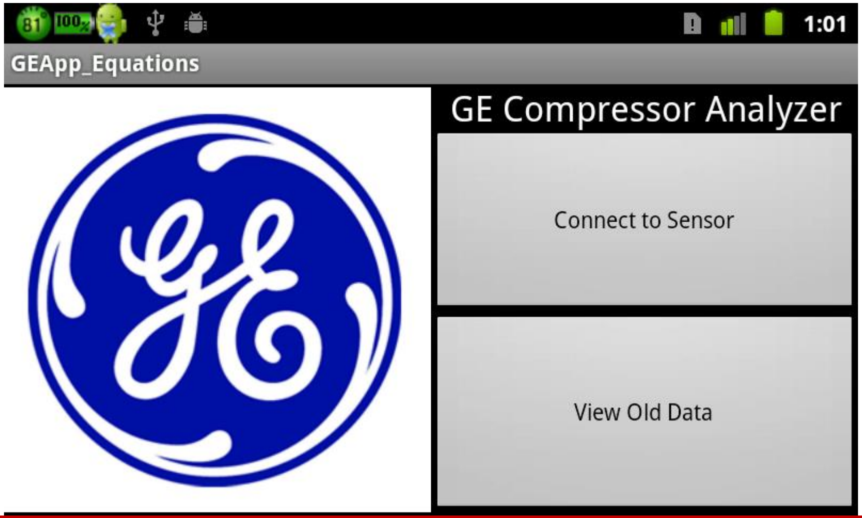
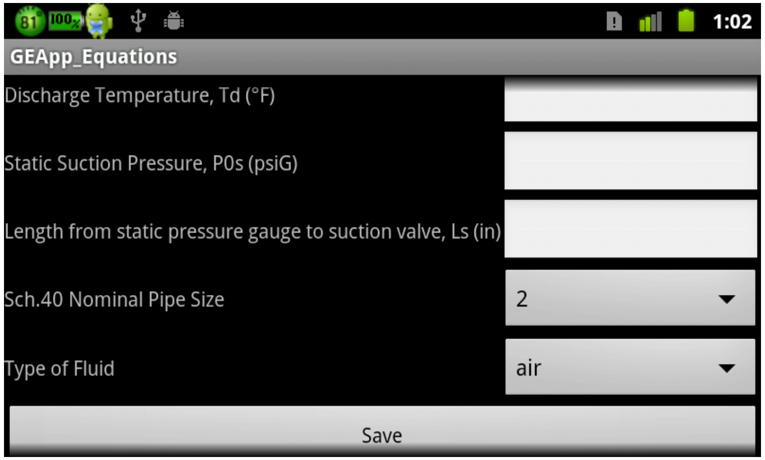
Mobile Application

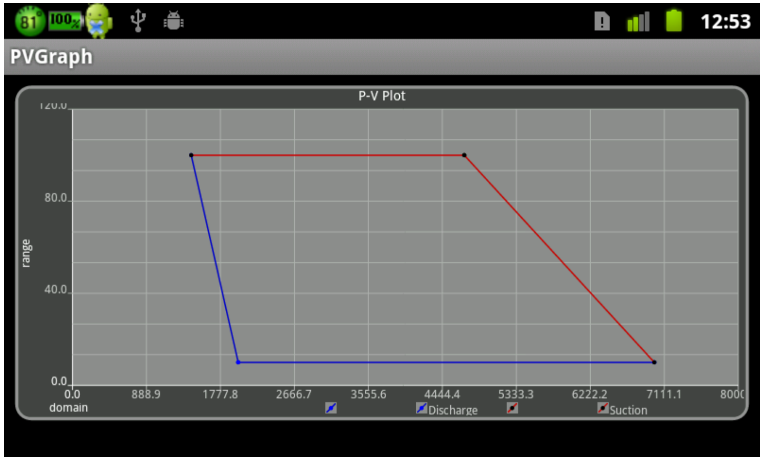
- Purpose of the app:
  - To collect data from Single Board PC
  - Store in database
  - Make calculations and display Flow Rate and PV graph



Graphical User Interface

- App currently takes user inputs and graphs a PV plot
  - Inputs: T_s, T_d, P_{0s}, L_s, select pipe size, select fluid
- Still perfecting equation implementations to make as accurate a graph as possible





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Current Implementation

- To minimize user inputs, lookup tables were coded into the database

Schedule 40 Pipe Sizes

Nominal Pipe Sizes	OD	ID
2	2.38	2.07
2.5	2.88	2.47
3	3.5	3.07
3.5	4	3.55
4	4.5	4.03
5	5.56	5.05
6	6.63	6.07
8	8.63	7.98
10	10.75	10.02
12	12.75	11.94
14	14	13.13
16	16	15

Air Density Table

temp	GP0	GP5	GP10
30	0.081	0.109	
40	0.08	0.107	
50	0.078	0.105	
60	0.076	0.102	
70	0.075	0.101	
80	0.074	0.099	
90	0.072	0.097	
100	0.071	0.095	
120	0.069	0.092	
140	0.066	0.089	
150	0.065	0.087	
200	0.06	0.081	
250	0.056	0.075	
300	0.052	0.07	
400	0.046	0.062	
500	0.041	0.056	

Future Implementation

- Adding security measures when looking at old data
- Sending data via email or web server when internet available
- Adding lookup table of known compressor specs, so user inputs compressor model

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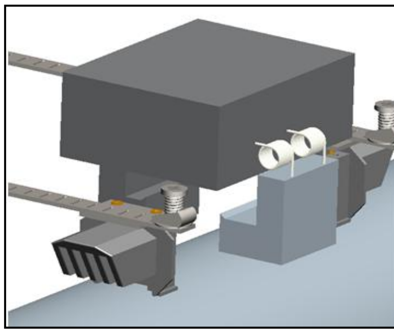
Attaching: Mounting and Housing Unit

Velcro Bands

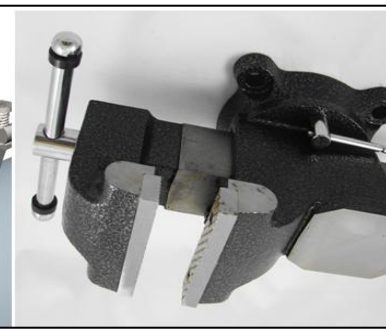
Quick Release Hose Clamps

Nylon interlocking clamps

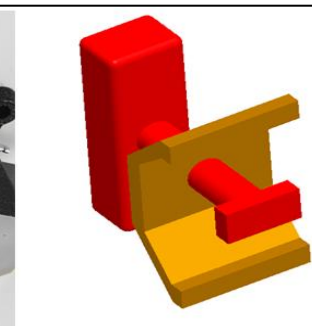
Magnetics



Spring Loaded Clips



Vise Attachment



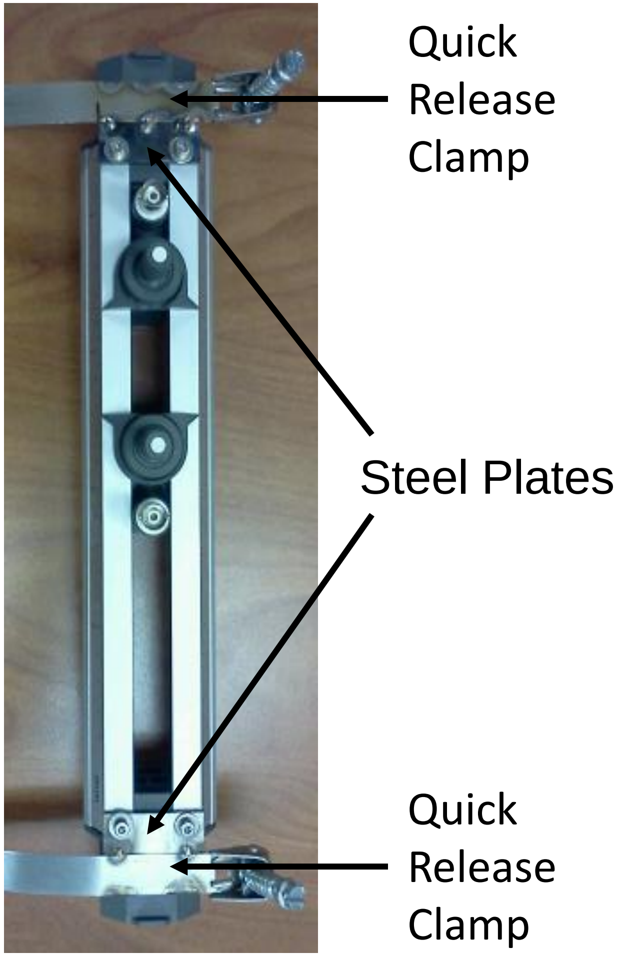
Key Attachments

Concept Selection for Mounting and Housing Unit

Pugh Matrix for Clamping System						
Design Features	Current Methods	Velcro Bands	Quick Release Clamps	Interlocking Clamps	Magnetics	Importance Rating
Cost	0	-1	-2	-3	-3	4.45
Lead Time	0	1	-1	-2	-1	1.73
Installation Time	0	-1	2	-2	3	18.33
Functionality	0	3	2	-1	-3	19.00
Usability	0	1	1	-1	2	17.00
Sum	0	3	2	-9	-2	
Total	0	52.94	81.02	-89.48	16.90	

- Same process done with housing unit

Final Concept and Results: Mounting System



Results

- Satisfies customer requirement
- Needed modification
  - Threaded holes needed to be unthreaded
  - Testing used two right sided clamping attachment

Final Concept and Results: Housing Unit

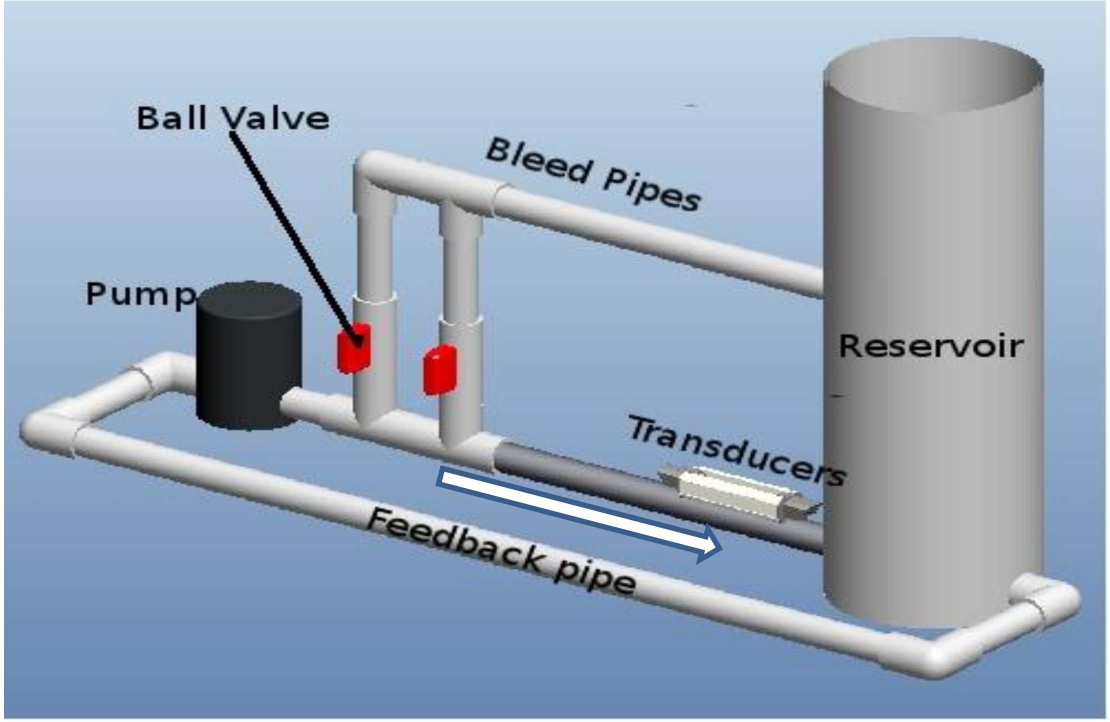
Final Concept

- Aluminum
- Has a ledge for bread boards (not shown)
- Fan for cooling
- Vents (Not shown)
- Four legs
- Top

Results

- Satisfies customer requirement
- Needed modification
  - Needed longer legs

Constant Velocity Test Apparatus



- 2 Ball Valves (3 total states)
- Variac (for variable voltage output) at 3 voltages
- 30 minutes for steady state

Flow Apparatus Calibration

Flow Situation	Both Closed	First Open	Both Open
Velocity (ft/s)	1.4	1.0	0.7

Change in velocity due to opened ball valves

Voltage (VAC)	60	90	120
Velocity (ft/s)	0.8	0.9	1.4

Change in velocity due to supply voltage level (valves closed)

Flow Situation	Both Closed			First Open			Both Open		
Voltage	60	90	120	60	90	120	60	90	120
Velocity (ft/s)	0.8	1.2	1.4	0.6	0.8	1.0	0.6	0.6	0.7

Change in velocity due to ball valves and supply voltage level

Budget

Budget Summary				
Budget	**Total Spent**	**Funds Available**		
$2,000.00	$919.12	$720.88		
		$1,080.88	*	
Vendor	**Part no.**	**Unit Price**	**Qty**	**Net Price**
Technologic Systems	TS-7800-128-512F	$269.00	1	$269.00
Technologic Systems	WIFI-N-USB	$35.00	2	$70.00
Technologic Systems	TS-ADC24	$109.00	1	$109.00
Technologic Systems	PS-12VDC-REG-2P2	$22.00	1	$22.00
Technologic Systems	KIT-7800	$100.00	1	$100.00
Digi-Key	DAC08CPZ-ND	$2.67	3	$8.00
Digi-Key	AD8561ANZ-ND	$4.67	3	$14.01
Digi-Key	438-1045-ND	$8.98	2	$17.96
Digi-Key	AD848JNZ-ND	$7.03	3	$21.09
McMaster-Carr	7750K196	$39.77	1	$39.77
McMaster-Carr	2389K113	$3.85	4	$15.40
McMaster-Carr	48925K16	$11.90	1	$11.90
McMaster-Carr	48925K93	$4.39	1	$4.39
McMaster-Carr	4880K46	$2.15	2	$4.30
McMaster-Carr	4880K43	$0.78	1	$0.78
McMaster-Carr	18815K62	$8.01	1	$8.01
McMaster-Carr	8249K81	$143.51	1	$143.51
Fouraker		$60.00	1	$60.00
Home Depot		$55.00	1	$55.00
Labor				
Vendor	**Part**	**Cost/hr**	**Hrs**	**Net Price**
College of Engineering	Mounting/Housing	$60.00	6	$360.00

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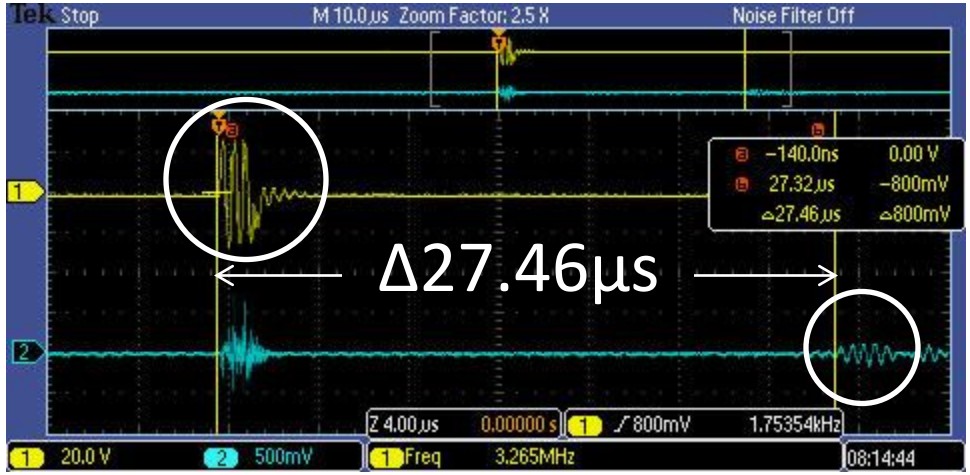
Signal Burst Proof

Downstream



Upstream

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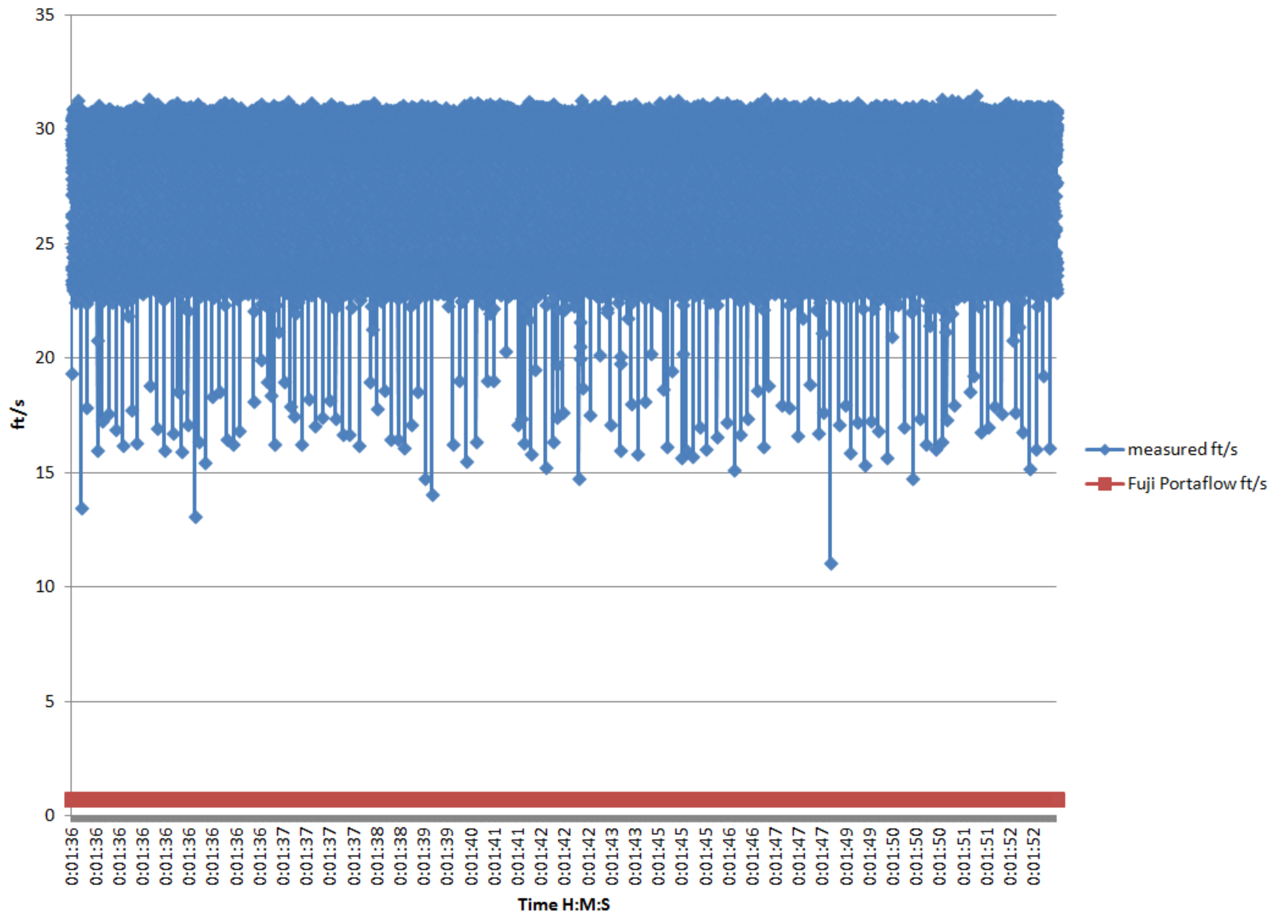
Data Acquisition Results



- ~5000 measurements per second
- Measurements taken on same setup
- Measured data fairly consistent but off by quite a bit, believed to be caused by spikes in the supply

Data Acquisition Results

Average *t* Values From Previous Graph

***t* up**	***t* down**	**Δ*t***
35.48µs	19.36µs	16.12µs

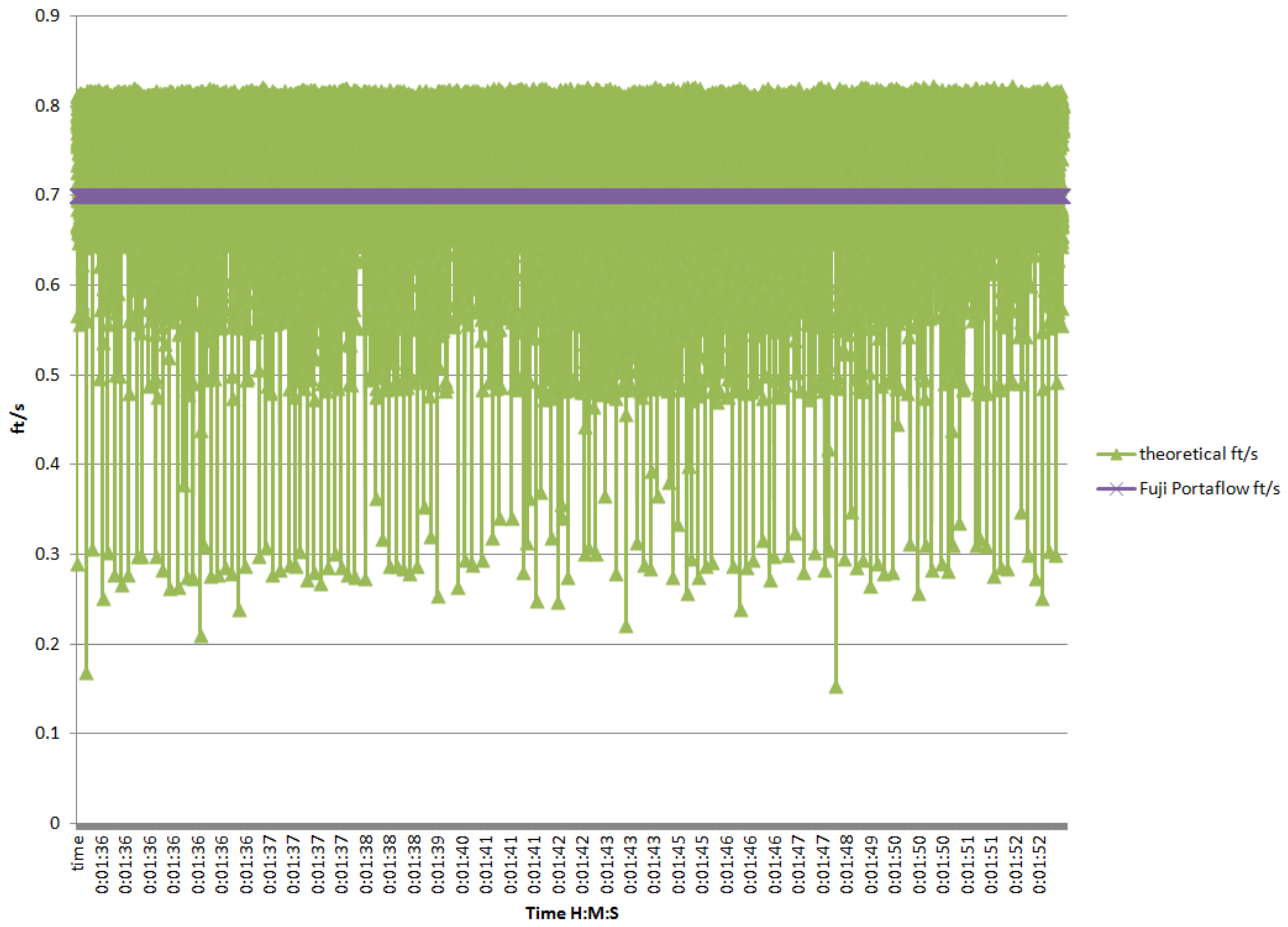
• After accounting for propagation delay through circuitry, *t* up appears to be a valid value when comparing to signal burst proof scope shots

35.48µs- 27.46µs=propagation delay of circuitry (to be later accounted for in calibration)

• From analyzing the circuit, supply spikes may be setting off the comparator too early for *t* down (each up and down are on different circuitry with same components)

• Solution for proof: Use Δ*t* value (80 ns) obtained from signal burst proof scope shots along with measured *t* up value to obtain velocities

Data Acquisition Results



- Used measured *t* up value along with Δ*t* value obtained from signal burst scope shots
- Average percent error of 10.28%

Conclusions

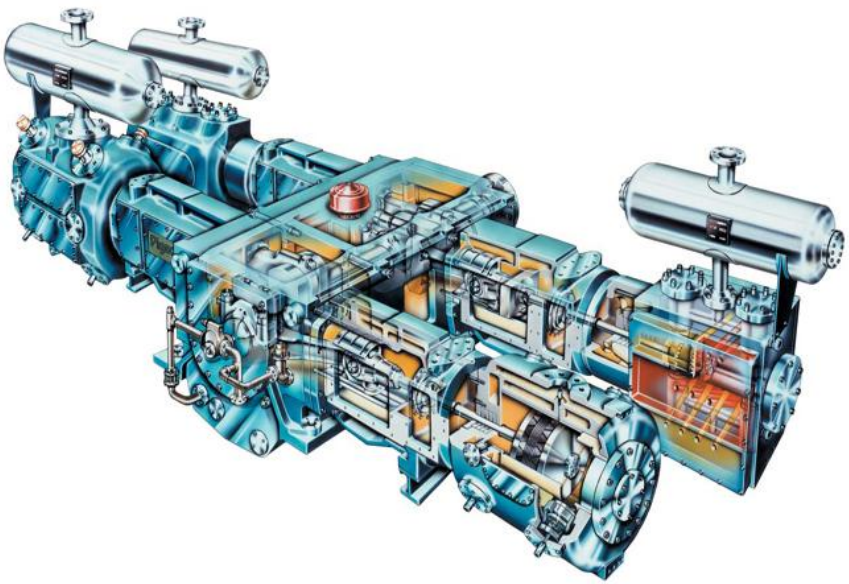
Achievements

- Instruments mount in roughly 2 minutes
- Signal is generated and received successfully
- Measurements accurate to 2 ns with use of the 500 MHz CPU timer
- ~5000 measurements per second
- Flow rate displayed real-time
- P-V curve successfully plots live in the App
- Enclosure protects electronics, cooling fan works

Future Improvements

- Housing could be made of lighter material (polymer, fiberglass, etc)
- Power supply (battery) needed, currently using lab's variable DC supply
- Diagnose spikes in supply
- Finalize Wi-Fi connection between SBPC and phone
- Solder circuitry to euro card so that it may be secured within housing
- Re-calibrate electronics to obtain less percent error in measurements

Questions?




htc
Sprint
10:08 AM
10
08
Seattle
73°
Messages
Voicemail
People
Mail
Market
Camera
Phone

Scope of Project
Functional Diagram
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Supplementary Information

Input Flow (ft^3/s), T (unitless, magnitude of degrees Fahrenheit), D (in) and ρ (lbm/ft^3).
Flow rates and temperatures taken from a GE HSR Compressor Performance Report.
Densities derived from temperatures and static pressures in report.
Diameter of pipe and Length (L) of pipe between valve and pressure gauge assumed.

$Flow_s := 10^8 \frac{ft^3}{day}$ $\rho_s := .128 \frac{lbm}{ft^3}$ $T_s := 60$

$D := 11.94in$ $L := 10 \cdot D = 119.4 \cdot in$

$A_{pipe} := \left(\frac{\pi}{4}\right) \cdot D^2$ $V_s := \frac{Flow_s}{A_{pipe}} = 1.489 \times 10^3 \frac{ft}{s}$

Dynamic Pressure

$q_s := \left(\frac{1}{2}\right) \cdot \rho_s \cdot V_s^2$

Pressure Drop in Pipe

$$\mu_s := \left[\left(-6.70244 \cdot 10^{-14}\right) \cdot T_s^2 + \left(5.05027 \cdot 10^{-10}\right) \cdot T_s + \left(3.43615 \cdot 10^{-7}\right)\right] lbf \cdot \frac{s}{ft^2} = 3.737 \times 10^{-7} \cdot lbf \cdot \frac{s}{ft^2}$$

$$Re_s := \frac{\left(\rho_s \cdot V_s \cdot D\right)}{\mu_s} = 1.577 \times 10^7$$

Laminar Assumption

$f_s := \frac{64}{Re_s} = 4.059 \times 10^{-6}$

$\Delta p_s := \frac{\left(f_s \cdot L \cdot \rho_s \cdot V_s^2\right)}{2 \cdot D}$

$\Delta p_s = 1.242 \times 10^{-3} \cdot psi$

Turbulent Consideration

$k := .045mm$ Absolute roughness steel

$\frac{k}{D} = 1.484 \times 10^{-4}$ Relative roughness

$f := .0032$ Looked up in Moody Chart

$\Delta p_{Moody} := \frac{\left(f \cdot L \cdot \rho_s \cdot V_s^2\right)}{2 \cdot D}$

$\Delta p_{Moody} = 0.979 \cdot psi$

Considering Discharge Pressure

$L_s := 6ft$ $T_s := 60$ $T_d := 120$ $\gamma := 1.4$ $P_{0s} := 10psi$

Laminar Assumption

$P_s := P_{0s} - \Delta p_s = 9.999 \cdot psi$

$$P_d := \frac{P_s}{\left(\frac{T_s}{T_d}\right)^{\left(\frac{\gamma}{\gamma-1}\right)}} = 113.123 \cdot psi$$

Turbulent Consideration

$P_{s.turb} := P_{0s} - \Delta p_{Moody} = 9.021 \cdot psi$

$$P_{d.turb} := \frac{P_{s.turb}}{\left(\frac{T_s}{T_d}\right)^{\left(\frac{\gamma}{\gamma-1}\right)}} = 102.056 \cdot psi$$

Conclusion:

May be useful for future design teams to explore, but not critical for initial development

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Moody Chart