Final Design Specification

EML 4551C – Senior Design – Fall 2011 Deliverable

Team # 19

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Google Mobile App for Compressor Performance (GE)

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Project Sponsor

General Electric

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Problem Statement

The purpose of our GE sponsored project is to make a preliminary diagnostic tool to analyze potential problems in a compressor. Our system must be non-intrusive, no modifications to the existing compressor needed, and have a set-up time of less than five minutes. Because it must be non-intrusive, ultrasonic methods must be used to calculate velocity of the fluid in the pipe. Although using velocity is a rather inefficient way to analyze potential compressor issues, it is sufficient enough to determine whether a problem may exist. Our system will therefore be used to determine whether or not it is necessary to bring in more expensive and time-consuming equipment potentially saving the company time and money.

Introduction

The purpose of this deliverable is to finalize the design of our system. Thus far we have explored many possible concepts for every component or process. The main components and/or processes of our system are the sensors, signal processing circuit, data processing unit, computations relating velocity and pressure and the mobile application used to store and display the data. Since our design parameters specifically state that the sensor must be unobtrusive in nature, most of the concept design and iteration will be limited to individual components and methods. Each aspect of our system will now be described in detail.

Flow Calculations

One of the most useful tools that is used when diagnosing a potentially-problematic HSR compressor is a P-V diagram. This diagram shows the relationship of the pressure versus the volume in the cylinder, and it can unveil various problems that would contribute to the compressor failing to achieve its specified flow characteristics, including problematic valves, worn compression rings, etc. Figure 1 shows the various stages in compressor operation on a P-V diagram.

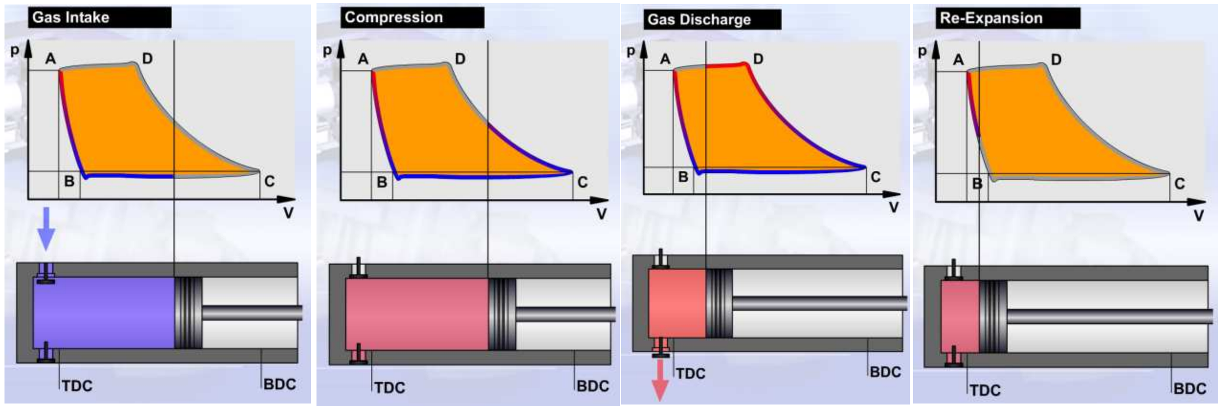


Figure 1 - P-V Curve of Typical Compressor

The incoming gas is pulled into the cylinder through its vacuum-operated valve from the suction pipe by the vacuum created from the piston's downward movement (toward Bottom Dead Center – BDC – point C in Fig. 1), where it is then compressed by the piston's upward movement (toward Top Dead Center – TDC – point A) until a pressure-operated discharge valve opens at point D and allows the compressed gas to escape through the discharge pipe. A quick process of re-expansion occurs as the piston begins its motion back down from TDC while both valves are closed, until the suction valve opens again at point B, at which point the cycle repeats.

Our task is to generate a P-V diagram unobtrusively, and currently the only feasible method to do this is by measuring the velocity of the fluid in the suction and discharge pipes via an ultrasonic method. If velocity of the fluid is measured, the dynamic pressure inside the pipes can be calculated using:

$$q = \frac{1}{2}\rho V^2$$

Eq. 2

The relationship of density (ρ) of air with respect to temperature and pressure is well established, and since the properties of natural gas are very similar to that of air, those values could be used here if measured. However, the pressure portrayed in a P-V curve is the total pressure, which includes the static pressure:

$$P_{total} = P_{static} + q$$

Eq. 3

Bernoulli's Equation

Since one of the most important specifications of this system is to be unobtrusive, the amount of parameters that can be measured is quite limited, including the static pressure. Some of the customers' compressors have pressure gauges installed in some locations, but not between each stage in every compressor, and there is a chance that compressors without any pressure gauges at all will need to be diagnosed at some point, so we cannot rely on the ability to measure or assume the static pressure. However, since the issues that our tool will be attempting to uncover stem from insufficient flow, the differences in dynamic pressure are the objects of higher interest, and as such we can model a P-V Curve on the dynamic pressure exclusively. While this is not a true P-V curve, the scope of this preliminary diagnostic tool is to quickly detect an appreciative deviation from normal operational flow rates, and measuring only the dynamic pressures will easily fulfill this task. Also, since this pressure cannot be measured, the true density of the gas will actually be unknown. However, we can normalize the measurements by using a constant density value (at 70°F and 1atm), which will yield a valid comparison for the variance in dynamic pressure from the case of the perfectly healthy compressor.

In order to avoid any turbulent flow areas in the pipe – and thus obtain accurate measurements - there is a published recommended distance from any valves, bends or reducers that the ultrasonic transducers must be attached. This is usually on the order of approximately 4 to 10 pipe diameters. Across a distance of this magnitude, the pressure drop due to frictional losses cannot be neglected. Also, since the sizes and locations of bends in each pipe will likely vary between each compressor and each facility, resulting in unpredictable distances of the transducers from the valve, a method of normalizing the pressure readings to comparable values from compressor to compressor needs to be established. This can be done simply by accounting for the frictional losses in the pipe, which is expressed as:

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

Eq. 4

This considers the distance between the transducers and the valve in this case (L), hydraulic diameter of the pipe (D) and the Darcy friction factor (f). The former two are easily measured, and the latter is dependent on the flow being turbulent or laminar. In checking if the flow is turbulent or laminar, the Reynolds number needs to be calculated:

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

Eq. 5

Using the properties of air, the density (ρ) and dynamic viscosity (μ) are known, the hydraulic diameter is measured, and the fluid velocity is measured by our ultrasonic instrumentation. Over the given range of fluid velocities that are expected, flow is actually found to be turbulent. This creates a problem for operational convenience since a Moody diagram would need to be employed to accurately determine the Darcy friction factor. However, once again considering the scope of this tool's use, a hard pressure value is not necessary; it is only the change in flow that is of interest. So since we are only using the pressure drop to normalize for differences in mounting locations on the suction vs. discharge pipes, we can model it using the assumption for laminar flow for simplified calculation and operation. Furthermore, Appendix XX mathematically shows that over the range of fluid velocities we are measuring, the rate of change in pressure drop when considering turbulent vs. laminar flow with respect to the magnitude of the dynamic pressure is approximately the same – within 10% - across the entire range of velocities with which we are dealing. This "error" is not actually error, but it is a difference between methods of normalization. Assuming laminar flow in this case is just a simpler method to achieve the same goal of normalizing flow measurements to comparable values at any pipe lengths from the valve. Thus, for laminar flow:

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

Eq. 6

Resolving pressure drop in the pipe:

$$\Delta p = \frac{32\mu LV}{D^2}$$

Eq. 7

Converting to commonly-used units:

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

Eq. 8

Where:

$$\mu \; is \; in \; \frac{lb_f * s}{ft^2}$$

$$L \; is \; in \; inches$$

$$V \; is \; in \; \frac{ft}{s}$$

$$D \; is \; in \;\; inches$$

So the pressures that will be calculated and displayed on our particular P-V curve are:

$$P_s = q_s - \Delta t$$

Eq. 9

Suction pipe, since transducers are upstream of the cylinder

$$P_d = q_d + \Delta t$$

Eq. 10

Discharge pipe, since transducers are downstream of the cylinder

The method we are using to measure these pressures will not facilitate a comprehensive generation of every point on the P-V curve, rather we are measuring and plotting the pressure during only the gas intake and gas discharge phases, separately. The operator will attach the ultrasonic sensors to the suction pipe, take measurements, then remove them and repeat the process for the discharge pipe in order to obtain one complete P-V curve for that particular compressor stage. The velocity measurement will likely be some small-amplitude sine wave with respect to time, but the mean value of this is the point of interest. The red Average lines in Figure 2 show each individual measurement that will be taken.

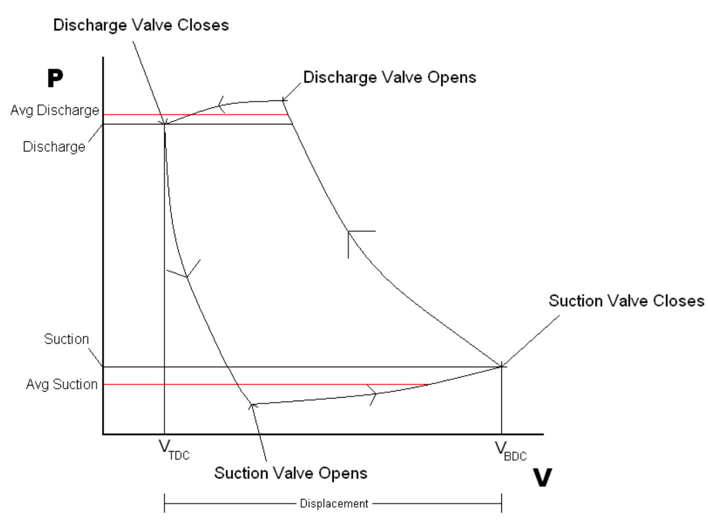


Figure 2 - Average Pressure Measurements

These measurements can be compared with the ideal suction and discharge flow rates for each compressor stage to determine the approximate efficiency:

$$\eta = \frac{v_{measured}}{\frac{\pi}{4} * bore^2 * stroke * rotational\ speed}$$

Eq. 11

Resolving to common units:

$$\eta = \frac{207360 * v_{measured}}{\pi^2 * bore^2 * stroke * rotational\ speed}$$

Eq. 12

Where:

$$bore\ is\ in\ inches$$

$$stroke\ is\ in\ inches$$

$$rotational\ speed\ is\ in\ RPM$$

$$A_{pipe} * V_{fluid} = v_{measured}$$

Eq. 12

Volumetric Flow Rate

Also, the volume in the graph can be found using the displacement and compression ratio of that compressor stage:

$$Vol_{BDC} = \frac{\pi}{4} * bore^2 * stroke$$

Eq. 13

And:

$$Vol_{TDC} = \frac{Vol_{BDC}}{compression\ ratio}$$

Eq. 14

If only a compression ratio is given, the data can be graphically modeled using V_{TDC} as a small, non-zero number, and:

$$Vol_{BDC} = Vol_{TDC} * (compression\ ratio)$$

Eq. 15

This will still provide a useful visual aid when comparing values on the graph.

Ultrasonic Transducers

The principle we are using for our non-intrusive flow measurement technique takes advantage of ultrasonic sensors, or ultrasonic transducers when they both send and receive information. Piezoelectric crystals in the sensor change size with an applied voltage, so by applying an alternating current (AC) they induce high frequency vibrations. The frequency at which the sensors vibrate can be tuned by the manufacturers, most of which are intended for hobbyists and are tuned to 40 kHz. They are available in analog and digital circuitry, the main difference being the information sent to and received by the sensors. Digital sensors will have onboard computation to change the analog data measured from the environment into 1's and 0's. This is useful when making simple calculations for distance, but in the case of flow velocity measurement the analysis must be done elsewhere.

Figure 3 – Example Ultrasonic Flow Meter w/ Transducers

We will be using analog ultrasonic transducers, located proximal to each other on an adjustable track to compensate for differences in pipe diameter. This adjustable track will then be attached to our clamping mechanism which is described later on in detail. During our experimental data acquisition it became apparent that the distance the ultrasonic transducers are spaced has a great impact on the measured velocity of the fluid. This is because ultrasonic sensors generate a sound pressure field, or an area where their vibration is radiated. The location at which a transducer focuses the sound can be determined by the active transducer area and shape, the ultrasound frequency, and the sound velocity of the propagation medium. The operation manual for the FUJI Portaflow X ultrasonic flow manual dictates a transducer spacing length equal to the pipe diameter.

$$L_{trans} = D_{pipe}$$

Eq. 16

This gives a semi-accurate representation of the location of the signal inflection point, but more can be done to improve accuracy and reduce the error given by incorrect transducer placement. By giving the transducer surface a spherical curvature, the sound pressure field can be greatly decreased. Fig. 4 is an illustration of the sound pressure field generated by an ultrasonic sensor in water. Fig. 5 is of the same sensor in the same medium with an affixed spherical curvature on the transducer head.

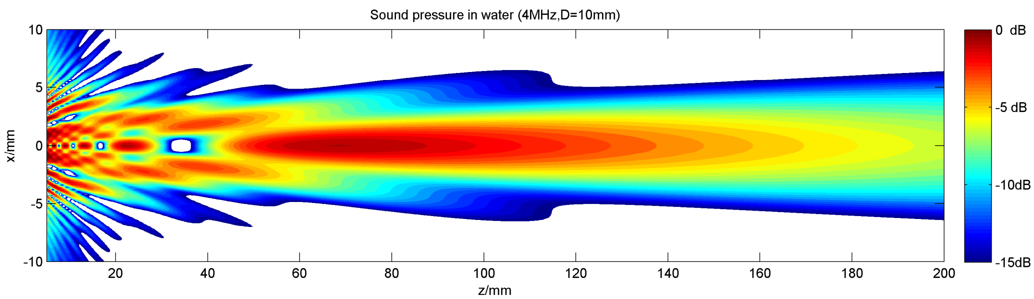


Figure 4 Non-Focused sound pressure field

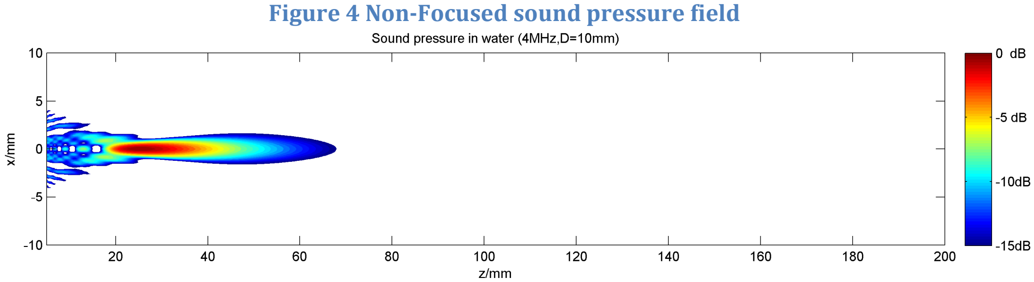


Figure 5 Focused sound pressure field

Adjusting the transducer surface curvature is out of the scope of our project, but should be a consideration for future GE design teams.

Transit Time Flow Analysis

There are several methods of obtaining fluid velocity with ultrasonic transducers. Several of these methods have a minimum particulate size restriction, usually around 100 PPM or 100 microns in size. Since we are measuring the velocity of natural gas there will be no particulate in the flow (natural gas is a 'clean' fluid). Others require that your fluid have a higher density than that of natural gas. Transit time flow analysis has no density requirement and works with clean fluids, as it doesn't require particles to reflect vibrations into the receiver. Looking at Fig. 6, ultrasonic vibrations are sent from transducer A., the signal bounces off the inflection point located on the inside of the rear of the pipe and into transducer B and the transit time is recorded. The same process is repeated, sending signal from transducer B to transducer A and the transit time is again recorded. The theory states that the transit time from the signal sent opposite of the direction of flow is longer than the transit time in the direction of the flow. This **Δ**t is directly proportional to fluid velocity (eq.1).

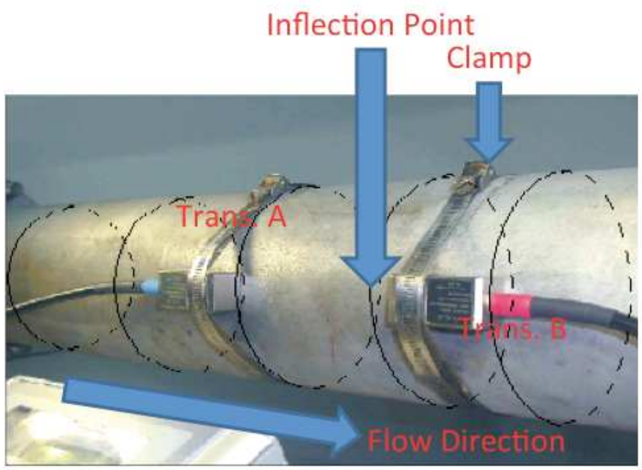


Figure 6 – Transducer Setup on Pipe

Transit Time Analysis Calculations

$$V_{ax} = \frac{L}{2\cos\theta} \times \frac{\Delta t}{t_{up} \times t_{down}}$$

Eq. 17

Where:

$V_{ax} = \text{the axial liquid velocity along the acoustic path}$

$$L = \boldsymbol{straight\ line\ distance\ between\ the\ centers\ of\ the}$$

$$\boldsymbol{faces\ of\ the\ upstream\ and\ downstream\ transducers}$$

$$\boldsymbol{\theta} = \boldsymbol{the\ path\ angle\ of\ transmission\ relative\ to\ the\ fluid\ at\ rest}$$

$$\boldsymbol{T_{up}} = \boldsymbol{the\ upstream\ transit - time}$$

$$\boldsymbol{T_{down}} = \boldsymbol{the\ downstream\ transit - time}$$

$$\Delta\boldsymbol{t} = \left(\boldsymbol{t_{up}} - \boldsymbol{t_{down}}\right) = \boldsymbol{the\ differential\ transit\ time}$$

Signal Burst Method

Transit time flow analysis explains how we derive the flow velocity, but it does not explicitly govern the method of transducer signal generation how to deduce transit time. There are several considerations to be made in regards to signal generation, most notably is controller hardware which will be later discussed in further detail. Among the options, signal burst generation had the most ideal combination of characteristics that allowed us to maintain a moderate bitrate for our A/D converter and provide a high level of accuracy. We recently experimentally found that flow meters on the market now also generate their signal using a burst method, which is a confirmation that we are headed in the right direction.

Signal burst generation is accomplished by sending a short period square wave from a function generator to a transducer. The transducer generates the frequency at which it is tuned for a period equivalent to that of the function generator. The microprocessor timestamps when the signal is sent, and again when the signal is first read. This method eliminates the need for waveform reconstruction and analysis to deduce the transit time, and greatly simplifies the required hardware, which will be highlighted in further detail. Fig. 4 illustrates the error vs. sampling rate at a sample frequency of 150 kHz. Because of the simplicity of sample burst generation we will be able to implement some circuitry that will greatly simplify the sampling process. We will go into further detail in a later section.

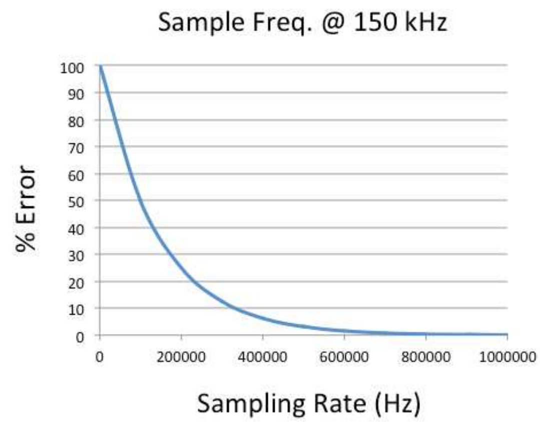


Figure 7 – Sampling Rate VS % Error

In order to justify using the signal burst method it needed to be verified that the transit time difference was large enough that digital equipment could realistically time stamp and calculate. The difference in upstream and downstream transit times will be smallest in the case where fluid velocity is closest to zero, which will be true when using the largest diameter pipe, lowest flow rate, and highest speed of sound (which is due to a higher temperature). This combination will never happen because the temperature will be lower where the flow rate is lowest, so this is quite a conservative calculated verification. The length between the transducers is recommended by the manufacturer to be the same as the outer pipe diameter, so L = D and the incident angle is 22.5°.

Volumetric Flow Rate:

$$\upsilon = 0.327\ \frac{ft^3}{s}$$

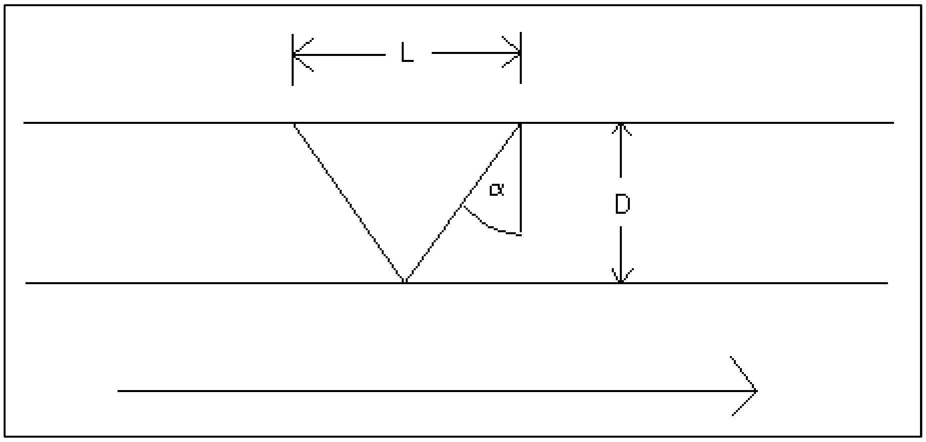
$$D_{pipe} = L_{transducers} = 6\ in$$

$$A_{pipe} = \frac{\pi}{4} {D_{pipe}}^2 = 12.566\ in^2$$

Eq. 17

$$V_{fluid} = \frac{\upsilon}{A_{pipe}} = 3.747 \frac{ft}{s}$$

Eq. 18



Speed of Sound in Air at 400°F:

$$c = 1339\frac{ft}{s}$$

Sound Velocities:

$$V_{up} = c * \sin(\alpha) - V_{fluid}$$

Eq. 19

$$V_{down} = c * \sin(\alpha) + V_{fluid}$$

Eq. 20

$$\alpha = 22.5°$$

$$t_{up} = \frac{L}{V_{up}}$$

Eq. 21

$$t_{down} = \frac{L}{V_{down}}$$

Eq. 22

$$\Delta t = t_{up} - t_{down}$$

Eq. 23

So, difference in transit time:

$$\Delta t = 14\ \mu s$$

With this worst case difference in transit time, the hardware that is planned to be used will be sufficient in precisely time stamping since it has nanosecond precision.

This is an image of the signal sent from a flow meter to the input of an ultrasonic transducer. It is a square wave with peak to peak voltage amplitude of 50V and 1.5 MHz frequency.

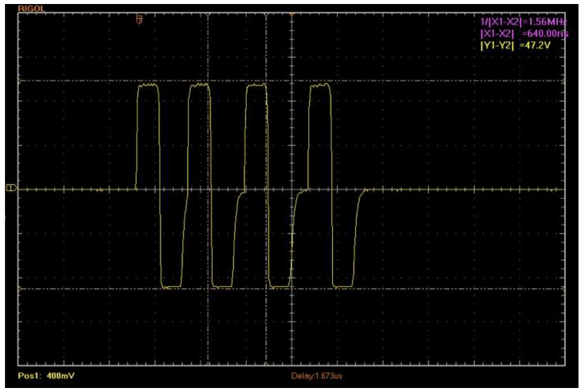


Figure 8 – Signal Sent From Fuji FLC-s1012 Meter

This signal activates the piezoelectric crystals in the transducer and it in turn sends out a signal. It is interpreted on the other end by the receiving transducer and it is pictured below. It has relatively low amplitude, which will need to be amplified and filtered before it is sent to the microprocessor for signal burst detection. This image verifies that the signal sent from the flow meter is in burst form, visible by the period of the high frequency signal.

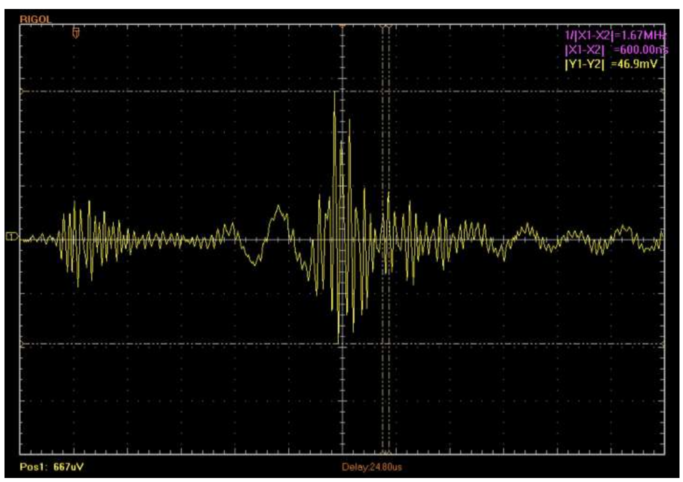


Figure 9 – Signal Received From Fuji Transducer

Cross Correlation Method

The method behind cross correlation is to find phase shift between two sine waves using signal reconstruction for cross correlation. If the signal burst method does not produce precise enough measurements, this method will be experimentally assessed. It only requires two samples per waveform and the information is in the signal. The transit time is calculated by finding the phase shift between the original sine wave sent out and the sine wave received.

$$(f \cdot g)(t) \stackrel{\text{def}}{=} \int_{-\infty}^{\infty} f*(\tau)g(t+\tau)d\tau$$

Eq. 24

The Nyquist–Shannon sampling theorem states that if a function contains frequencies of B hertz, it need only be sampled 1/2B times per second to perfectly reconstruct the signal. Realistically it would be desired to sample at least 5 times the frequency to reduce errors incurred by noise. When you consider the frequency our ultrasonic transducers operate at, the hardware requirements when considering cross correlation are discouraging, since it requires an expensive analog to digital converter. This is still well within our budget and remains a solid candidate for signal generation and transit time deduction.

Flow Meter Experimental Data

We have obtained a Fuji Portaflow X ultrasonic flow meter for temporary use that has been used to obtain experimental data, and will be used as a validation and calibration tool for our upcoming prototypes. The experimental data was acquired while measuring flow velocity on a pipe with flowing chilled water. There was an issue accessing the serial port of the flow meter so we were unable to include it and any information learned from it in this report.

Data Processing Unit

Originally using a simple microcontroller such as an Arduino board was considered in order to process incoming data and send it out to the phone. It was learned that the Arduino could not quickly process floating point numbers nor could it keep time as well as a single board PC. A single board PC also has an easier method of interfacing with a Wi-Fi or Bluetooth module since you can install an operating system on it. After much research the Technologic Systems TS-7800 single board PC was chosen to be the data processing unit. Listed below are its important features:

- 500Mhz ARM9 CPU
- Internal PCI bus, PC/104 connector
- 12,000 LUT programmable FPGA
- 128MB DDR-RAM
- 512MB NAND Flash, high-speed (17MB/s)
- 2 USB 2.0 480Mbps host/slave ports
- 5 10-bit ADC channels
- Fanless: -20° to +70°C
- Low power 4W@5V
- Optional 8-30V input voltage range (default is 5V)
- runs Kernel 2.6 and Debian Linux by default

Figure 10 – TS-7800

One of the USB slots will be used to host the Wi-Fi module and the Debian Linux operating system will serve as a good interface between the software and the hardware.

Sending and Receiving the Signal

In order to transmit an ultrasonic pulse from the transducer, an electrical pulse of a specified frequency and magnitude must be sent to it. The current transducers that are in possession require a pulse of 1.5 Mhz at an amplitude ranging from 25V to -25V. A digital to analog converter will need to be used in order to generate this type of signal along with an amplifier for it to reach 50Vpp. Below is the schematic of the digital to analog converter that is planned to be used:

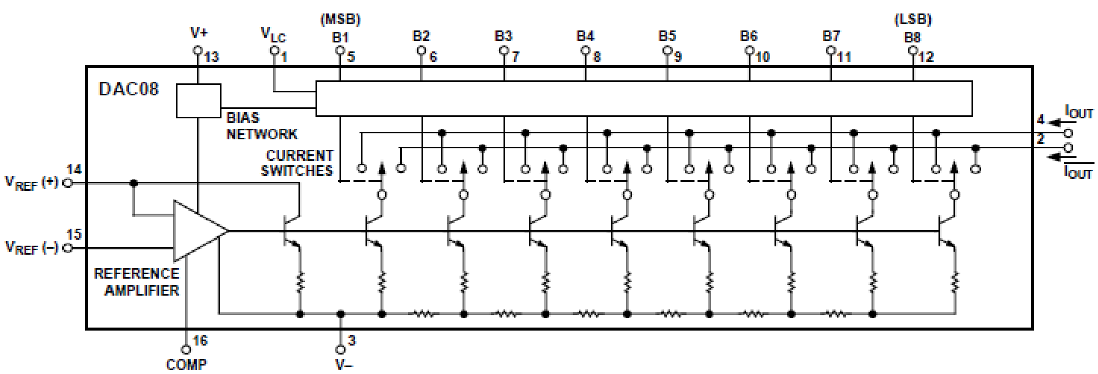
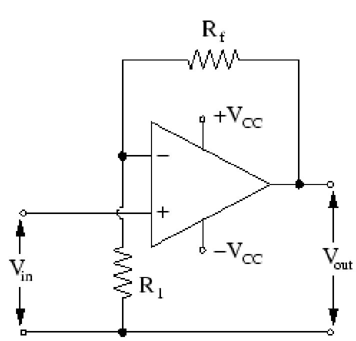


Figure 11 – Analog Devices DAC08

This device can be controlled via the SPI port of the chosen microprocessor. The signal sent out from the DAC08 needs to be amplified in order to meet 50 Vpp. It can be fed into a simple non inverting amplifier. With a 2Vpp signal coming from the DAC08, the gain of the amplifier will need to be 25.



$$A = \frac{R_1 + R_f}{R_1}.$$

Figure 12 – Non-Inverting Op Amp Example

For a gain of 25, Rl=1k and Rf=24k. Many different combinations of values can be used depending on resistors available.

The same transducer that sends out a signal will also be receiving one. The signal that is received is of the same frequency of sent signal but has very low amplitude that needs to be amplified. Firstly the signal needs to be filtered of noise; this can be done by using a band pass filter since we know the frequency. Frequencies between 1.3 Mhz and 1.7 Mhz will be allowed through with the following values:

C1=C3=97.9 pF
C2=14.2 pF
L1=L3=28.4 µH
L2=795.7 µH

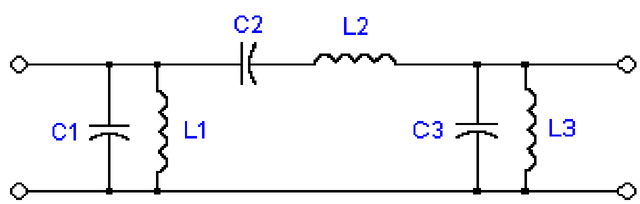


Figure 13 – Example Band Pass Filter

After being filtered, the received signal is still approximately 50mVpp. In order to properly detect the signal burst, it should be amplified to at least 10Vpp. This requires another amplifier that has a gain of 200.

The signal is now filtered and amplified, now for detecting the burst. Below is the analog to digital converter that will be used in order to detect the signal burst.

- Two AD7266 ADC chips
- 24 channels 12-bit ADC
- Sampling rate up to 2msps
- Single ended or differential channels
- Takes 4 samples simultaneously
- Internal 512 x 16bit RAM-FIFO
- Jumper selectable I/O and IRQ
- PC/104 Dimensions 3.6 x 3.8 inches
- Linux drivers available

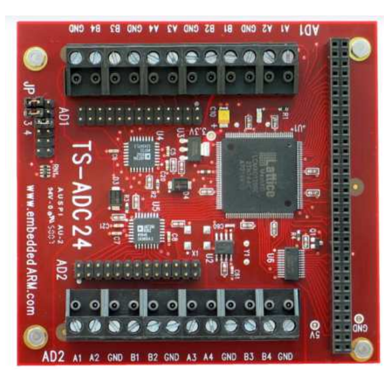


Figure 14 – TS-ADC24

Alternatively, a single comparator may be used. With a single comparator, a reference voltage will be determined and set and once the voltage of the incoming signal exceeds that reference voltage it will trigger signifying that the signal burst was received. Below is the comparator to be used:

- 7 ns Propagation Delay at 5 V
- Single Supply Operation: 3 V to 10 V
- Low Power
- Latch Function
- TSSOP Packages

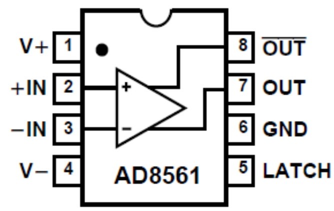


Figure 15 – Analog Devices AD8561

With only a 7ns propagation delay, it is more than fast enough to detect a burst from a 1.5 Mhz signal. While this is a simpler solution, it may end up being harder to detect errors. Both methods will be tried out in the lab to determine which produces the most precise and lowest error signal burst detection.

Since one line connected to the transducer will be sending and receiving the signal, a diode and a tri-state buffer will be needed in order properly channel the signal when going out or in. Below is a top-level diagram of how this will be achieved:

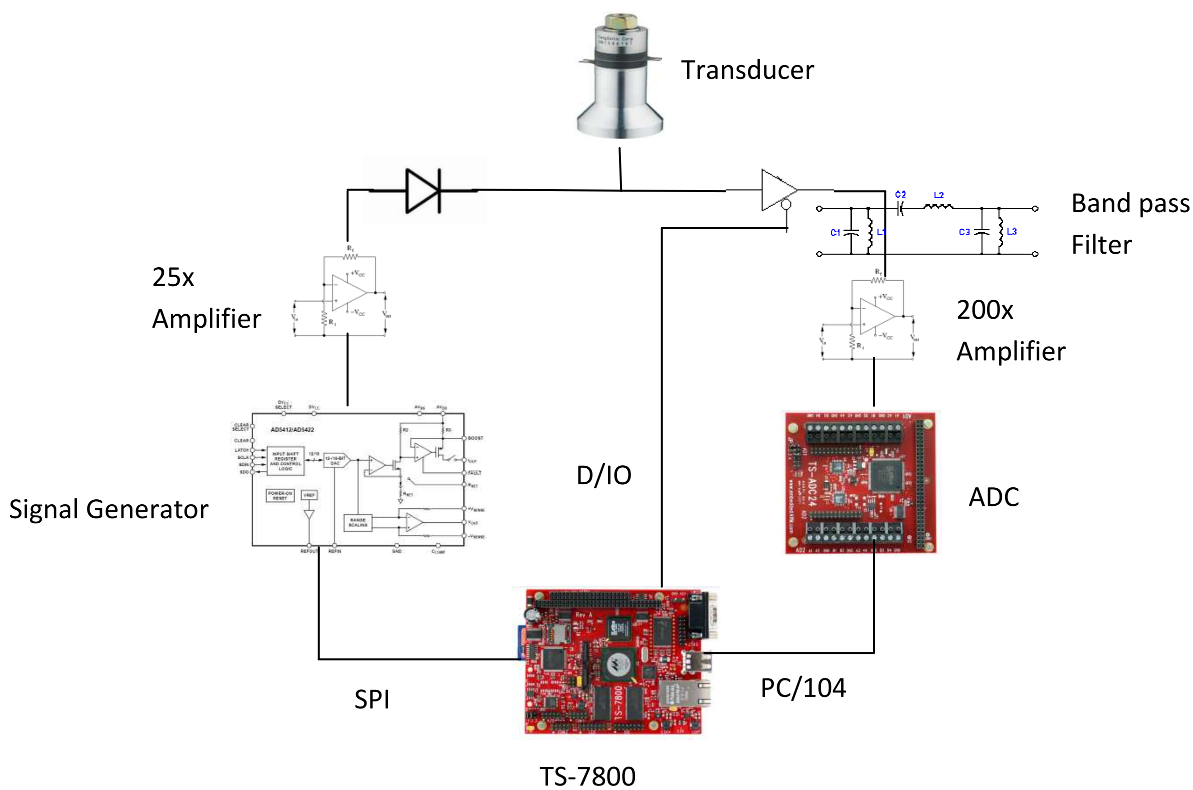


Figure 16 – Top-Level Diagram of Signal Processing

The digital I/O line going to the tri-state buffer will be set to 1 when sending out the signal and 0 otherwise.

Time Stamping

The tick rate as defined by the kernel will be crucial for time stamping. The tick rate determines how quick the CPU responds to a new instruction. In this case, the tick rate will determine the time in between detecting the signal and stamping the time. Some sort of get_time() command of which precision will be in the nanoseconds will be used, therefore how quickly that command is executed once the signal is detected is important. By default the Kernel 2.6 has a tick rate of 100 Hz. This will not produce precise enough measurements, so the tick rate will need to be modified to the highest stable tick rate that the ARM9 CPU can handle. Typically that is 1000 Hz. It may be possible that the time taken in between detecting the signal and stamping the time will always be the same. Lab experiments will need to be conducted in order to determine this. If the time taken is always the same, then there will be no need to modify the tick rate and an offset will just need to be applied to the recorded time.

Alternatively (and preferable) the kernel can be patched with a real-time patch. This eliminates the CPU scheduler from allowing preemption on time-dependent tasks. By creating a kernel module for time stamping and allowing it to be real time with the highest priority, the minimum time between receiving the signal and stamping the time can be achieved.

In programming terms, a hrtimer (High Resolution Timer) object can be used. The hrtimer is a bit different from usual timer APIs in that it maintains a time-ordered data structure of timers instead of using timer cascading. The hrtimer is a kernel-space function so a kernel module will be created in order to properly use the hrtimer in the user-space program. Using it as a kernel module improves precision as well since it will be ran as its own thread and can be prioritized above other less time important functions such as calculating the velocity from the recorded times.

More research and experimentation will need to be done with the hrtimer to determine if it is indeed the most precise option. It may well be that a timer will be made directly from a clock on the ARM9 CPU instead of using a hrtimer object.

Below is some sample pseudo showing the order in which how the time stamping process will work in the program in order to obtain velocity.

```
//Thread1
While(1)
{
        Lock_thread();
        Send_Signal_Trans2();
```

```
        Double time_sent2=time_stamp();
        While(!Signal_Received_Trans1);
        Double time_received2=time_stamp();
        Send_Signal_Trans1();
        Double time_sent1=time_stamp();
        While(!Signal_Received_Trans2());
        Double time_received2=time_stamp();
        Unlock_thread();
}

//Thread 2
While(1)
{
        Lock_thread();
        Transtime1=time_received1-time_sent1;
        Transtime2=time_recevied2-time_sent2;
        Velocity=((Transtime2-Transtime1)/(Transtime1*Transtime2))*(L/cos(theta)); //theta and L are known
        Send_to_phone(velocity);
        Unlock_thread();
}
```

Sending to the Phone

The two most viable options for sending data to the phone are Bluetooth and direct Wi-Fi. Wi-Fi will be used in the design because of its security feature and range capabilities. Setting up an Ad-Hoc network for direct Wi-Fi access was considered first but after doing much research it was found out that a better configuration can be setup in the Linux operating system. In Debian, the linux distribution that will be used with the TS-7800 single board PC, the network interfaces allow for additional network devices to be manually added. Once a network device is manually added with the proper IP and DNS settings, it will be secured via WEP and will be bridged so that connected devices can access velocity data. The single board PC can now be accessed on the phone just as if it were connecting to any router.

Application Design

The purpose of the application is mainly to connect to the sensors via the MCU, take in all the data transmitted, make the appropriate calculations, store the data on the phone, and display the data in a PV graph. Below is a detailed description of the applications interface. Each screen and possible path will be discussed. You may also refer to a flow chart representation in the Appendix.

Main Screen

Figure 17 – Phone App Main Screen

The main screen will consist of buttons corresponding to the four major activities of the application. If any button is pressed the appropriate process will begin. After pressing the "Connect Sensor" button the application will check if the device is connected to a sensor. If the check passes the user will be brought to the input screen if not an alert will be displayed requesting the user connects to a sensor via their Wi-Fi settings. The "View Old Data" button will bring the user to a listview of all the previous data currently on the phone. The "Settings/Preferences" button consists of a checklist of settings the user will have the option to enable or disable. The "Help" button will bring you to an expandable-listview with helpful information.

Input Screen

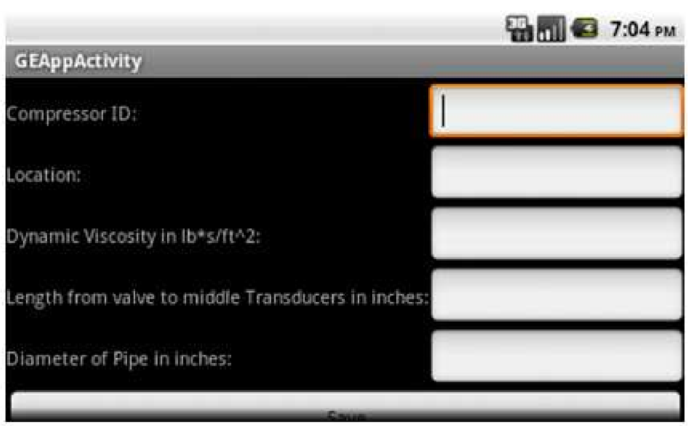


Figure 18 – Phone App Main Screen

When the connection check clears the input screen is called. The user will be prompted to create a new compressor file. They must input the name of the compressor and other identifying information as well as some specifications of the compressor which will be used for calculation. After pressing “Enter” the path will continue to the data display screens.

Data Display Screens

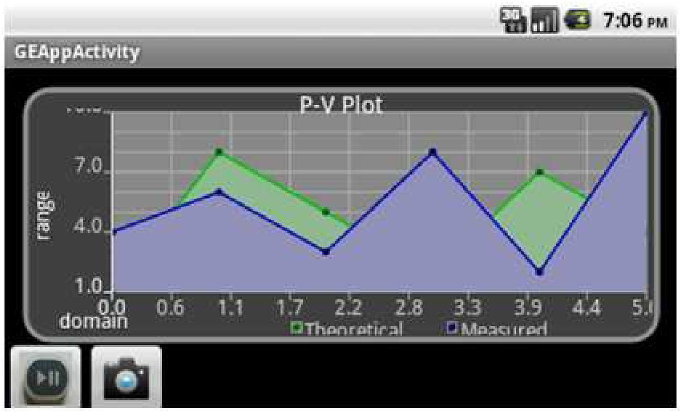


Figure 19 – Data Display Screen Graph

The data will be displayed in two separate methods, via a PV curve and a table highlighting important values. These two displays will run simultaneously and the user may switch between them by sliding their finger across the screen. Two options available to the user from this screen are the “Pause/Resume” and “Screenshot” buttons. As their names suggest the “Pause/Resume” button will stop the graph from plotting live or resume it and the “Screenshot” button will save a picture of the graph and store it with the data in the database. Pressing back should return to the main screen.

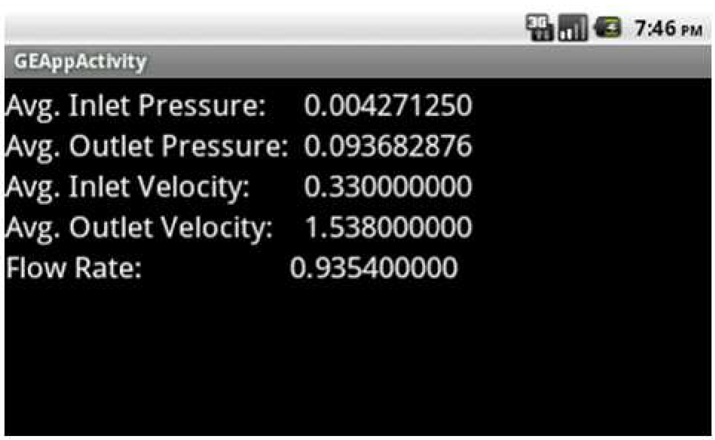


Figure 20 – Data Display Screen Raw

Listview Screen

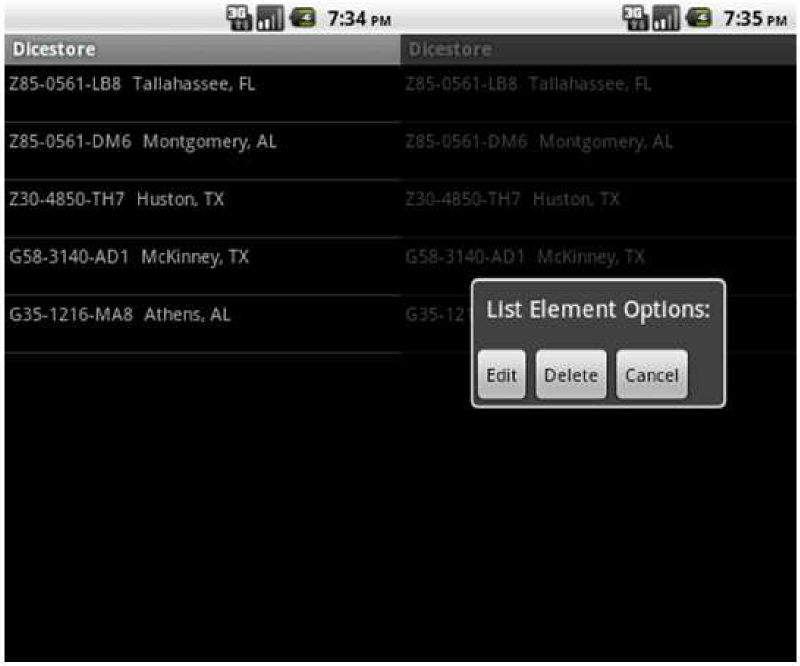


Figure21– Listview Screen

Called by the "View Old Data" button this screen will display a list of all the previous compressor data still stored on the device. At the bottom of the screen the user will be given the option to change the order of the files via a scroll bar of options including: name, date and location. Also on the screen will be a "Clear Data" button; if pressed an alert-box will pop up asking the user to confirm the selection. Pressing yes will delete all compressor data from the device and return to an empty listview. Pressing on any list element will bring up a dialog box with more options. "Edit" will bring you to a screen similar to the input screen already filled with the information corresponding to that list element. Any changes made will update the information in the database and pressing "Enter" will take you back to the listview. "View" will take you to the data display screens. Because it will be displaying old data it will not plot in real-time as it would for new data being recorded, however, it may or may not be possible to simulate real-time plotting (more research needed). The option to "Screenshot" will be available as it was for the new data displaying screen. Pressing back will bring you to the listview again. "Email" will open a screen to input an email address and send a data file. "Delete" will bring up a confirmation alert-box similar to the "Clear Data" button, however, if confirmed it will only delete the single list element. "Cancel" will close the dialog box. Pressing back from the listview will bring you back to the main screen.

Checklist

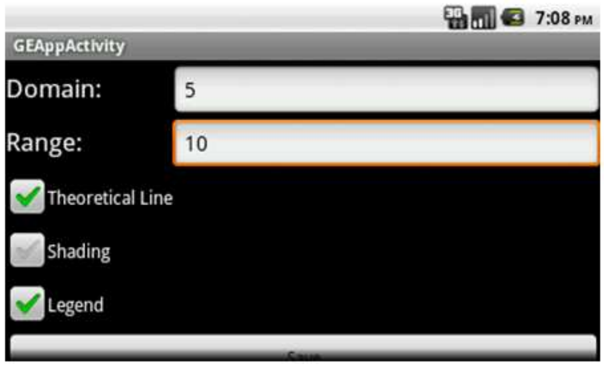


Figure 22 – Checklist Screen

Called by the "Settings/Preferences" button this checklist consists of features that may be enabled or disables by the user. Most of the option will involve the display of the PV graphs when viewing data. Such option may include: displaying axis labels, theoretical line, shading options, etc. Pressing back will return to the main screen.

Expandable-Listview

Called by the "Help" button this activity will display information explaining all the various options and settings of the application. The information will be organized into categories which can be expanded to show more information making it more user friendly and visually accessible.

Mounting System

In order to satisfy one of the customer's needs to install the diagnostic system on the inlet and outlet pipe within a five minute time frame, a mounting system was developed to lessen the current mounting time of fifth teen minutes. The mounting system for the proposed design is composed of three different operations: lubricating, measuring and attaching.

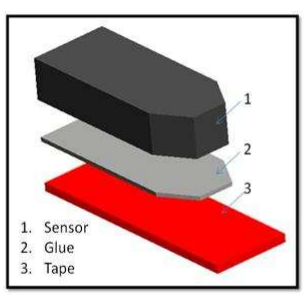


Figure 23 – Pre-lubricated Sensor

The lubrication operation is necessary to establish an acoustic couplet for proper sensor reading. Currently the pipe surface must be clean prior to lubrication and a silicon based gel is applied to the sensor. For a cleaner and more effective lubrication method, a thin layer of silicone gel will be already placed on the sensor and a foil based tape will be placed on top of the gel to keep it from drying out, as seen in Figure 23. Three different types of tape and adhesives are investigated. The results are feature in Table 1 and a Pugh Matrix is included in Table 2. As indicated in the Pugh Matrix, high quality aluminum foil with Uglu will be used for ensuring the pre-lubricated sensor remains lubricated because of it feasibility and functionality.

Tapes and Adhesives	Description
Polyamide film coated with a high performance silicone adhesive (PFC)	This is a thin and conformable tape that is resistant to tear and abrasion at high temperatures. Unfortunately, the adhesive will thermo-set to increase adhesion values, which is not ideal for application. This increase the probability of residual during removal. It has outstanding resistance to acids, oils, solvents, aging, staining, and water immersion.
Low density polyethylene film tape with Acrylic adhesive (LDP)	Low density polyethylene film tape with acrylic adhesive is conformable with great moisture barrier properties. It is very strong and will probably leave residual. It works well for applications that require long term bonding. It has good abrasion and chemical resistance. The tape is also UV resistant.
High Quality aluminum foil with Uglu (HQA)	Uglu is a liquid adhesive in solid form. It provides an instant grip with a powerful, but removable bond. The product is nontoxic, acid free, waterproof and weatherproof. It can be cleanly removed. It bonds to any surface including rough or uneven surfaces, plastics, metal, glass, cement, fiberglass, and laminates. Aluminum foil is the basic liner used in various packaging containers and tubes including tooth paste, cosmetic, drugs and food

Table 1: Options for Tape for the silicone gel

Push Matrix for Lubrication Tape					
Design Features	Current Methods	PFC	LDP	HQA	Importance Rating
Cost	0	-2	-1	-1	1.00
Removability	0	-2	-2	-1	2.00
Feasibility	0	-1	-1	3	4.00
Functionality	0	2	2	3	3.00
Sum	0	-3	-2	4	
Total	0	-4	-3	18	

Table 2: Pugh Matrix for Lubrication Tape

The second operation is measuring. This operation involved determining where each sensor is placed on the pipe to obtain proper readings. It is suggested that sensors are placed a distance that is equal to the pipes diameter. In order to accomplish this operation, the sensors will be placed on a track that has a ruler on it. The sensors will be locked in place when they are properly displaced from each other on the track.

The third operation is attachment. This involves attaching the pre-lubricated sensor. Velcro bands, quick release hose clamps, Nylon interlocking clamps and magnets were analyzed for attaching the sensor to the inlet and outlet pipes. Based on design features that were created based on customer needs, an Analytical Hierarchy Process was conducted to determine the importance ratings. Definitions for these design features are provided in Table 2

Design Feature	Definition
Cost	The amount of capital need to implement the mounting system
Lead Time	Time required to get components
Installation Time	Time required to complete installation of sensors
Functionality	How well a method attaches and stay attach
Usability	The ease of use and learn ability of a human-made object.

Table 2: Design Feature Definitions

The design features were evaluated against how important they are against other design features on a scale of one through nine in odd increments. One meaning that the design feature is equally as important and nine meaning that the design feature is significantly more important, the results can be seen in Table 2. After the importance ratings were determined for each design feature, a Pugh Matrix was used to determine which attachment concept will be best for the project. As seen in Table 3, quick release hose clamps have the highest weighted total. Therefore, the proposed design use quick release hose clamps for attaching the mechanism.

Analytical Hierarchy Process for Clamping System						
Design Feature	Cost	Lead Time	Installation Time	Functionality	Usability	Importance Rating
Cost	1	3	1/7	1/9	1/5	4.45
Lead Time	1/3	1	1/9	1/7	1/7	1.73
Installation Time	7	9	1	1	1/3	18.33
Functionality	9	7	1	1	1	19.00
Usability	5	7	3	1	1	17.00

Table 3: Analytical Hierarchy Process

Push Matrix for Clamping System						
Design Features	Current Methods	Velcro Bands	Quick Release Clamps	Interlocking Clamps	Magnetics	Importanc e 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	

Table 4: Pugh Matrix

The proposed design that is provided in figure 24 and 25 do not have the sensors on the track, the mounting system also has a microcontroller housing to make this solution more effective. This housing can be seen on a 6 inch pipe in figure 26. A finite element analysis (FEA) was conducted to determine the principle stresses in the elements. The mesh grid for this analysis can be seen in figure 27 and the results of this analysis are seen in figure 28. These results prove that the principle stresses in the mounting system are not high enough to cause deformation. The light colors in the results reveal the low stresses that equipment experiences with a distributed 300 pound force. This force is extremely high compare to the force that average human exerts when moving their arm in the clamping motion, which is at most 20 pound force, and it is higher than the normal force the clamp exerts when on fastened on the pipe.   Thus, the proposed design should not deform or fail.

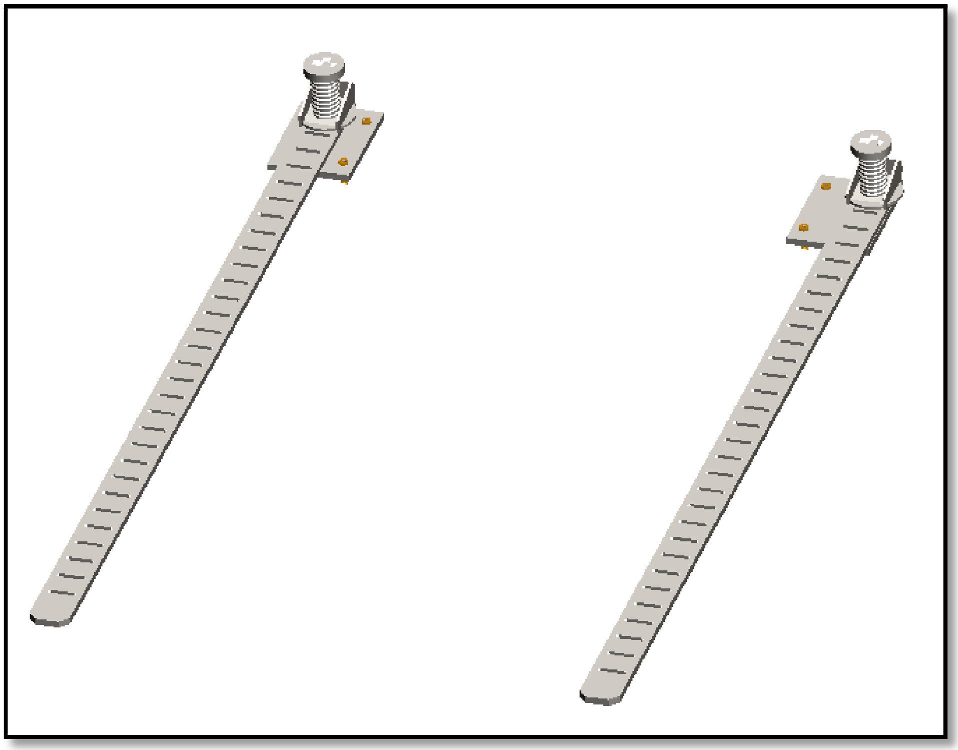


Figure 34: Attachment Design System

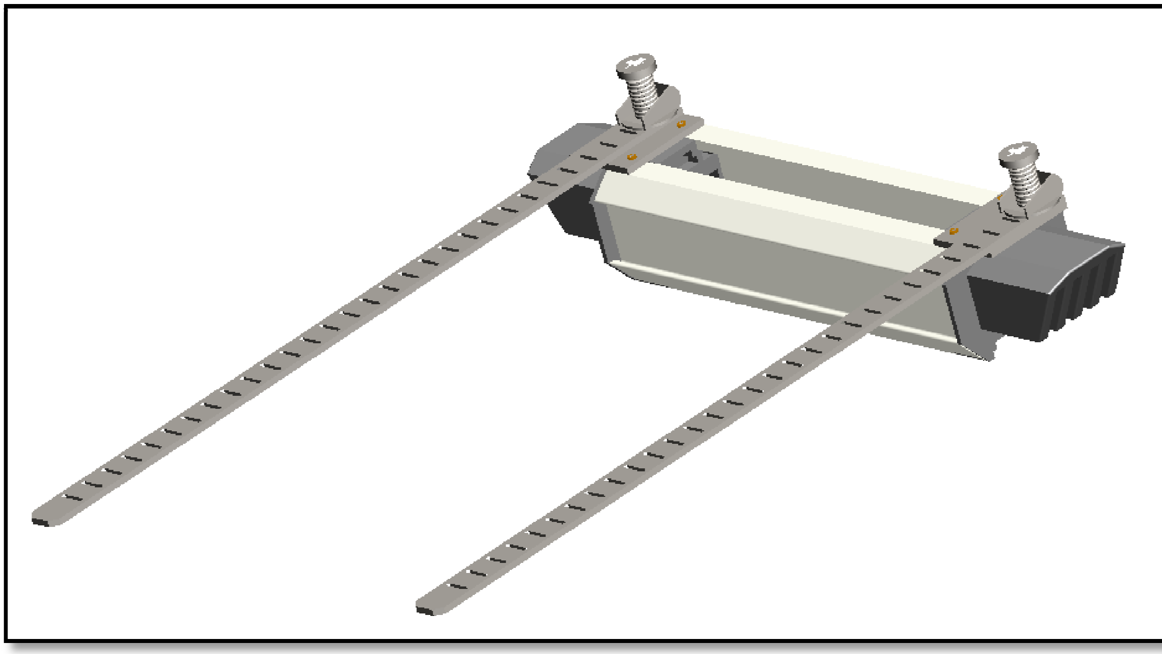


Figure 25: Entire Mounting System

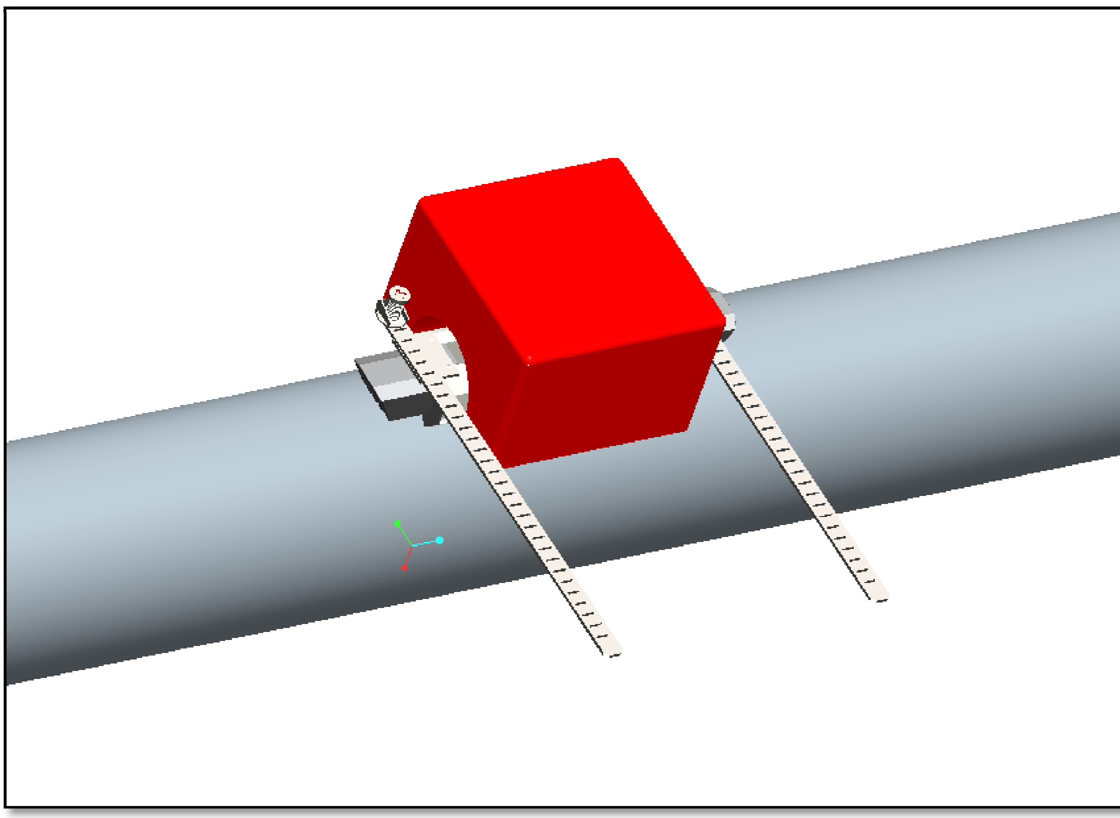


Figure 26: Mounting System with Electronics Housing

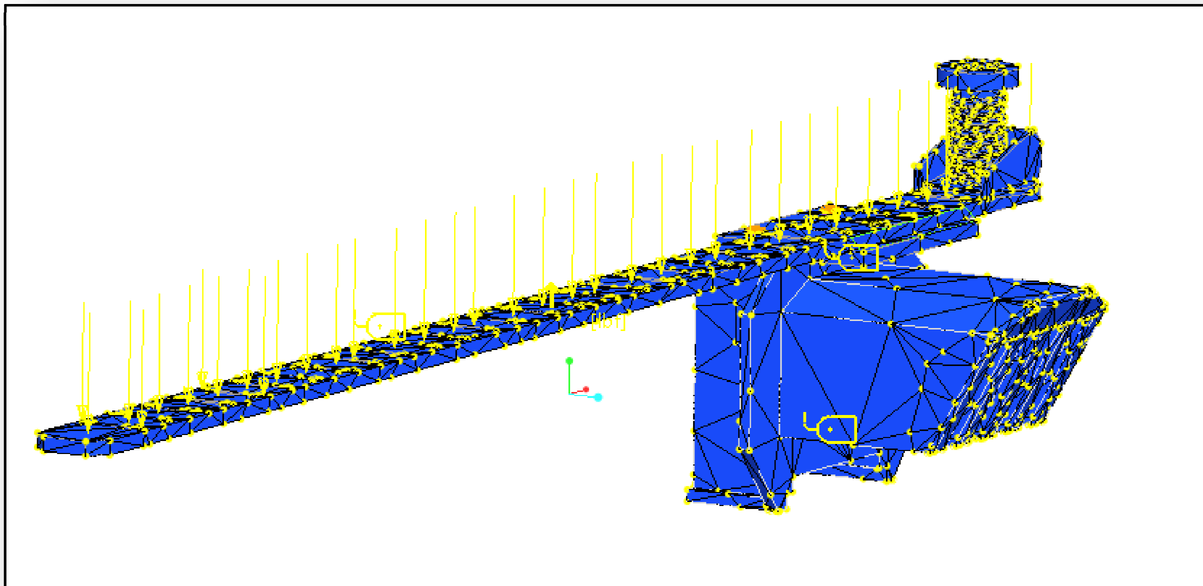


Figure 27: Mesh Grid for FEA

Figure 28: FEA of Principle Stresses

Environmental, Health, and Safety Concerns

There are plenty of environmental, health, and safety concerns that pertain to a natural gas compressor system. However, the use of the particular device discussed and designed here raises no environmental concerns in and of itself. The system is essentially a very small PC, a set of transducers that emit sound well out of the range of human hearing abilities, and a standard Smartphone – the same health and environmental risks that one faces every day while using a computer and mobile phone are the ones posed by this system. However, the environment in which this tool is used creates some safety issues. HSR compressors are often systems that vibrate and shake violently, and thus have the capability to strike a lackadaisical operator with great force, potentially causing blunt force injury. This is why wireless connection of the phone to the flow sensors was a critical design specification – the greater the radius, the better. The wireless network connection allows the operator to set up the sensors and retreat to a safe location to read and analyze flow data.

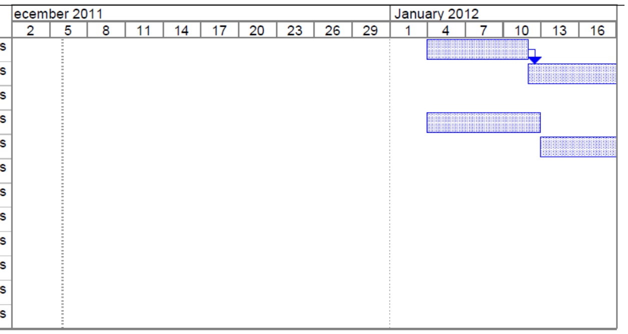
Some legal restrictions have been discovered pertaining to the design of the device, due to the environment in which it will be operated. “The meter shall be suitable for operation in a facility subject to the U.S. Department of Transportation’s (DOT) regulations in 49 C.F.R. Part 192, Transportation of Natural and Other Gas by Pipeline: Minimum Federal Safety Standards” [Code of Federal Regulations, Title 49 — Transportation of Natural Gas and Other Gas by Pipeline: Minimum Federal Safety Standards]. Also, AGA 9 requires the meter be electrically rated for a hazardous environment as defined by the National Electrical Code [NFPA 70, National Electrical Code]. Before the product enters production, it is recommended that an attorney be hired to investigate any other regulations for operating such equipment in a natural gas compressor environment.

Conclusion

After doing much research and calculations, the team has verified that using the signal burst method should be a viable solution in properly obtaining flow through a pipe. The protoytpe produced will be up to current industry standards, if not better. Transit time measurements will be precise to the nanosecond and the electronic equipment used will have fast enough throughput in order to quickly display data on the phone. The displayed data will provide enough information to the GE technician on site to determine if there is indeed a problem with their compressor. Our current clamping mechanism can be applied faster than the implementation on the FUJI flow meter and will be continually refined and upgraded. Based on these verifications, we can conclude that our product meets the specific needs outlined by General Electric.

Below is a tentative schedule on how the team will be going about completing and testing its prototype:

ID		Task Name	Duration
1		Configure Linux OS on SBC	6 days
2		Configure Electrical components for Signal Processing	14 days
3		Verify Sending and Receiving Signal, Calibrate Accordingly	15 days
4		Setup Android Database	7 days
5		Simulate Receiving Data	7 days
6		Configure conversion from velocity to PV	7 days
7		Configure Graph for data we get	7 days
8		Code Kernel Modules for Time Stamping	20 days
9		Code User-Space program for Top-Level Functions	15 days
10		Configure Wireless Access Point	7 days
11		Test and Calibrate Entire System	30 days
12		Construct Housing Solution For Electrical Components	30 days



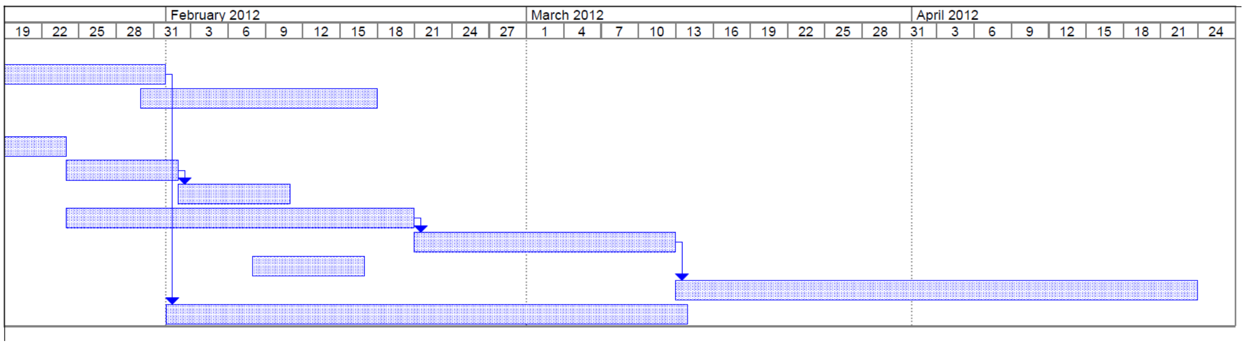


Figure 29: Tentative Schedule for Spring

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Appendix

Some sample calculations:

Input v (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 assumed, and L chosen based on pipe diameter.

$\nu_s := 9.375\frac{ft^3}{s}$ $\nu_d := 19.329\frac{ft^3}{s}$ $\rho_s := 2.9\frac{lbm}{ft^3}$ $\rho_d := 6.18\frac{lbm}{ft^3}$

$T_s := 298.4$ $T_d := 225.5$

$D := 4in$ $L := 10 \cdot D$

$A_{pipe} := \left(\frac{\pi}{4}\right) \cdot D^2$ $L = 40in$ $V_s := \frac{\nu_s}{A_{pipe}}$ $V_d := \frac{\nu_d}{A_{pipe}}$

Dynamic Pressure

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

Pressure Drop in Pipe

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

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

$Re_s := \frac{\left(\rho_s \cdot V_s \cdot D\right)}{\mu_s}$ $Re_d := \frac{\left(\rho_d \cdot V_d \cdot D\right)}{\mu_d}$

$f_s := \frac{64}{Re_s}$ $f_d := \frac{64}{Re_d}$ $V_s = 107.43\frac{ft}{s}$

$\Delta p_s := \frac{\left(f_s \cdot L \cdot \rho_s \cdot V_s^2\right)}{2 \cdot D}$ $\Delta p_d := \frac{\left(f_d \cdot L \cdot \rho_d \cdot V_d^2\right)}{2 \cdot D}$ $V_d = 221.494\frac{ft}{s}$

$P_s := q_s - \Delta p_s$ $P_d := q_d + \Delta p_d$

$\Delta p_s = 3.498 \times 10^{-4} \cdot psi$ $\Delta p_d = 6.705 \times 10^{-4} \cdot psi$

$q_s = 3.612psi$ $q_d = 32.72psi$

$P_s = 3.612psi$ $P_d = 32.721psi$

Transit Time Calculations

Smallest Δ t will occur in case where fluid velocity is closest to zero, thus using largest diameter pipe, lowest flow rate, and highest speed of sound (higher temperature). This combination will never happen, so this is a conservative calculated verification. Also, the length between the transducers is recommended to be same as the outer pipe diameter, so L = D and the incident angle = 45deg/2

$\nu := .327\frac{ft^3}{s}$ $\qquad$ $D := 6in$

$A_{pipe} = 12.566in^2$ $\qquad$ $V := \frac{\nu}{A_{pipe}}$

$V = 3.747\cdot\frac{ft}{s}$ $\qquad$ $\alpha := 22.5deg$

$$a := \left[\left(-2.0388810^{-4}\right)T_s^{\,2} + (1.00405)\cdot T_s + \left(1.0571310^{3}\right)\right]\frac{ft}{s}$$

$V_{up} := a\cdot\sin(\alpha) - V$ $\qquad$ $V_{down} := a\cdot\sin(\alpha) + V$

$V_{up} = 508.507\frac{ft}{s}$ $\qquad$ $t_{up} := \frac{D}{V_{up}}$

$V_{down} = 516.001\frac{ft}{s}$ $\qquad$ $t_{down} := \frac{D}{V_{down}}$

$t_{up} = 9.833\times 10^{-4}s$ $\qquad$ $t_{down} = 9.69\times 10^{-4}s$

$\Delta t := t_{up} - t_{down}$ $\qquad$ $\boxed{\Delta t = 1.428\times 10^{-5}s}$

Established Transit Time Velocity Equation

$V_{ax} := \left(\frac{D}{2\cdot\cos(\alpha)}\right)\cdot\left(\frac{\Delta t}{t_{up}\cdot t_{down}}\right)$ $\qquad$ $Error := \left[1 - \left(\frac{V}{V_{ax}}\right)\right]$

$V_{ax} = 4.056\frac{ft}{s}$ $\qquad$ $\boxed{Error = 7.612\%}$

Therefore, correct method was used to calculate Δ t

Justification for Laminar Flow

$$\rho := .075\frac{lbm}{ft^3}$$

$$V_{high} := 3000\frac{ft}{min} \qquad V_{low} := 100\frac{ft}{min} \qquad k := 1.5\cdot 10^{-3} ft$$

$$D_{high} := 6in \qquad D_{low} := 4in \qquad L_{high} := 10\cdot D_{high} \qquad L_{low} := 10\cdot D_{low}$$

$$T_{high} := 30(\qquad T_{low} := 6(\qquad r_{high} := \frac{k}{D_{high}} \qquad r_{low} := \frac{k}{D_{low}}$$

$$\mu_{low} := \left[\left(-6.70244 10^{-14}\right)\cdot T_{low}{}^2 + \left(5.05027 10^{-10}\right)\cdot T_{low} + \left(3.43615 10^{-7}\right)\right] lbf\cdot\frac{s}{ft^2}$$

$$\mu_{high} := \left[\left(-6.70244 10^{-14}\right)\cdot T_{high}{}^2 + \left(5.05027 10^{-10}\right)\cdot T_{high} + \left(3.43615 10^{-7}\right)\right] lbf\cdot\frac{s}{ft^2}$$

$$Re_{high} := \frac{\left(\rho\cdot V_{high}\cdot D_{high}\right)}{\mu_{high}} \qquad Re_{low} := \frac{\left(\rho\cdot V_{low}\cdot D_{low}\right)}{\mu_{low}}$$

$$f_{high} := \frac{64}{Re_{high}} \qquad f_{low} := \frac{64}{Re_{low}}$$

$$Re_{high} = 1.192\times 10^5 \qquad Re_{low} = 3.466\times 10^3$$

$$r_{high} = 3\times 10^{-3} \qquad r_{low} = 4.5\times 10^{-3}$$

$$f_{high} = 5.371\times 10^{-4} \qquad f_{low} = 0.018$$

$$f_{high.Moody} := .02\text{8} \qquad f_{low.Moody} := .04\text{9}$$

$$\Delta f_{high} := f_{high.Moody} - f_{high} \qquad \Delta f_{low} := f_{low.Moody} - f_{low}$$

$$\Delta f_{high} = 0.027 \qquad \Delta f_{low} = 0.031$$

$$\Delta p_{high.1} := f_{high} \cdot \left(\frac{L_{high}}{D_{high}}\right) \cdot \frac{\left(\rho \cdot V_{high}^{2}\right)}{2}$$

$$\Delta p_{high.2} := f_{high.Moody} \cdot \left(\frac{L_{high}}{D_{high}}\right) \cdot \frac{\left(\rho \cdot V_{high}^{2}\right)}{2}$$

$$\Delta p_{low.1} := f_{low} \cdot \left(\frac{L_{low}}{D_{low}}\right) \cdot \frac{\left(\rho \cdot V_{low}^{2}\right)}{2}$$

$$\Delta p_{low.2} := f_{low.Moody} \cdot \left(\frac{L_{low}}{D_{low}}\right) \cdot \frac{\left(\rho \cdot V_{low}^{2}\right)}{2}$$

$$\Delta p_{high.2} - \Delta p_{high.1} = 5.557 \times 10^{-3}\,\text{psi}$$

$$\Delta p_{low.2} - \Delta p_{low.1} = 6.865 \times 10^{-6}\,\text{psi}$$

$\Delta p_{high.2} = 5.666 \times 10^{-3}\,\text{psi}$ $\Delta p_{low.2} = 1.102 \times 10^{-5}\,\text{psi}$ Moody Diagram

$\Delta p_{high.1} = 1.087 \times 10^{-4}\,\text{psi}$ $\Delta p_{low.1} = 4.152 \times 10^{-6}\,\text{psi}$ Laminar

$$q_{high} := \frac{\left(\rho \cdot V_{high}^{2}\right)}{2} \qquad q_{low} := \frac{\left(\rho \cdot V_{low}^{2}\right)}{2}$$

$$q_{high} = 0.02\,\text{psi} \qquad q_{low} = 2.248 \times 10^{-5}\,\text{psi}$$

$$\frac{\left(\Delta p_{high.2} - \Delta p_{high.1}\right)}{q_{high}} = 0.275 \qquad \frac{\left(\Delta p_{low.2} - \Delta p_{low.1}\right)}{q_{low}} = 0.305$$

$$1 - \left[\frac{\left[\frac{\left(\Delta p_{high.2} - \Delta p_{high.1}\right)}{q_{high}}\right]}{\frac{\left(\Delta p_{low.2} - \Delta p_{low.1}\right)}{q_{low}}}\right] = 10.056\%$$

Difference in total Δ p is a maximum of 10% when assuming laminar vs. turbulent flow