# Developing Accurate Methods to Measure Pressure Fluctuations in Fluidized Beds

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## Introduction

In gas-solid fluidized beds, pressure measurements provide essential information on bed hydrodynamics and any issues in signal detection. Solids tend to pass through a fluidized bed's airway that connects the pressure tap[1] to a pressure transducer. Gas backflushing can prevent the plugging of this line by directing air in the opposite direction (Grace et al., 2020). This study focuses on designing the backflushed system to minimize any degradation in the pressure signal between the fluidized bed and the pressure transducer. To test, a vessel was pressurized to compare the responses of a backflushed system and a reference transducer to a sudden change in pressure.

## Objectives

The short-term objectives of this study are to examine the effects of the backflushing gas flowrate, $f_b$, and the hose lengths $L_1$, $L_2$, and $L_L$, from the pressure transducers and the backflushing gas supply to the tap, on the following:

- Lag time, $t_L$ (in ms): time difference between the actual signal and the detected response.
- Speed, s (in m/s): acquired from the lag time vs. hose length plot.
- Frequency response, $f_r$ (in ms): how fast the pressure transducers respond to changes in pressure.

[1] A pressure tap is the point where you install a connection to a pressure transducer.

- Distortion Index, DI: $\frac{1}{N}(\sum_1^N \Delta y_{dif}{}^2)$ – distortion describes how two signals respond differently. N is the number of points, in ms, a full test lasts for and $\Delta y_{dif}$ is the difference in the signal outputs between the backflushed system and the reference transducer. The derivation and application of this formula will be covered in the analysis section of this report.

The diameters of the hoses $L_1$, $L_2$, and $L_L$ connecting one of the pressure transducers to the backflushing system, and the reference transducer to the atmosphere were chosen to be as small as possible. This is since having hoses that are wide and long would require the air a longer period of time to reach the vessel and the resultant signals would need more time to be detected.

The long-term objectives of this research study include using the lag time to determine the rise velocity of bubbles in fluidized beds (Yates & Lettieri, 2016). Also, each differential pressure transducer used has two ports for signal detection. The distance between these ports reflects the distance bubbles and particles would cross as they rise (Grace et al., 2020). Lastly, the degradation of pressure signals can be analyzed to identify the fluidization regime in a fluidized bed, and to identify potential dipleg flow issues by considering the pressure differential across certain pipes (Broodryk et al., 1993).

## Methodology[2]

### Backflushing

Compressible backflushing gas enters the vessel through a ¼-inch wide hose, and 14.5 mg of that air passes through a sonic orifice per second, eventually to the vessel's central port. See Figure 1 for the backflushing system. The backflushing transducer detects the pressure changes, caused by placing and removing the metal plate, through the hose $L_L$: a clear 0.051-inch hose. The reference

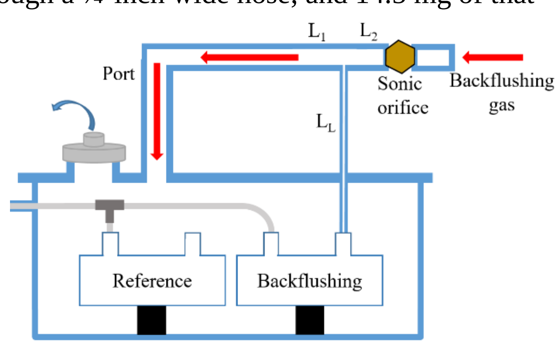

*Figure 1 - Backflushing system in the vessel.*

[2] See appendix for a detailed process of recreating the vessel's physical assembly.

and backflushing transducers are both connected to the atmosphere using another 0.051-inch clear hose. Figure 21 shows an assembly constructed to connect the reference transducer to the atmosphere.

## Procedure

The tests performed required pressure readings, and because the software used receives the data in terms of voltage[3] in VDC[4], a calibration was performed to get pressure values in kilopascals[5]. A 3.2 kg metal plate was used to cover and uncover an 8 cm hole in the vessel's lid; this simulates the increases and drops in pressure in a fluidized bed. An orange rubber gasket was placed underneath the plate to prevent any damage to the bottom surface of the metal plate. The first two series of tests investigated the effect of changing $f_b$ on the $t_L$, $f_r$, and DI of the signals. In the first series, the vessel was pressurized at 6 psi and the initial backflushing gas input was set at 20 psi. The knob of the pressure regulator was turned to increase the backflushing gas input by 10 psi after every test, until 80 psi were reached for the seventh test; increasing the pressure input of the backflushing gas ultimately increases its flowrate. Once recording the data starts, it is important to wait for a minimum of 30 seconds before removing the plate to ensure a stable plateau of values for reliable results. After waiting for the data to stabilize, the metal plate was removed quickly and recording the data ended. A data text file was saved automatically to a DAQ folder. The second series of tests related to $f_b$ was performed using a much smaller range of pressure values, where throughout six tests, the pressure input started at 0 psi and was increased by 1 psi increments up to 5 psi; this was done to check if the previous higher range caused any saturation (i.e. cap) to the sonic orifice that would in return not reflect the actual higher pressure values.

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[3] The voltage from the pressure transducers is proportional to the pressure difference between the two ports of each transducer.

[4] Volts Direct Current

[5] See appendix for calibration process.

The second possible factor[6] in this study is the group of hoses connecting the pressure transducer and the backflushing system. Figure 20Figure 18 shows the three hoses on the vessel's lid: $L_1$ connects the central port to one end of the t-tube connection, $L_2$ connects the second end of the t-tube to the sonic orifice, and $L_L$, connects the t-tube to the backflushing transducer. The lengths of these hoses were changed in a variety of combinations. To start, all three hoses were set at their minimum lengths: $L_1$ is 2cm, $L_2$ is 2cm, and $L_L$ is 177 cm. Then, the vessel was pressurized and the metal plate was placed over the hole on the vessel's lid. Recording of the data started and once the data values seemed to stabilize, the metal plate was removed to release the pressure.

In the second combination of lengths, all three hoses were set at maximum lengths: $L_1$, $L_2$, and $L_L$ are 60.5 cm, 60.5 cm, and 499 cm, respectively. This was done to compare the lower end of the length range to its upper end. The third combination consisted of three series, where in each series only one hose was increased from its minimum to a maximum by a certain length after each test, to see each hose's impact on the response of the pressure transducers. The first series involved increasing only $L_L$ from 177 cm up to 499 cm in 20 cm increments in order to produce sufficient data points. Since the pressure changes underneath the port will go up through the port, $L_1$ and go directly to the backflushing transducer through $L_L$, it was predicted that $L_2$ will not have a strong impact on the $t_L$, $f_r$, and DI of the signals. However, a series of tests was performed to verify this hypothesis by increasing $L_2$ from 2 cm up to 60.5 cm in 11.5 cm increments. Lastly, $L_1$ was increased from 2 cm up to 60.5 cm as well. The tests were as follows: putting the metal plate on the hole, waiting for 30 seconds, and removing the plate.

## Analysis

### Determining the four variables

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[6] The first possible factor was $f_b$. It is a possible factor because it is not yet guaranteed to have any effects on the properties of the pressure responses, until the results are analyzed.

In this study, the pressure transducers were connected in a way that provides two types of readings: a reference signal that is as close as possible to the real signal, and a signal for the backflushing system. Determining $t_L$ refers to determining the time difference between one specific value for both signals: $t_{value}$. Taking $t_{50\%}$ as an example, this would be the number of points, in milliseconds, between the 50% point of the response for both signals. For instance, if the halfway point of two signals is 5 ms apart, then the lag time would be 5 ms. When plotting $t_L$ as a function of the lengths of the hoses, the reciprocal of the slope in ms/cm produces a speed in m/s, which is then compared to the speed of sound; getting a higher speed requires changing the $t_{value}$ used for the lag time. As for the $f_r$ of the signals, this is directly proportional to their degradation: how inclined a signal is. High degradation indicates that the pressure transducers take much longer to respond to a change in pressure.

Lastly, DI indicates by how much two signals respond differently. Visually, the distortion of a graph appears as the inner space between two plots after matching them at one point. The value can be $t_{50\%}$, or any other point, but $t_{50\%}$ was used since its location at the center of a response makes it greatly affected by the distortion. The main term in the DI's definition, $\frac{1}{N}\left(\sum_1^N \Delta y_{dif}{}^2\right)$, is the difference in the signal outputs at every point, as denoted by $\Delta y_{dif}$. It is important to take the sum of all the differences from the start to the end of the response because this considers the full distortion of the signals; taking the average does not truly reflect the variation in the differences. Moreover, $\Delta y_{dif}$ was squared as it was in the work of Beaty et al. (2004). N represents the number of points in the longest response to a pressure drop. In this study, N is 1300 points since the longest response took 1300 ms from the peak to the bottom, and this is shown in Figure 2. It is important to keep the largest value for N the same value for all the DI calculations even if shorter responses occurred; this provides a consistent equation to use. Lastly, the definition uses the reciprocal of N to maintain the consistency with a similar definition by Beaty et al. (2004).

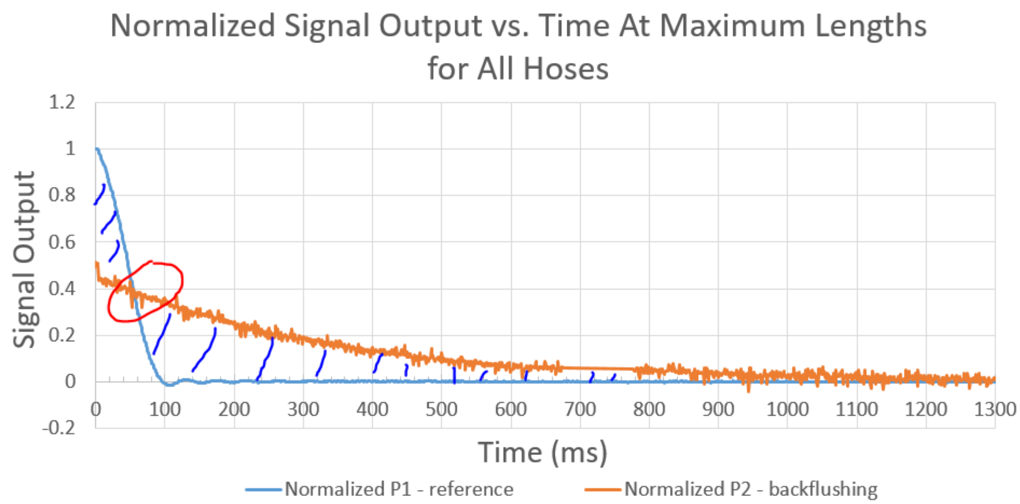



*Figure 2 - After shifting the backflushing signal backwards to meet the reference signal at the point circled in red, the distortion of these two signals is the shaded space in blue. Also, the orange response is the longest in this study, and took 1300 ms. This is why 1300 is used as a value for N in the distortion index formula for this study.*

The Results

$f_b$

To start, the tests showed that changing $f_b$ does not have a specific impact on the $t_L$, s, $f_r$, & DI of the signal outputs. This was the case for both ranges used: increasing the backflushing gas pressure from 20 to 80psi, as shown in Figure 3, and increasing the backflushing gas pressure from 0 to 5 psi, asFigure 4 Figure 5 shows.

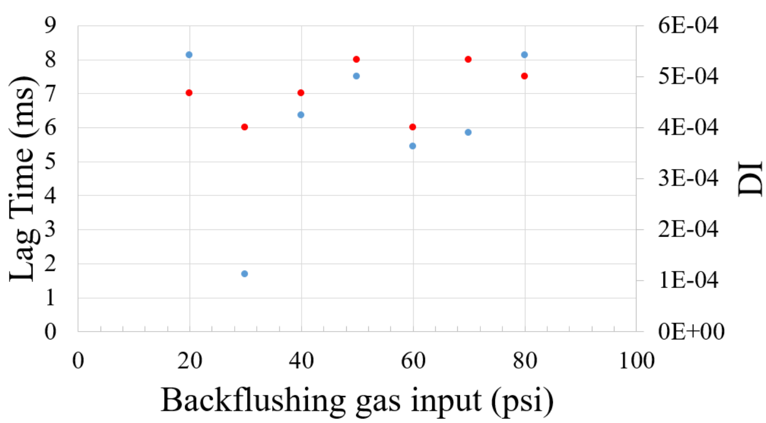



*Figure 3 - $t_L$ and DI as a function of the backflushing gas pressure. There is no clear correlation between $t_L$ (blue) & DI (red) and the input pressure of the backflushing gas.*

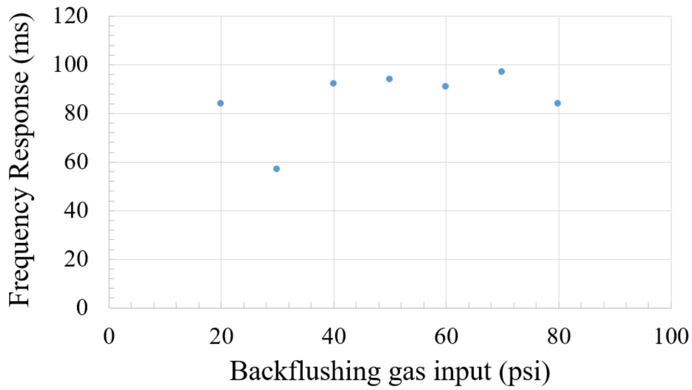



*Figure 4 - $f_r$ as a function of the backflushing gas pressure. This plot shows that $f_r$ of a pressure transducer has no specific dependence on the backflushing gas pressure when a large range of pressure is used.*

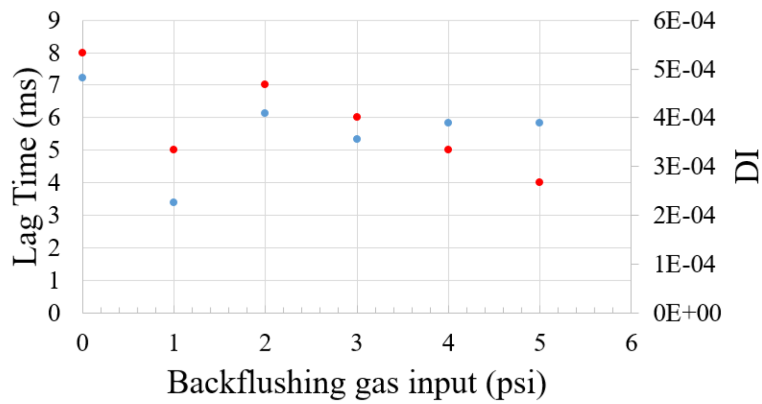



*Figure 5 - $t_L$ and DI as a function of the smaller range of backflushing pressure values. $t_L$ (blue) does not have any specific dependence on the backflushing pressure, while DI (red) seems to decrease with more pressure. Yet, this is not sufficient to declare as a reliable trend.*

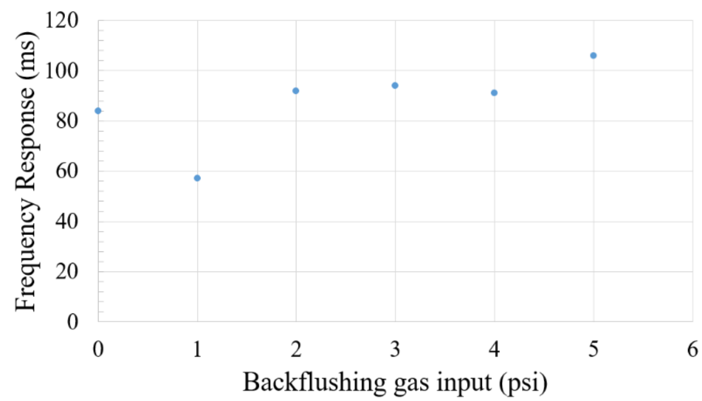



*Figure 6 - In this $f_r$ vs. backflushing gas pressure plot, there is a slight directly proportional relationship between the $f_r$ and the pressure input. This might be because the scale used is more detailed, but more future tests with precise pressure regulators must be used in order to declare this a reliable relationship.*

Hose Lengths

With the combination of the hose lengths $L_1$, $L_2$, and $L_L$, the first variable to analyze is speed, *s*. To determine the speed of a response, the resultant graphs of $t_L$ vs. $L_1$, $t_L$ vs. $L_2$, and $t_L$ vs. $L_L$ were analyzed. The slope of $t_L$ vs. $L_2$ rounds to zero as shown in Figure 7, which proves the earlier hypothesis that $L_2$ is not significant when backflushing is utilized. Also, there is no identifiable correlation between $t_L$ and $L_1$. Therefore, only $L_L$ will be considered to determine the speed of the response. To get the speed, the slope of the plot with $t_{50\%}$, 0.0939 ms/cm, was converted to 0.00939 s/m and then to 106.5 m/s. In order to get a faster speed, different $t_L$ adjustments were used: from $t_{0.5\%}$ to $t_{90\%}$ as shown in Figure 8. It is important to remember that the $t_L$ adjustment moves a signal closer to the reference signal, which corresponds to a smaller lag between the source of the signal and its detection. The largest speed obtained is 140.6 m/s with an adjustment at $t_{3\%}$, which refers to shifting the backflushing signal left to meet the reference signal at 3% from the top of their responses. See Figure 9 and Figure 10 for an illustration when $L_L$ = 499 cm.

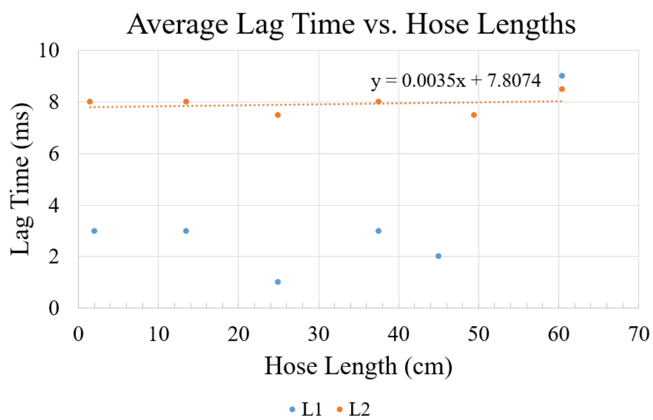



*Figure 7 - Both $L_1$ and $L_2$ are not significant for speed calculations because the lag time does not show any dependence on them.*

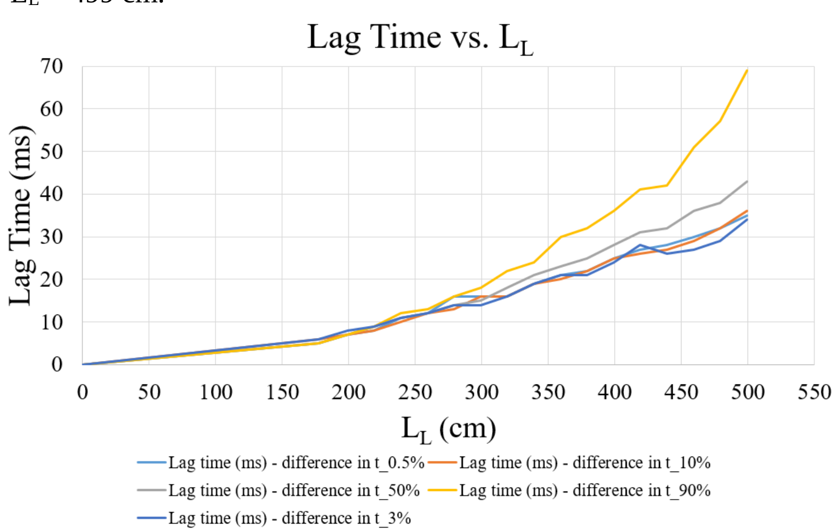



*Figure 8 - Changing the signal output value at which the signals are matched changes the slope of the $t_L$ vs. $L_L$ graph. This in return produces a different speed for the response. Furthermore, this plot shows that the longer $L_L$ is, the longer the lag time.*

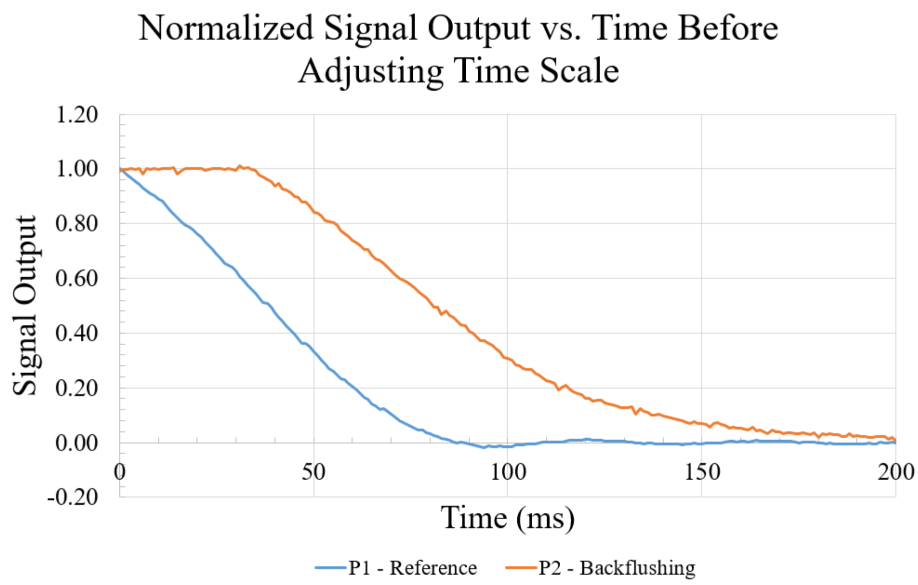



*Figure 9 - This test used $L_L$ = 499 cm, with the signals still not matched at a point. It is not surprising that the lag between the reference and the backflushing signal is high given the length of $L_L$ used is the maximum: 499 cm.*

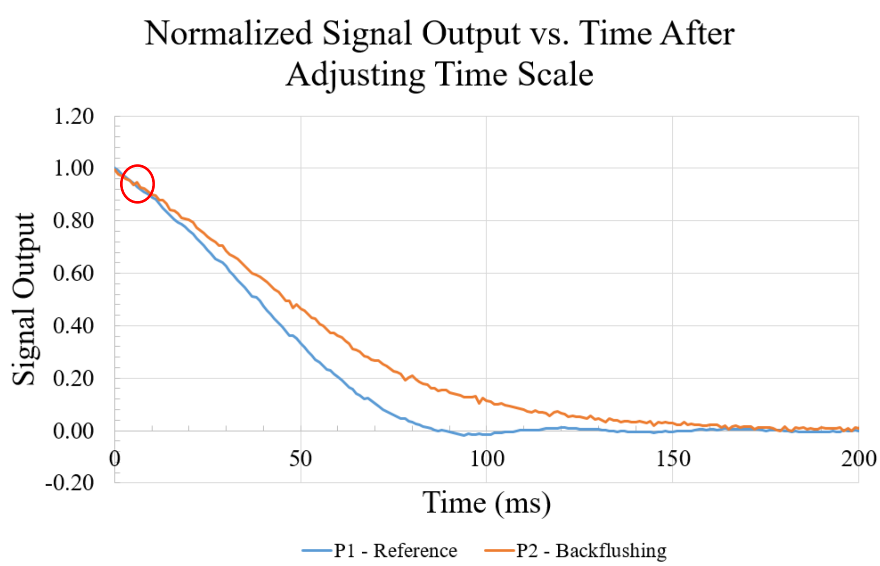



*Figure 10 – The backflushing signal was shifted left to meet the reference signal at 3% of the reference signal's response.*

Therefore, for $t_L$, Figure 7 shows that $L_1$ and $L_2$ do not have significant impacts on the $t_L$, and Figure 8 shows the impact of $L_L$ on $t_L$. These patterns are also similar for DI, as shown in Figure 11 and Figure 12.

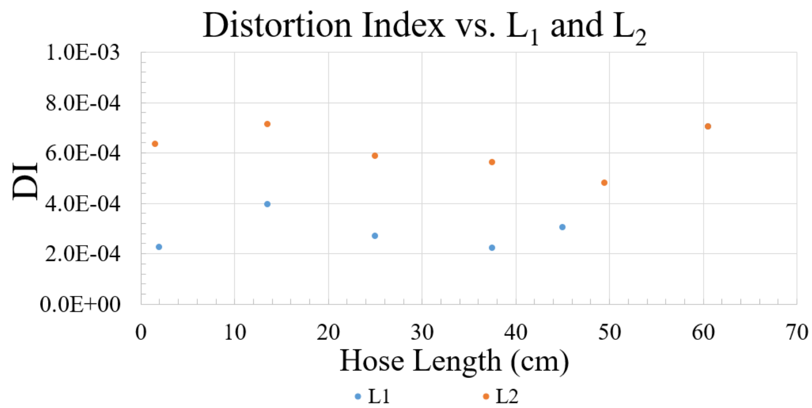



*Figure 11 - This plot shows that DI does not necessarily depend on the lengths of $L_1$ and $L_2$. Please note that the points at 49.5 cm and 60.5 cm overlap.*

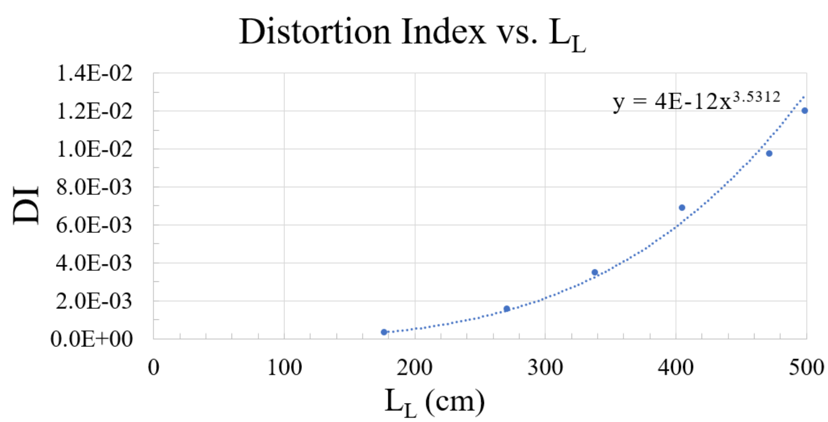



*Figure 12 - From the tests, DI appears to have an exponential dependence on $L_L$. So far, it has been shown that $L_L$ is the main factor out of the three lengths that affects the $t_L$ and DI of pressure signals.*

The last variable in this section to analyze is $f_r$, the frequency response. This describes the duration of time pressure transducers need to respond to changes in pressure.

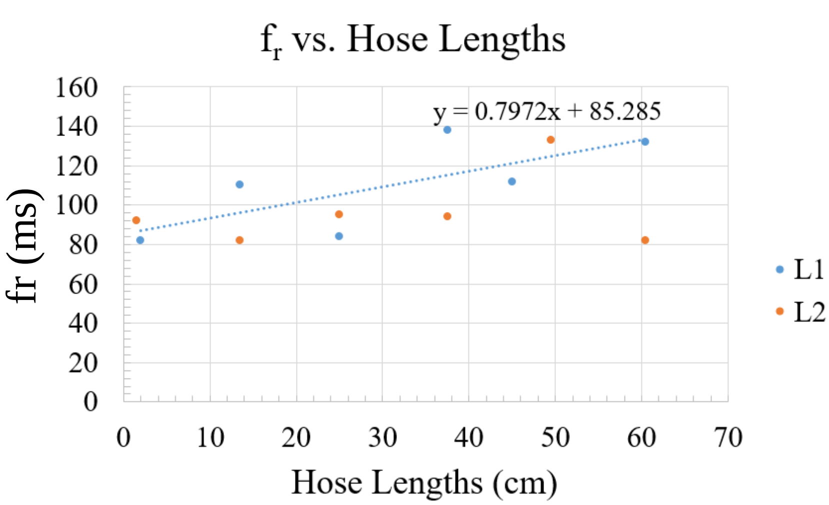



*Figure 13 - This plot shows that as $L_1$ increases, the pressure transducers need slightly more time to respond to a change in pressure. This is because $L_1$ is along the main backflushing line leading to the vessel's interior. However, $L_2$ does not have an identifiable relationship with $f_r$ and this was also the case with DI and $t_L$.*

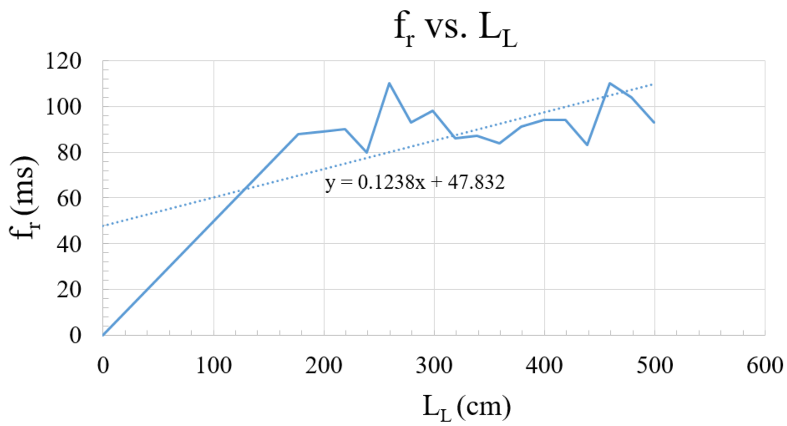
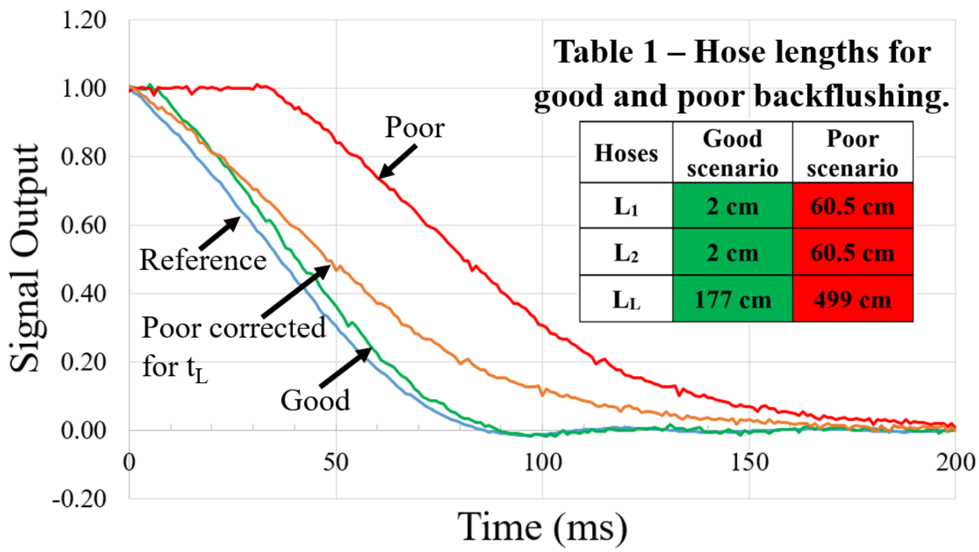



*Figure 14 - As $L_L$ increases, fr increases significantly. This is justifiable since as the distance between the backflushing system and the backflushing transducer increases, more time will be required to respond to the same change in pressure.*

Finally, this last section discusses the impact of the hose lengths $L_1$, $L_2$, and $L_L$ on the quality of backflushing in a fluidized bed. Figure 15 shows that using minimum lengths of hoses results in a shorter $t_L$ and better backflushing since the pressure transducer will be closer to the backflushing system. This was also shown in the previous plots of $f_r$ as a function of the hose lengths, and DI as a function of the hose lengths.




| Hoses | Good scenario | Poor scenario |
|---|---|---|
| $L_1$ | 2 cm | 60.5 cm |
| $L_2$ | 2 cm | 60.5 cm |
| $L_L$ | 177 cm | 499 cm |

*Figure 15 - Signal output of pressure transducers as a function of time. Minimum hose lengths result in better backflushing in a fluidized bed. The orange signal was shifted left to correct for $t_L$.*

## Conclusion

All in all, this study found that utilizing a backflushing system prevents the blocking of the airway that transmits pressure to the backflushing pressure transducer. Changing $f_b$ does not affect the response of the pressure transducer in terms of their $t_L$, $f_r$, and DI. However, having short connections between the backflushing system and the pressure transducer results in signals of little degradation and distortion, and a fast response to the change in pressure. Also, the $t_L$ will be shorter, which corresponds to a smaller adjustment for the backflushing signal.

Overall, this research study would serve as a helpful tool for other studies aiming to further improve the efficiency of detection of pressure changes in fluidized beds. This, as result, can help with the long-term objectives stated above: determining the fluidization regime, and identifying any dipleg flow issues and the rise velocity of bubbles in fluidized beds.

## Abbreviation Index

| | |
|---|---|
| $f_b$ | backflushing gas flowrate |
| $t_L$ | lag time |
| s | speed |
| $f_r$ | frequency response |
| DI | distortion index |

Appendix

## 1. Pressure calibration

The calibration started with turning on the gas input and setting the pressure regulator of the vessel at a preliminary pressure (e.g. 2 psi). Then, a water manometer was connected to a hole in the back side of the vessel in order to measure the change in the water's height. This was repeated nine times, as shown in the diagram on the right, until sufficient data points can produce the following equation:

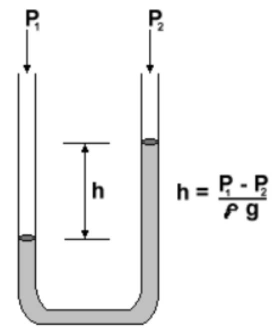



*Figure 16 - U-tube manometer used to calibrate the pressure transducers (Devenport and Borgoltz 2016).*

$$P = aV + b$$

where P is pressure and V is voltage. With this equation, any voltage reading can be converted to pressure.

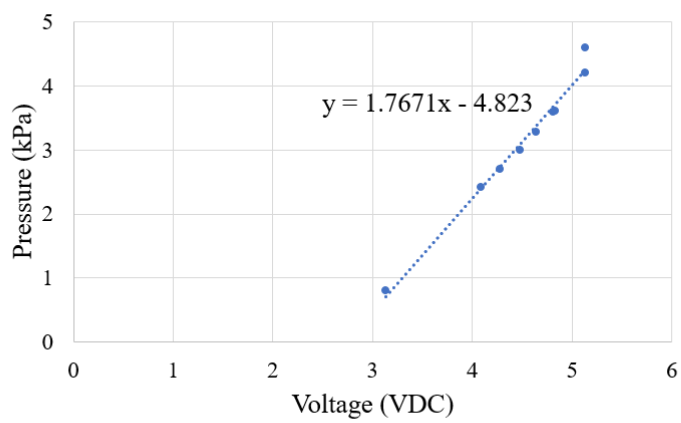



*Figure 17 - Pressure vs. Voltage plot to calibrate the pressure transducers.*

## 2. Emergency procedure

In the case of an emergency involving excessive pressure accumulation inside the vessel, the metal plate must be removed immediately (i.e. uncover the hole on the lid), the handle of the main gas pipe's valve must be closed, as shown in Figure 23, to prevent any more air from going into the tank, and the pressure regulators in Figure 24 must be turned off by turning the handles of their valves to block the airway.

### 3. Full assembly of vessel

The vessel was assembled to simulate the pressure changes in a fluidized bed. The vessel has a volume of 242 L, and is covered with a metal lid of a 0.865 m diameter, as shown in Figure 19. To pressurize the vessel, compressed air from a gas pipe flows into the pressure regulators, and 6 psi of air is the maximum the tank can take as a setting on the top pressure regulator's gauge. Air enters the half-inch wide hose leading to a one-inch metal valve on the tank's lid. A pressure relief valve of 10 psi (6.89 kPa) is attached on top of the pressure input column, and acts as a safety tool in the case of excessive pressurizing of the unit. The second safety measure is securing a glass window on the front side of the vessel using bolts and duct tape, as shown in Figure 25; this prevents the glass window from ejecting away from the vessel once the vessel is pressurized.

The wires of the pressure transducers connect from the transducers' pressure cart inside the vessel up through the port at the centre of the vessel's lid. Then, these wires reach the exterior of the vessel and connect to the National Instruments Data Acquisition system NI USB-6009. A USB cable is then used to connect the DAQ unit to the computer for data recording, and a LabWindows CVI program is used to acquire and display the pressure readings.

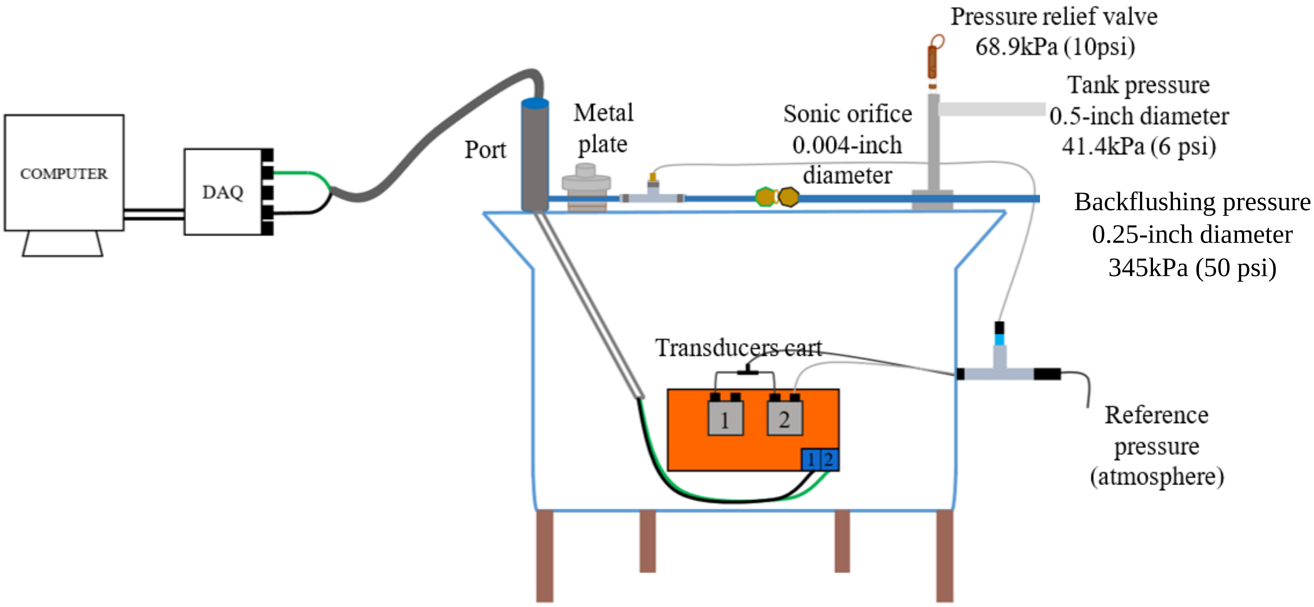



*Figure 18 - Overview of vessel assembly.*

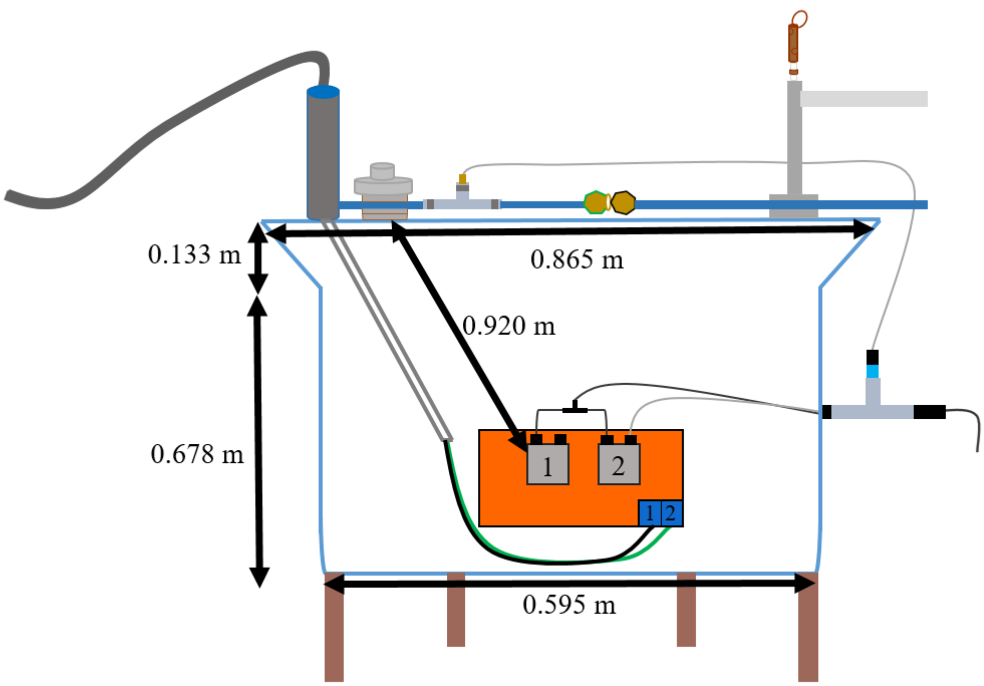



*Figure 19 - Dimensions of vessel.*

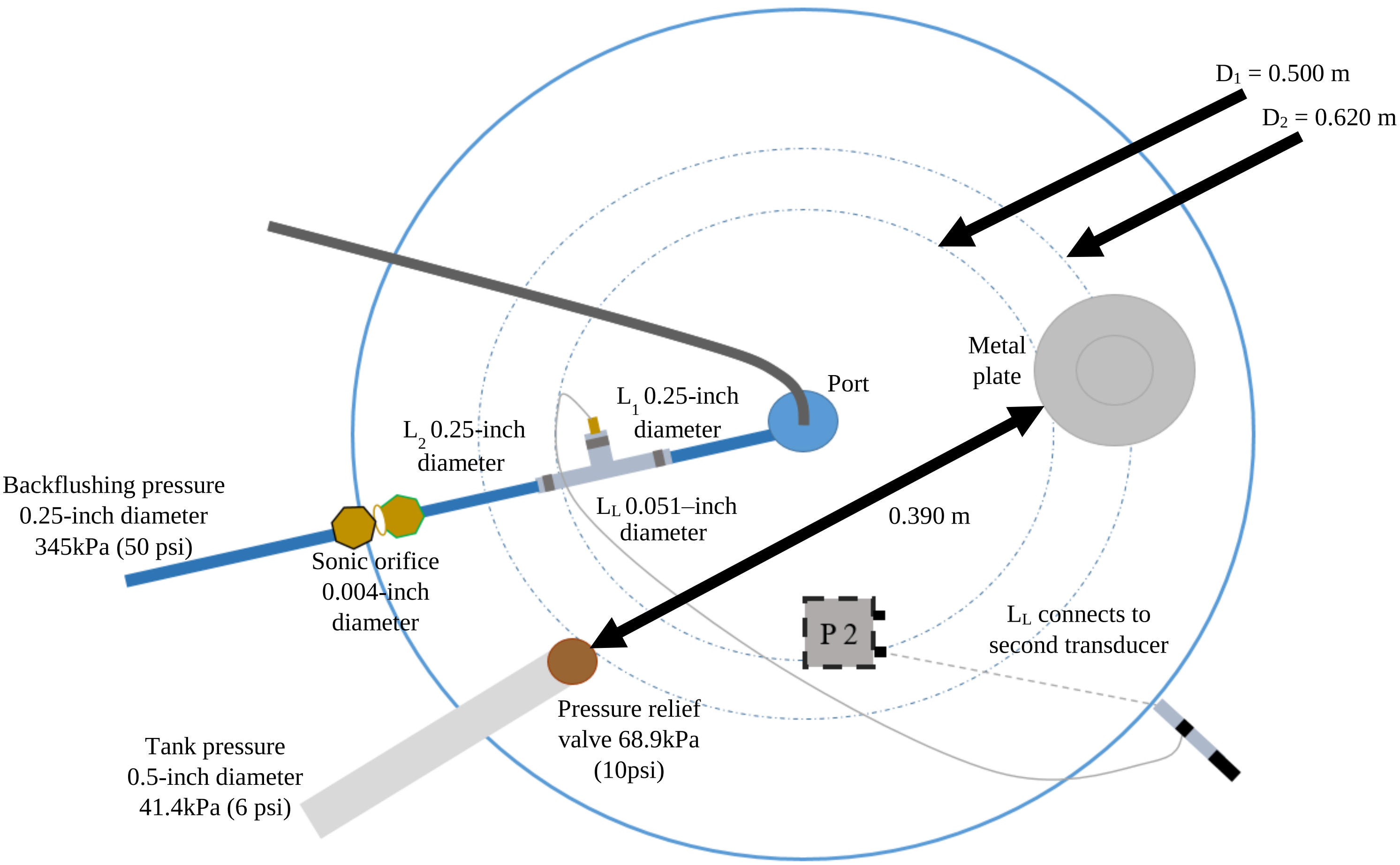



*Figure 20 - Dimensions and parts of the vessel's lid.*

*Figure 21 - T-tube connection with pressure transducer hoses passing through it to reach the backflushing system and the atmosphere. Since this assembly was constructed with materials on hand, possible alternatives can be used to simulate the same process.*

*Figure 22 - 10 psi (6.89 kPa) pressure relief value is included as a safety tool. It's top part moves up to let the extra air leave the vessel.*

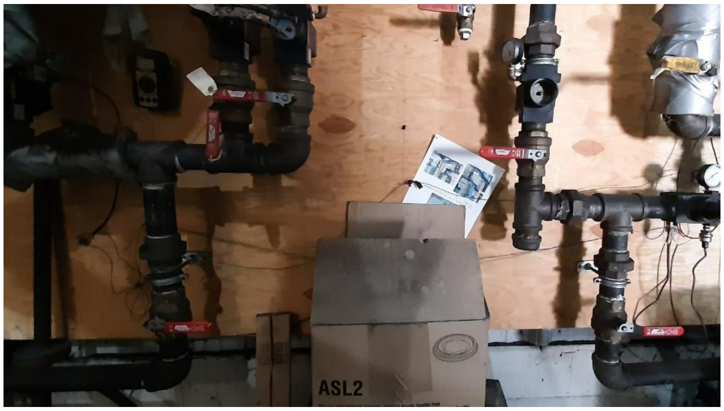



*Figure 23 - The bottom left red handle is to be opened and closed for gas entry into the vessel.*

*Figure 24 – The top pressure regulator is for the whole vessel, and the middle pressure regulator supplies the backflushing gas.*

*Figure 25 - Secured window of the vessel.*

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