Time Series Analysis and the Propagation of Pressure Pulses in a Solids Circulation System

Ronald W. Breault[*] *and Lawrence J. Shadle*

National Energy Technology Center
[*]*National Research Council Senior Associate*
U.S. Department of Energy
3610 Collins Ferry Road, Morgantown, WV 26507-088

Abstract

In advanced energy process technologies, like the advanced pressurized circulating fluidized bed (CFB) process conceptualized by Foster Wheeler Corp., there exists a need to transport and control the flow of solids from a high pressure vessel to a low pressure vessel. Solids transport has long been done in the refinery industry and in the CFB combustor industry, but always from a low pressure vessel to a high pressure with the use of a pressure building standpipe. The key issue in the transport of solids from a high pressure vessel to a low pressure vessel is in the control of this process. At low temperatures, a valve can be used. However, at high temperatures, the use of a valve is not possible. A non-mechanical solution is required: the N-Valve.

The N-Valve is a non-mechanical valve developed to control the transfer solids from a high pressure vessel to a low pressure vessel. Unlike conventional non-mechanical valves (L-Valve, J-Valve and Loop seal) pressure does not have to be built within a standpipe to promote the transfer of the solids. The differential pressure between the two vessels is more than enough to cause the solids to flow from the high pressure vessel to the low pressure vessel. Thus, the N-Valve was configured with a vertical lift which dissipated the pressure difference between the two vessels.

The work presented in this paper outlines the successful operation of a cold flow scaled model of the N-Valve conceptualized for the advanced pressurized CFB. Specifically, the paper reports on the stability of the solids flow rate entering and exiting the N-Valve, the ability to control/modulate solids flow with move air, and the effect of the particulate filter back pulse on the system static pressure and on the N-Valve pressure drop.

Introduction

The N-Valve is a non-mechanical valve developed to control the transfer solids from a high pressure vessel to a low pressure vessel. Unlike conventional non-mechanical valves (L-Valve, J-Valve and Loop seal) pressure does not have to be built within a standpipe to promote the transfer of the solids. The differential pressure between the two vessels is more than enough to cause the solids to flow from the high pressure vessel to the low pressure vessel and given that you could have a mechanical valve operate in the hot-erosive hostile environment solids transport could be done quite easily and effectively. The problem is that mechanical valves will not operate in the hot erosive environment. Thus, the N-Valve was configured with a vertical lift which dissipated the pressure difference between the two vessels.

N-Valve Concept

In an Advanced Pressurized Fluid Bed (APFBC) application [1] an N-valve has been proposed to transfer a char fuel from a high-pressure, spouted fluid bed carbonizer to a lower pressure, circulating fluid bed combustor. An N-Valve is a non-mechanical device that is used to provide a pressure seal and to control the solids flow rate between a high pressure vessel and a low pressure vessel. Foster Wheeler and PSRI had designed a completely integrated APFBC system using this non-mechanical valve in the Power System Development Facility (PSDF) in Wilsonville, Alabama [1,2]. In that pilot plant the N-valve was designed to carry hot char from a fluidized bed carbonizer to a circulating fluidized bed combustor.

A simplified sketch of an N-Valve system is shown in Figure 1. In this figure, solids are shown being transported from the high pressure fluidized bed to a lower pressure riser of a circulating fluidized bed reactor. Solids spill from the pressurized fluidized bed at A and descend to point B where they are picked up in a vertical transport section. The solids are transported vertically up in a step that dissipates the pressure difference between the high pressure vessel and the low pressure vessel (location C). The solids then fall into the riser (location D). The “N” in the N-Valve is more apparent when looking at the pressure plot in Figure 1. The pressure plot for the N-Valve looks like the letter “N”. The two solids descent lines are represented by the vertical lines on the pressure plot and the lift line consumes the excess pressure between the two vessels and is represented by the line with the negative slope connecting the two vertical lines.

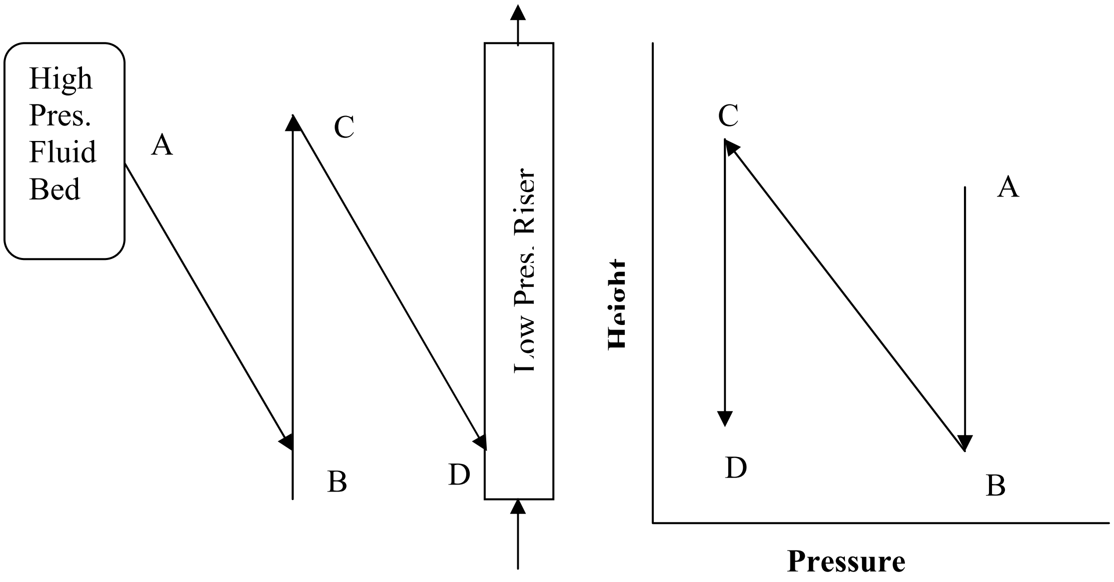


Figure 1 N-Valve Concept Sketch

N-Valve Experimental Test Program

An experimental test program was developed and conducted to obtain operating parameters to support the APFBC combustor concept using an N-valve char transfer system. Upon developing a commissioning plan for the N-valve the researchers identified a number of potential issues that required technical assessment to insure safe and reliable operations. Shadle et al. [3] studied the concerns that a fluidized bed coal carbonizer with limestone would exhibit a wide distribution of particle sizes and densities leading to segregation and eventually plug the N-valve. Their demonstration scale tests in a 5-foot high 10-inch diameter loopseal identified a fluidization rate, defined as the complete fluidization velocity, above which all segregation is avoided. It was found that accumulated coarse and dense particles are mixed and transferred using high gas flows between 3 and 20 times the minimum fluidization velocity. The pressure seal is relatively stable even at these high gas flow rates requiring more than 20 minutes to reduce 50% of the pressure difference across the loopseal.

However, the N-valve in the APFBC is smaller in diameter and much taller than the loopseal tested and more complex having several additional solids streams entering at intermediate heights along the lift-leg. The question of pressure seal or solids blow out is thus exacerbated due to the high length/diameter that favors slugging rather than smooth fluidization. In addition, the seal may be adversely affected by back-pulse cleaning of the candle filters situated directly above the highest solids feed leg into the N-valve lift-line. The circulating fluidized bed combustor also relies upon the N-valve for relatively stable fuel feed rate. Thus, the purpose of this evaluation of the N-valve is to observe the operating characteristics, identify necessary parameters for stable operations, and better understand critical design features. This program consisted of designing and building a pilot scale N-Valve test loop at DOE's cold flow test facilities at the National Energy Technology Center in Morgantown, WV. The N-Valve is 6 inches in diameter and has an overall solids transport length of about 90 feet. This consists of a 28 foot pressure dissipating lift line and two sloped downcomers: one from the fluid bed entering the bottom of the lift line, and the second being the overflow from the top of the lift leading to the riser.

The modified (Breault 2004) N-Valve was conceptualized to eliminate the effect the diplegs filling and emptying have on the solids flow rate. The modified system is shown in Figure 2. Specifically, the transport line between the top of the N-Valve liftline and the CFB riser in the original configuration was replaced with an L-Valve and gas vent system at the top of the liftline. The vertical section of the L-Valve within the overall N-Valve allows for the incorporation of a solids spiral as noted in the figure. A detailed description of the operations and calibration of the spiral flow meter can be found elsewhere [4]. In this application the spirals were 4 inches wide twisted vanes placed in the moving solids bed such that the rotational rate could be used to provide a continuous measurement of the volumetric flow rate of solids. For steady operation, that is constant heights in the diplegs, the flow rate in the two spirals will be equal.

A typical pressure plot profile of the modified configuration is shown in Figure 3. The effect of the L-Valve within the N-Valve appears in the line segment GG'H as compared to the original configuration GH. The section GG' resembles the original configuration and is the section of GG'H that runs empty of solids. In the section G'H, pressure builds as the solids descend in the L-Valve. The results of this pressure rise lead to the bend in the line segment GG'H as noted in the insert. This pressure rise adds stability to the N-Valve system. However in comes at the expense in the size of the possible N-Valve pressure drop.

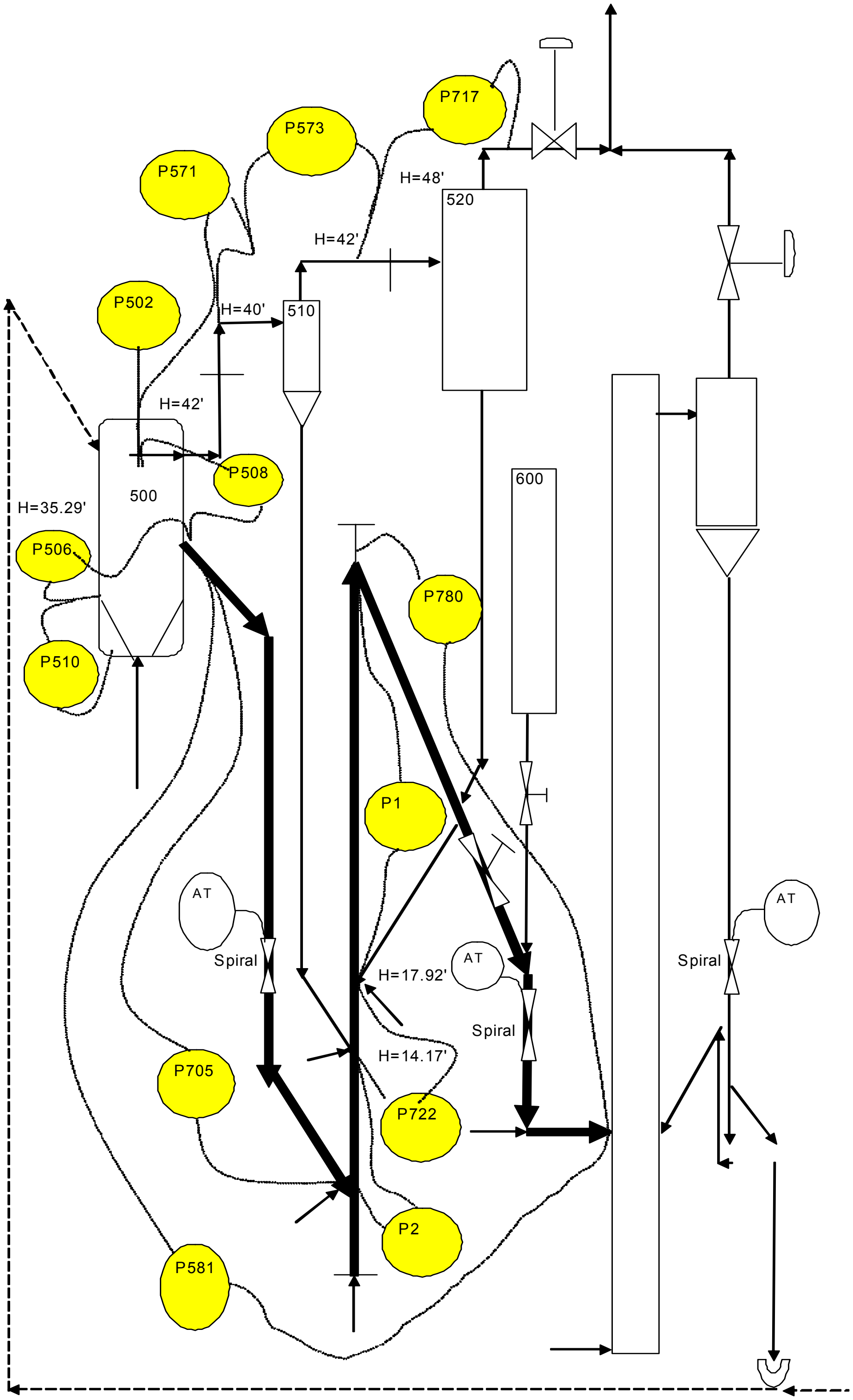


Figure 2 Modified System Configuration

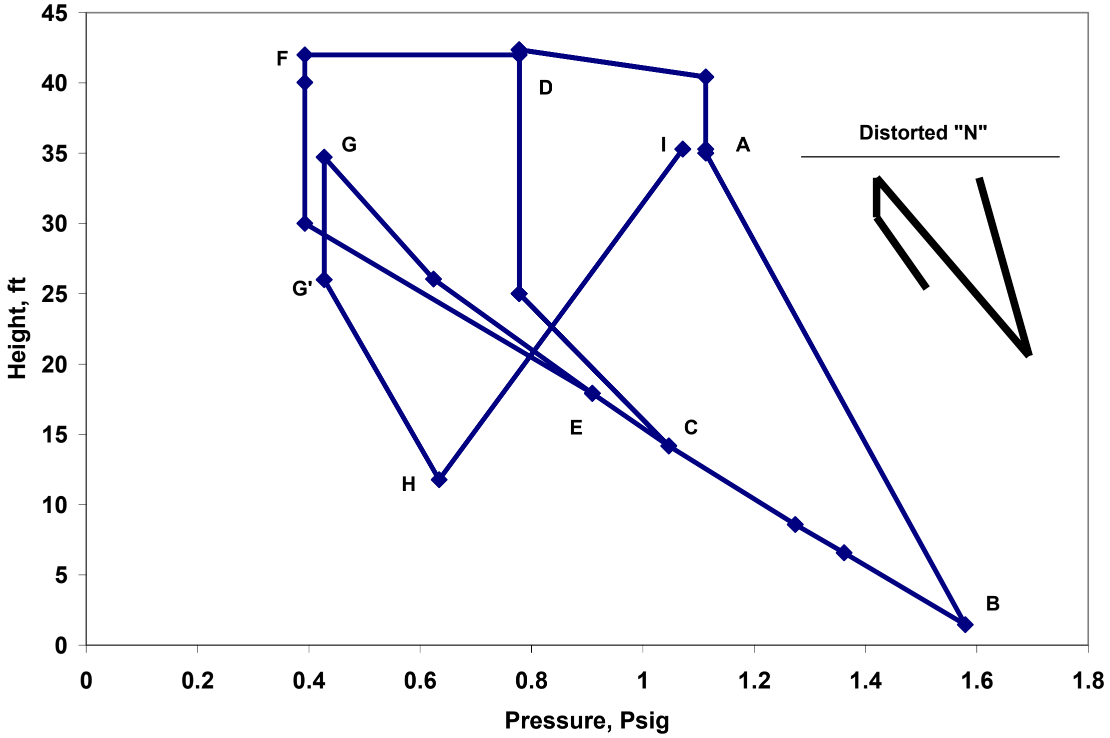


Figure 3 Modified Pressure Profile

Operational Parameters Investigated

N-Valve Pressure Drop. The primary variable explored during the N-Valve testing was the N-Valve Pressure drop. This pressure drop is measured from the entrance to the N-Valve in the fluidized bed to the exit of the N-Valve in the riser of the CFB. It is a composite measurement of the pressure drop in the N-valve downcomer, liftline and discharge line (L-Valve in modified configuration). This pressure drop was explored over the range from 0.35 psi to 1.5 psi.

System Pressure. The static pressure of the system was explored over the range between atmospheric conditions (0 psig) and 2 atmospheres (15 psig). This allowed the effect of gas density to be examined.

Gas-side Pressure drop. This is a measurement of the pressure drop across the gas path from the fluidized bed to the candle filter. With respect to Figure 2, it is the sum of P571, P573 and P717. This pressure drop is a nominal upper bound to the N-Valve pressure drop.

Solids Flow rate. Solids flow rate through the N-Valve was varied between 1 nominal value of 100 lb/hr to a nominal value of 400 lb/hr.

Solids. A relatively light material was selected for the initial work on the N-Valve. This was selected to generate data relevant to advanced high-pressure coal conversion technologies. By using a Buckingham-Pi analysis of a pressurized CFB riser, the density ration between the gas and the solids is identified as a critical parameter. A Cork and low pressure air density ratio provides a comparable value to that of coal and high pressure (10 to 20 atm.), high temperature (1000 C) gas. The cork properties are provided in Table 1 and the size distribution presented in Figure 4.

Table 1 Cork Properties

ρ_s	kg/m^3	189
ρ_s	kg/m^3	95
ε_b	------	0.45
d_{p50}	μm	1280
d_{av}	μm	1007
U_t	m/s	0.86
U_{mf}	m/s	0.17
ε_{mf}	------	0.50
φ	------	0.69

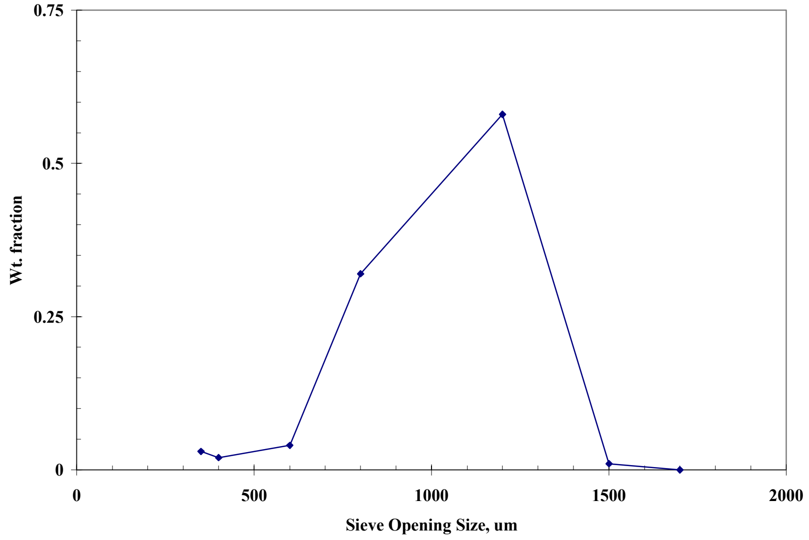


Figure 4 Typical Size Distribution of Cork Bed Material

Transient and Time Series Data Analysis

Data from the experiments is collected and stored every second. This data is explored and analyzed in this section of the report to better define the operating characteristics of the N-Valve. The times series data discussed are for the following three test days: March 13, 2003, April 17, 2003 and May 9, 2003. The following characteristics have been analyzed.

- Stability of Solids Flow Rate Entering
- Stability of Solids Flow Rate Exiting

- Comparison of Solids Flow Rate with Move Air
- Comparison of Solids Flow Rate with Lift Line dP_{top}
- Effect of Back Pulse on System Static
- Effect of Back Pulse on N-Valve dP
- Effect of plenum flow(gas side dP) on N-Valve dP
- Effect of static Pressure on Solids Flow (see #3)
- Comparison of solids flow to N-Valve dP

Stability of Solids Flow Rate Entering

The solids flow rate is shown as a function of time in Figure 5. As can be seen from a review of the figure, the solids flow rate has considerable variation on a second by second basis. The figures also show the 5 minute average, the solids flow set point values and the times in which the steady state data was saved. The solids flow rate average value correlates good with the set point values. This is a significant finding in that it infers that with active control, a “steady” flow rate of solids into the N-Valve can be maintained. A question that does arise from this data is: can the reactor which is being fed with the N-Valve absorb the instantaneous spikes without experiencing adverse performance.

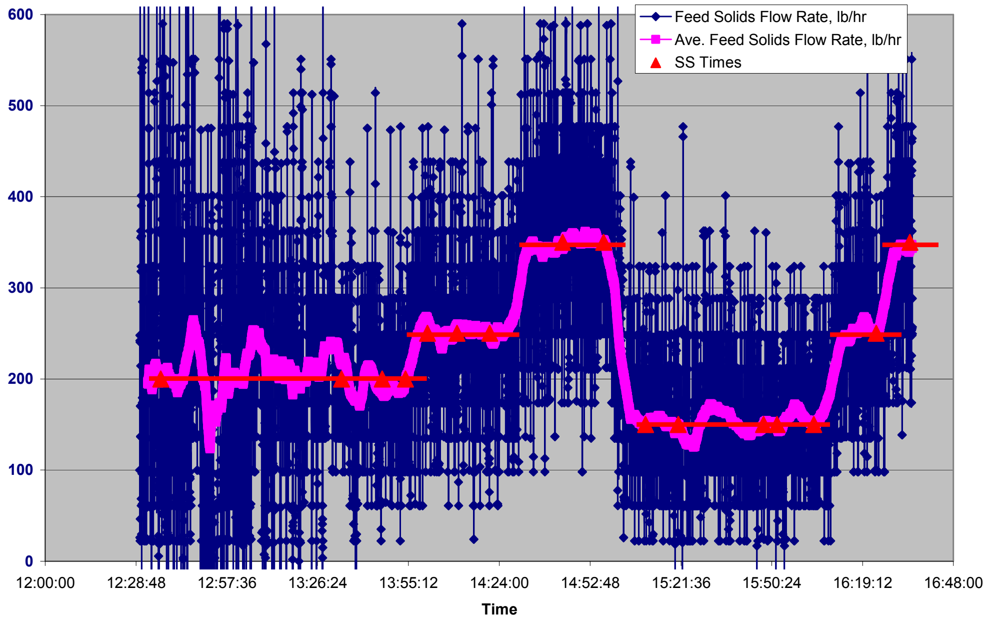


Figure 5 Solids Feed Rate Data for 03/13/03 Test

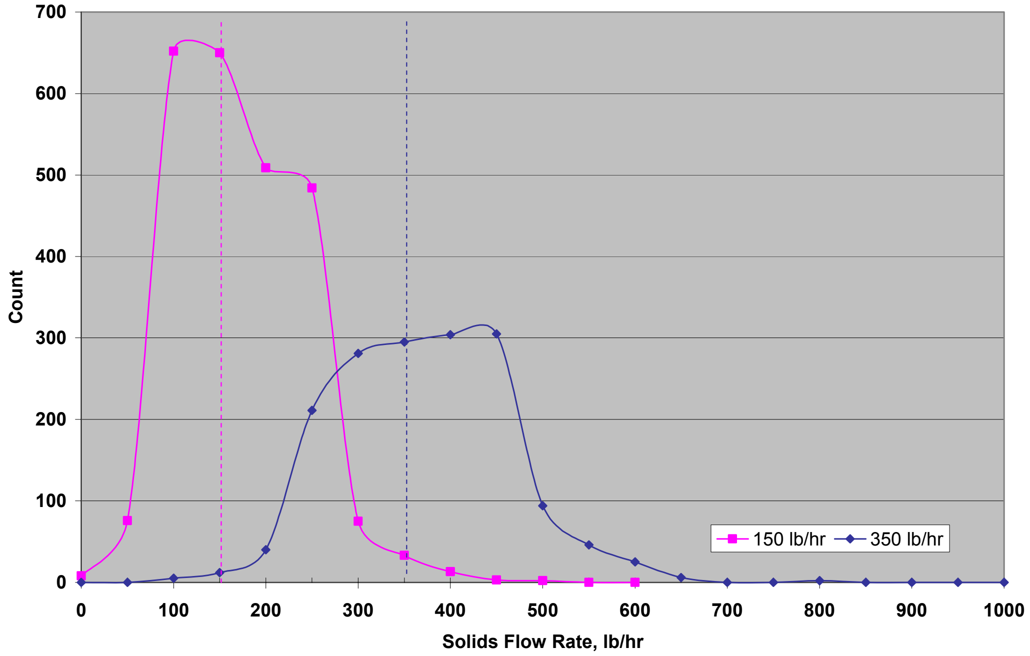
The data seemed to indicate that the fluctuation in the second by second values for the solids flow rate were considerable greater as the solids flow rate increased. In order to verify this hypothesis, the time series data for the most stable periods were analyzed by developing the frequency histogram shown in Figure 6. This figure compares the frequency of the flow rate reading (count) versus the solids flow rate for two sets of data taken form the 03/13/03 time series run. The data in both traces in the figure substantially follow a normal distribution about the mean. Deviation form normal behavior is most likely related to other process parameters changing during the test period.

The statistical parameters for the data shown in Figure 6 are presented in Table 2 (first two columns). Comparing the mean, mode and median for the feed, it can be seen that they are approximately equal to each other, another indication that the feed data is normally distributed. The standard deviation for the 150 lb/hr data is 66 where as it is 89 for the 350 lb/hr data. The magnitude of the second by second variations in the solids flow as determined by the standard deviation increases by about 50% as the solids flow doubles.

Figure 6 Comparison of Velocity Distribution for 03/13/03 Test

Table 2 Solids Flow Rate Distribution Statistics

	Feed		Exit
Set Point	150 lb/hr	350 /b/hr	350 /b/hr
Mean	150.969	346.741	332.1344
Standard Error	1.329315	2.215794	3.916804
Median	136.803	329.067	332.599
Mode	134.954	323.521	258.651
Standard Deviation	66.5322	89.34898	157.94
Sample Variance	4426.534	7983.241	24945.04
Kurtosis	0.538547	0.563414	1.332577
Skewness	0.490811	0.319059	0.614086
Range	491.7515	680.3184	1360.111
Minimum	-14.7895	97.9806	29.3689
Maximum	476.962	778.299	1389.48
Sum	378177.4	563800.9	540050.5
Count	2505	1626	1626
Confidence Level(95.0%)	2.60667	4.346114	7.682519



Stability of Solids Flow Rate Exiting

The N-Valve system was modified as discussed by Breault [5] to incorporate an L-Valve with in the N-Valve to provide more stability and allow for a solids flow rate spiral to be included in the vertical leg of the imbedded L-Valve. The system in this configuration proved to be problematic to operate. This is due to the in ability of the modification to vent the liftline gas and not convey the solids down through the imbedded L-Valve. The most stable exiting solids flow rate data was obtained on 03/13/03. This data is plotted in Figure 7 and compared to the entering solids flow rate data. Observance of the two average trend lines shows that the exiting solids flow rate tracks the feed solids flow rate reasonable well. The most startling observation is the huge oscillations in the solids exiting flow rate as compared to the feed

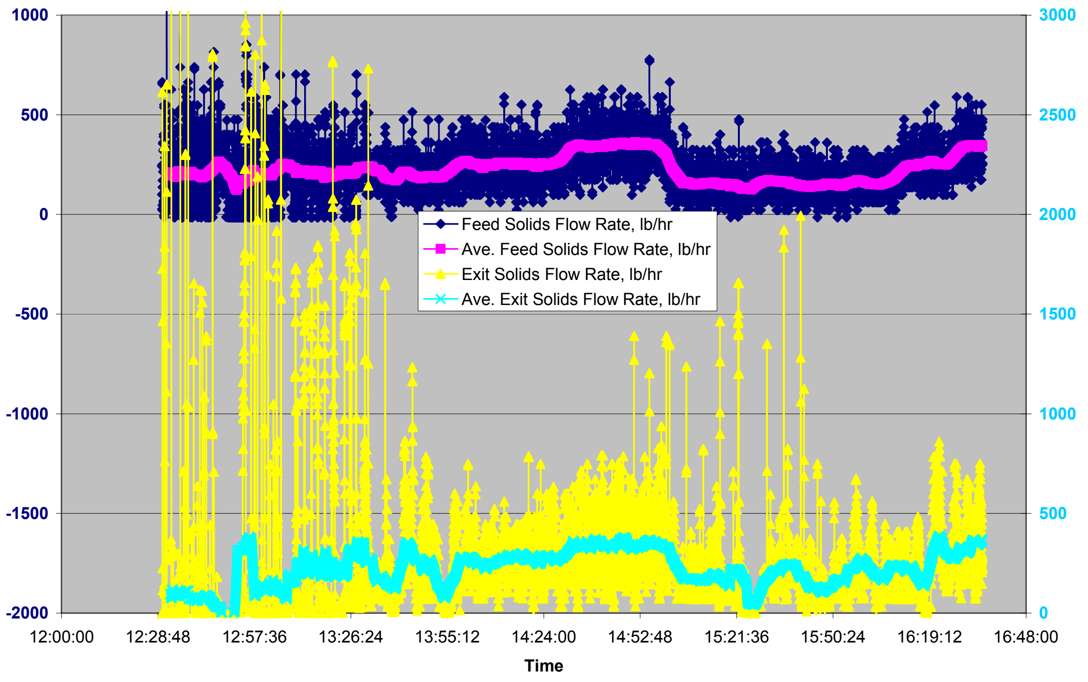


Figure 7 Comparison of Solids Feed and Effluent Rates for 03/13/03 Test

The constancy of solids flow rate leaving the N-Valve is compared to that of the solids entering in the plot of the frequency of the second by second data shown in Figure 8. The distribution of the exiting solids flow rate is far from being normal; it has four peaks and is significantly broader. The statistical parameters for data are shown in Table 2. A comparison of the range between the entering and exiting solids flow rates for the 350 lb/hr set point data reveals that the range for the exiting data is about twice that of the entering data. This same trend in the breadth of the data is seen by comparing the standard deviations. The standard deviation of the solids feed is 89 where as that for the solids leaving is 158. A measure of the distribution's Gaussianisity is obtained from the kurtosis, a normalized version of the fourth central moment. The greater the kurtosis, the more none Gaussian (normal) the distribution is. The value for the exiting solids flow rate is more then twice that of the feed solids flow rate.

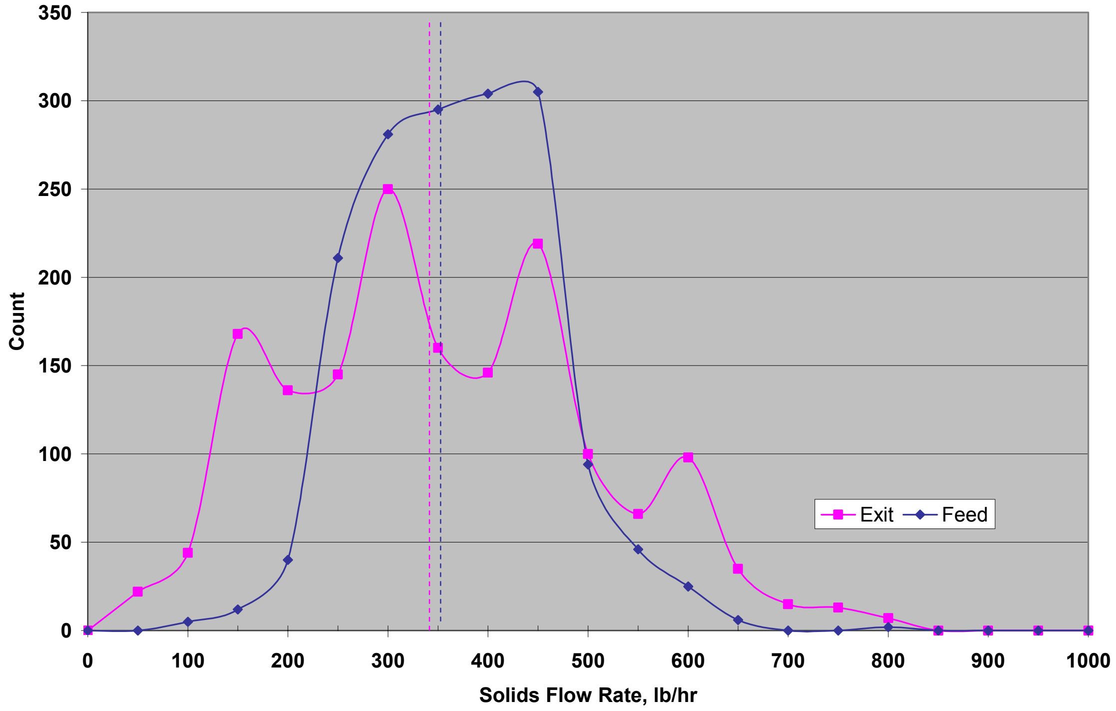


Figure 8 Comparison of second by second frequency data for feed and exiting solids

Comparison of Solids Flow Rate with Move Air

The ability of the move air to affect the solids flow rate in the N-Valve is shown in Figure 9. Examination of the plot reveals that a change in the move air was followed by a change in the solids flow rate. Specifically looking at Figure 9, two areas can be seen. One of these is prior to a time reading of approximately 13:26, while the other is after this time. Looking back at Figure 7, the same demarcation can be seen at the time of about 13:26 in the exiting solids flow rate. After this time, the solids flow rate tracked the move air flow rate closely. This same tight coupling was also seen in the May 5th data. The absence of the observations on 4/17/03 data is creditied to operating the N-Valve without any venting the lift line. The sensitivity of the solids flow rate to the move air flow magnitude favors the modified configuration in commercial installation.

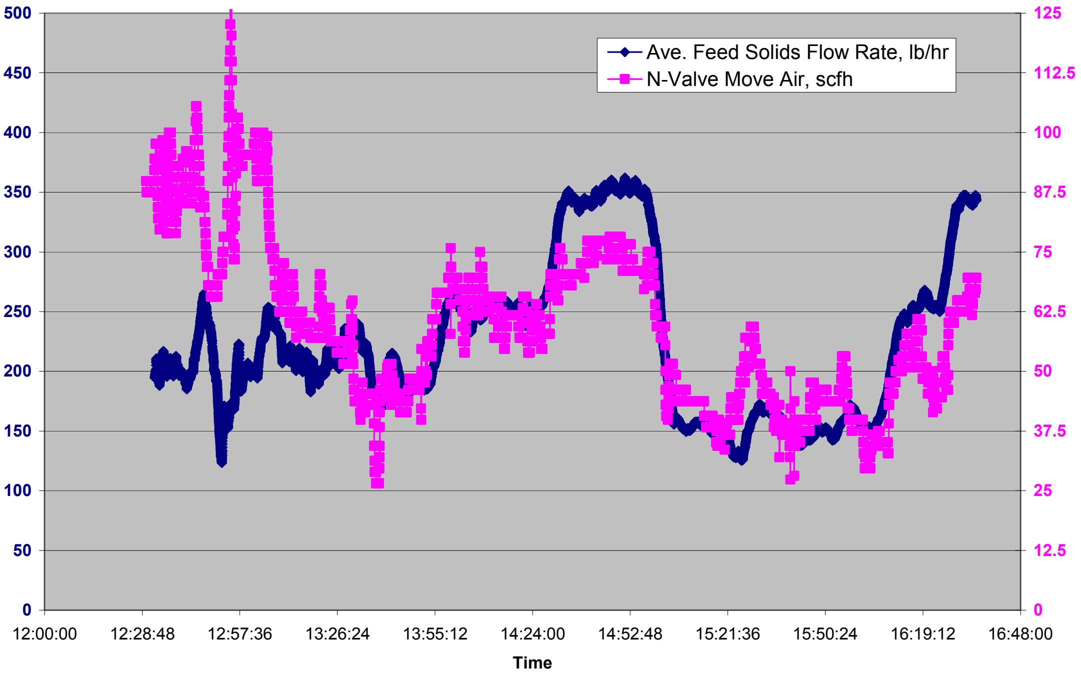


Figure 9 Comparison of Solids Flow Rate with Move Air for 03/13/03 Test

Comparison of Solids Flow Rate with Lift Line dPtop

The correlation between the N-Valve solids flow rate and the pressure drop in the top of the liftline is shown in Figure 10. It was believed that the slugging behavior in the liftline translated its oscillatory behavior up stream to the feed solids flow rate seen in figures presented in Figures 5 and 7. Selecting one of the more stable time periods, that being between 15:10 and 15:27 for the 03/13/03 test, a Fourier transform analysis was conducted to compare the frequency spectrum of the second by second data. This spectrum comparison is shown in Figure 11. Comparing the spectrum data for both measurements reveals local maxima a little less than 0.2 HZ and another at about zero. The similarity of the shape of these two curves indicates that the slugging behavior in the liftline drives the oscillation in the solids flow rate through the N-Valve.

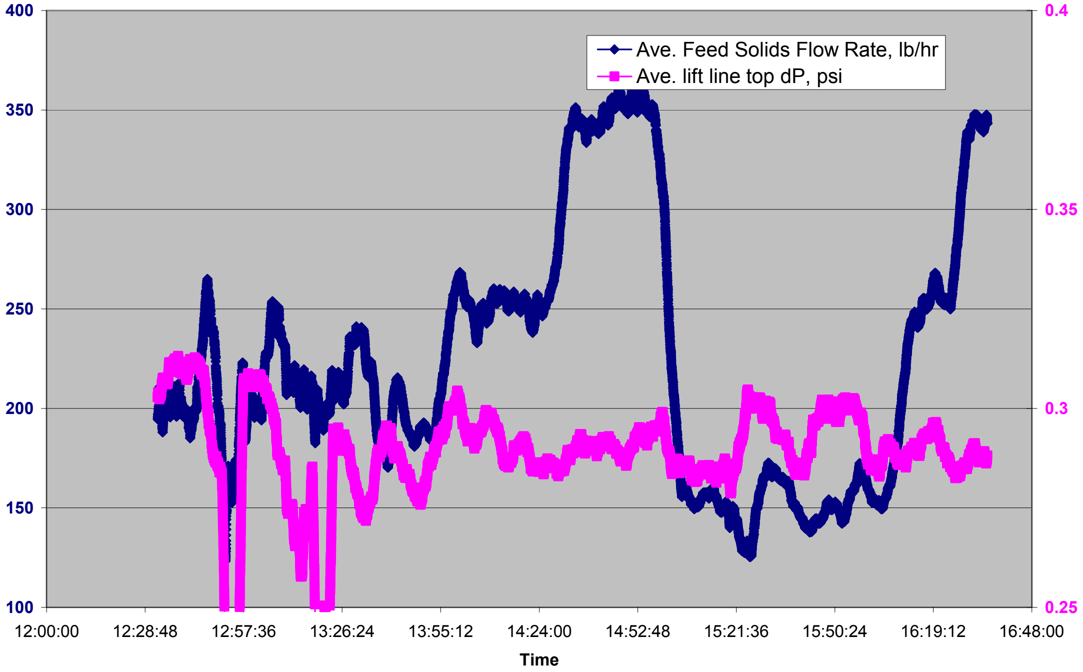


Figure 10 Comparison of Solids Flow with Pressure Drop in Top of Lift Line for 3/13/03 Test

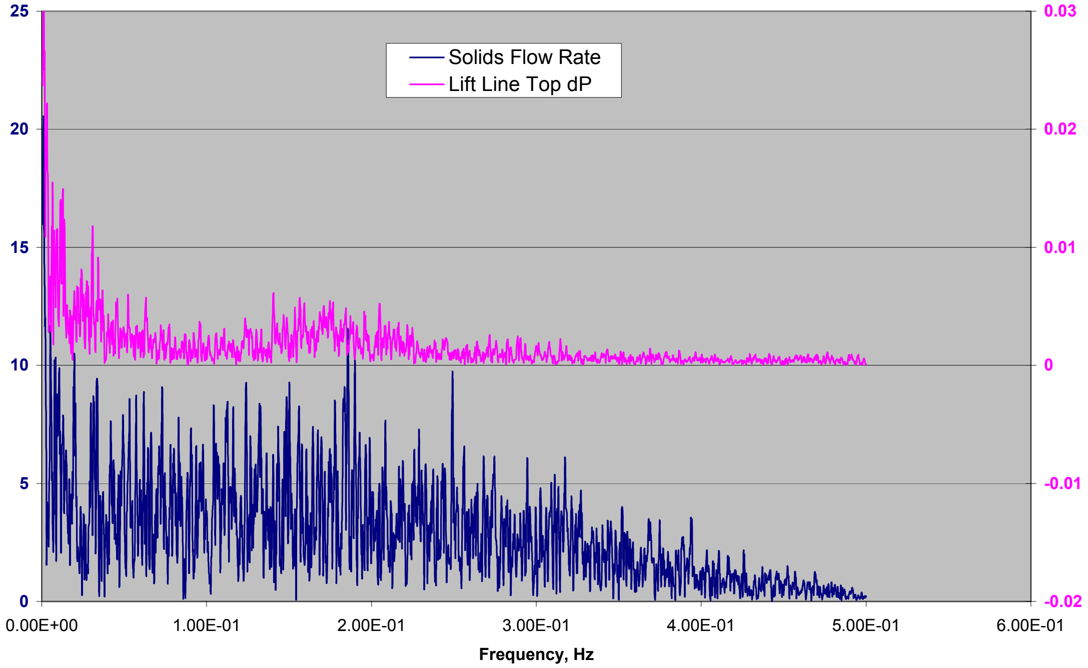


Figure 11 Frequency Spectrim Analysis for 03/13/03 Test between 15:10:22 and 15:27:49

Effect of Back Pulse on System Operating Characteristics

Another important operating characteristic that needs to be understood is the effect that the candle filter back pulse has on the system. What influences are observed throughout the N-Valve system when a pressure pulse several times the operating pressure propagates through the system? This effect could bee seen of two process parameters, the system static pressure and the N-Valve pressure drop.

System Static Pressure

The effect of the candle filter back pressure of the system pressure is seen in Figure 12. There is a one to one correspondence between the drops in the candle filter header pressure and the rise in the static pressure.

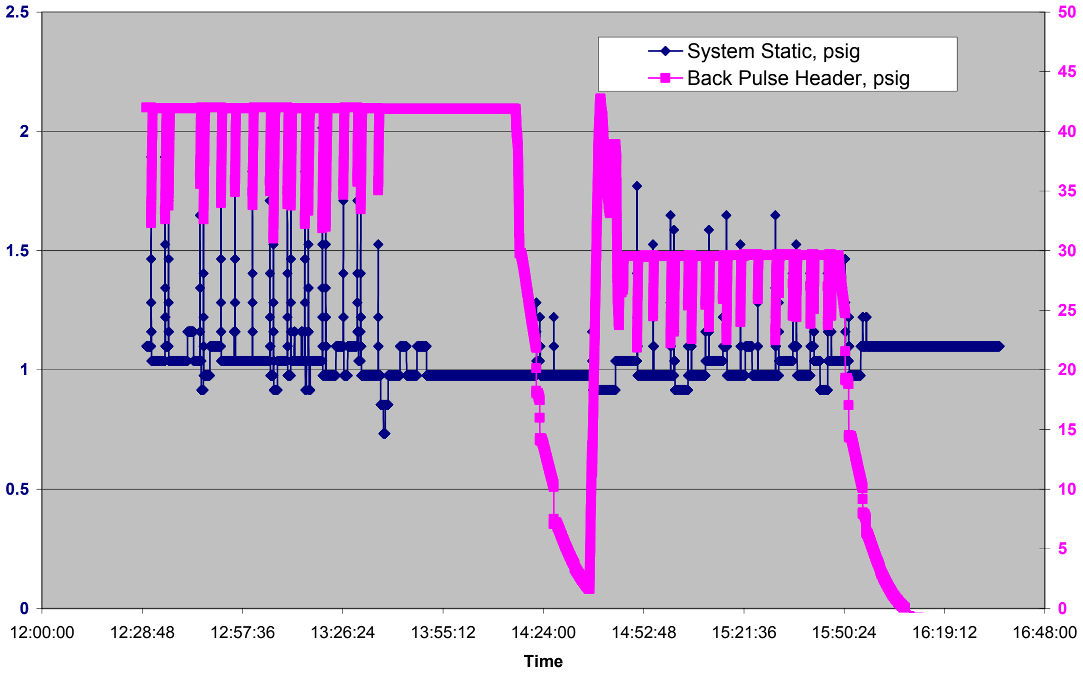


Figure 12 Effect of Candle Filter Back Pulse on System Pressure for 03/13/03 Test

N-Valve dP

Like for the system static pressure, the effect of the candle filter back pulse can be seen on the N-Valve pressure. This data is seen in Figure 13. The propagation of the pulse to the N-Valve pressure drop is easily seen

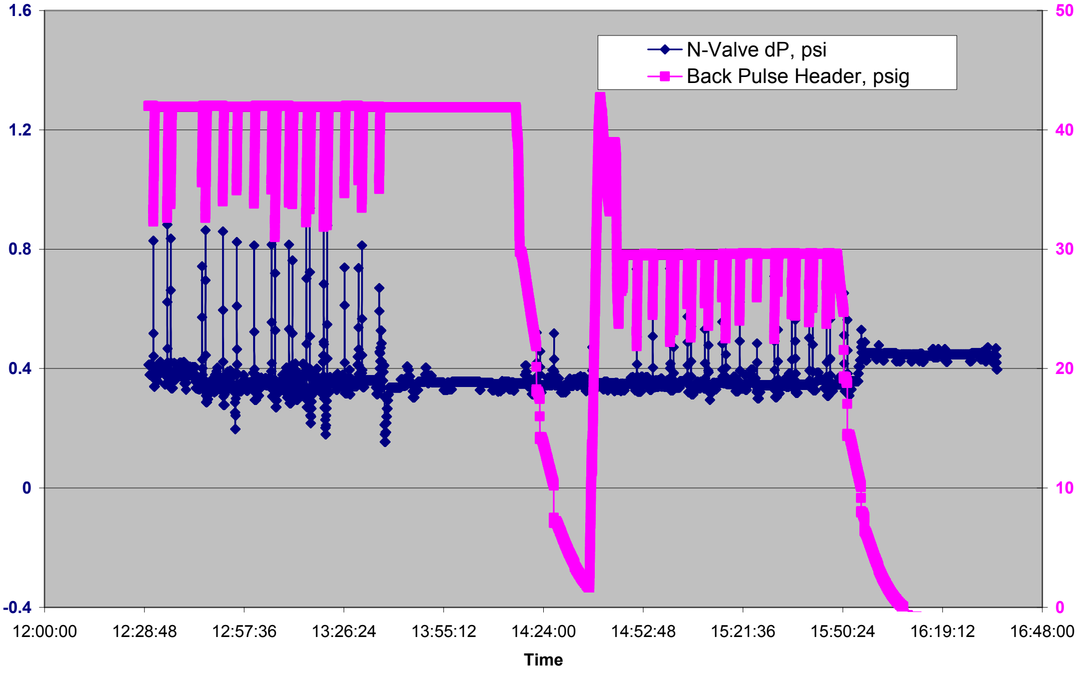


Figure 13 Effect of Candle Filter Back Pulse on N-Valve Pressure Drop for 03/13/03 Test

Effect of Plenum Flow (Gas Side dP) on N-Valve dP

An objective for the 04/17/03 test was to determine the maximum the N-Valve operational pressure drop. As previously discussed the maximum N-Valve pressure drop is limited to the gas side pressure drop. Therefore, the gas side pressure drop was increased by increasing the air flow through the gas side. This was accomplished by increasing the fluidizing air into the fluid bed. Prior to the upset that can be seen at about 15:40, the maximum N-Valve pressure drop is seen at three different gas flow rates (6000, 12000 and 9000) in Figure 14. This provided maximum N-Valve pressure drops of 0.7 psi, 1.3 psi and 1 psi, respectively. The two stable regions after the upset follow the same trend. The difference between the before and after upset conditions is likely due in part to the solids inventory in the fluidized bed and the increased staic pressure. Modifications after this run placed a pressure transducer in the fluid bed to monitor the inventory.

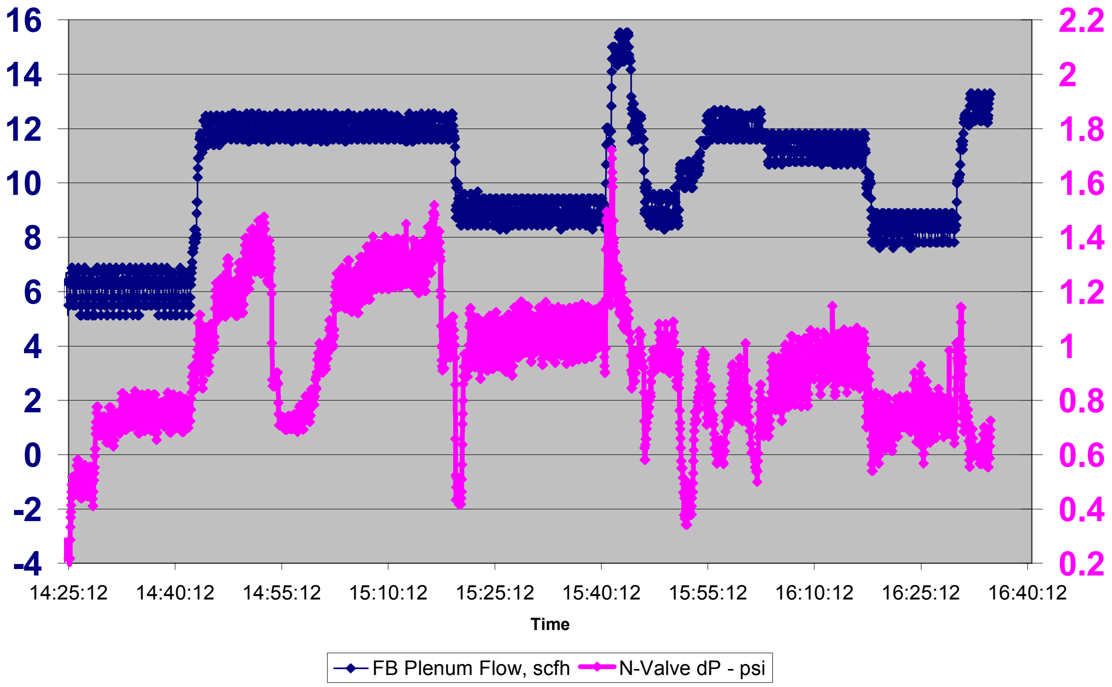


Figure 14 Effect of Gas Side Pressure Drop (FB Plenum Flow) on N-Valve Pressure Drop for 04/17/03 Test

Comparison of Solids Flow Rate to N-Valve dP

A series of tests were specifically carried out on 03/13/03 to investigate the effect that the solids flow rate may couple back to the N-Valve pressure drop, both controlled process variables. The data taken during this test is presented in Figure 15. With a constant N-Valve pressure drop of .35 psi, the solids flow rate was steppe from 200 lb/hr to 250 lb/hr to 350 lb/hr and to 150lb/hr. The move air (Figure 18) during this period from about 13:26 to about 15:50 was changed from about 40 scfh up to 50 scfh then up to 75 scfh and finally down to about 35 scfh.

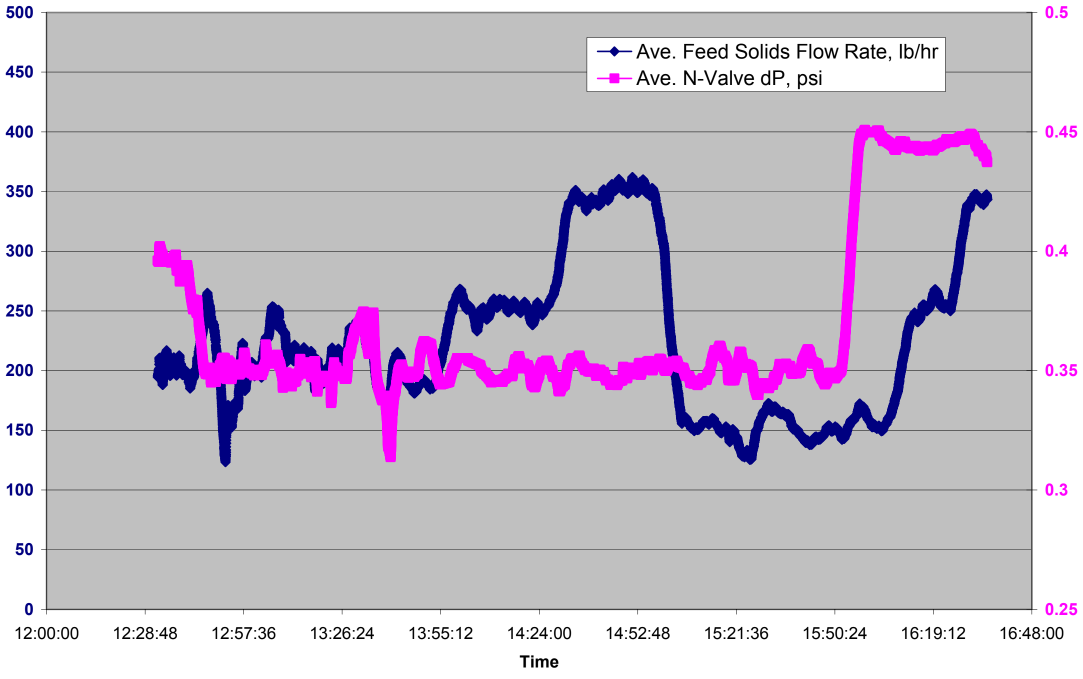


Figure 15 Comparison of Solids Flow Rate to N-Valve Pressure Drop for 03/13/03 Test

Conclusions

The conclusions from the steady state analysis of the N-Valve are:

1. The N-Valve is an effective devise for transferring solids from a high pressure vessel to a low pressure vessel in a controlled manner.
2. The N-Valve operated more smoothly without the embedded L-Valve, however control of the solids inventories in the cyclone and filter vessel diplegs is necessary to ensure that the solids leaving the fluidized bed are entering the CFB riser.
3. Effective gas venting at the top of the N-Valve lift line is essential to the operation of the N-Valve with the embedded L-Valve.
4. Pressure pulses can be seen to propagate throughout the L-Valve

References

1 Findlay, J.G., and T.M. Knowlton (1994) Pressurized fluidized bed combustion (PFBC) second generation system research and development, Phase 3: Carbonizer to CPFBC char transfer tests, Topical Report for Contract DE-AC21-86MC21023-3743 (DE94004117), 24 pp.

2 Adams, D., Dodd, A., Geiling, D., Robertson, A. (1999), The Lakeland McIntosh unit 4 advanced circulating fluidized bed combined cycle demonstration project, Proceedings of the 15t^{h} Int'l Conf. On FBC, FBC99-0076, 12 pp.

3 Shadle L. J., E. R. Monazam, J. Christopher Ludlow, D. E. Romans, and J. M. Wheeldon (2001) Evaluation of an inverted loopseal for use in advanced pressurized fluid bed applications, *Proceedings of the 16th International Conference on Fluidized Bed Combustion*, FBC00-0109, Reno Nevada, 28 pp.

4 Ludlow, J. C., L. J. Shadle, M. Syamlal (2002) Method to continuously monitor Solids Circulation Rate, in: J. R. Grace, J. Zhu, H. de Lasa (Ed.), Circulating Fluidized Bed Technology VII, Canadian Society of Chemical Engineering, Ottawa, Canada, 2002, p. 513-520.

5 Breault, R. W. and L .J. Shadle, "Steady State Operational Characteristics of an N-Valve", Proceedings of the 29th International Conference on Coal & Slurry Technologies, Clearwater, FL, 2004.