DEPARTMENT OF ENERGY (DOE)

ENHANCED GEOTHERMAL SYSTEMS (EGS)

PROJECT

WELLFLO SIMULATIONS REPORT

STEP 4: DRILLING 10,000 FT WELLS

WITH SUPERCRITICAL STEAM, NITROGEN

AND

CARBON DIOXIDE

by

Mehmet Karaaslan, MSI

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EXECUTIVE SUMMARY

The scope of this report is to provide simulation results for drilling 10,000 ft vertical wells utilizing supercritical fluids; Nitrogen and Carbon dioxide. The WellFlo Version 8.013 (by SPT) under balanced drilling hydraulic program was used to perform all modeling runs.

Operational envelopes were created based on erosion velocity limit which is 1800 ft/min. Five different coiled tubing and hole size combinations were used for all cases. Runs were started with 1.25” coiled tubing and 2.25” hole size and a wide range of run points were used in order to create an operational envelope.

Runs were started with using supercritical nitrogen as the drilling fluid. In this part; nitrogen was injected to the system for three different cases, namely: 1) Nitrogen without water, 2) Nitrogen with water addition, and 3) Nitrogen with water influx at the bottom of the well. A high temperature drop across the nozzle occurred for all nitrogen only injection cases. In nitrogen with water addition cases, different amount of water was injected with the nitrogen. In these cases, the temperature drop across the nozzle decreased significantly and also hydrate formation did not occur in the system. In the third case, 5 gpm water influxes were allowed from the bottom of the well in the annulus and nitrogen was injected to the well with different amount of water. In these cases, high amount of liquid fraction after the nozzle occurred in the system which is an undesirable condition for the efficient ASJ cutting operation.

For CO_2 cases, similar procedures were followed for all the runs. CO_2 was injected to the system in three cases; 1) CO_2 without water, 2) CO_2 with water addition, and 3) CO_2 with water influx at the bottom the well. Similar to N_2, significant

temperature drop occurred for CO_2 without water additions and due to the pressure-temperature values at the bottom of the well, liquid fraction of CO_2 was found high after the nozzle. Possible hydrate formations were reported on the operational envelope graphs. In the second case, different amounts of water were added to CO_2 injection during the operation. Water addition decreased the significant temperature drop and amount of hydrate formation became less than 1%. Third case started with adding 5 gpm water influx at the bottom of the well in the annulus. Liquid fraction after the nozzle increased significantly due to the water influx and pressure-temperature combination at the bottom of the well.

In the last part, runs were made in order to analyze cutting transport efficiency in the annulus. Different casing and cutting sizes were used and cutting transport ratio graphs plotted. These runs showed that increasing casing and cutting size effect cutting transport efficiency negatively.

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1. Overall Approach

Drilling vertical 10,000 ft. wells were modeled using supercritical fluids (nitrogen and carbon dioxide) under different conditions to create operational envelopes, pressure and temperature profiles for such operations. SPT 's WellFlo version 8.0.13 program was used for this effort.

Runs were performed for three different conditions: 1) Only N_2 or CO_2 injection, 2) N_2 or CO_2 injection with water addition, 3) Allowing 5 gpm of water influx from bottom of the well at the annulus.

As known, in order to provide proper FLASH ASJ™ cutting at the bottom of the well, gas fraction should dominate after the nozzle. In all the cases 0.25 liquid fraction was taken as a maximum liquid fraction that the operation can tolerate. Also, due to the erosion velocity limit of 1800 ft/min, mixture velocity in the annulus should be less than this erosion limit. In order to decrease effect of the erosion velocity problem, all runs were performed with 4" surface pipe and 5.5'' hole size for the first top 500 ft to keep the mixture velocity lower.

Computer runs were also performed for different coiled tubing and bore hole sizes. For 1.25" coiled tubing and 2.25" hole size, a wide range of flow rate conditions were used to create the operational envelope. Table 1 gives the coiled tubing and hole sizes used for all conditions.

Table 1: Coiled Tubing and Bore Hole Sizes

Coiled Tubing Outer Diameter (in)	Coiled Tubing Inner Diameter (in)	Bore Hole Size (in)
1.25	1.08	2.25
1	0.83	2.25
1	0.83	1.75
1	0.83	2.5
0.75	0.58	1.75

WellFlo Version 8.0.13 allows the user to add coiled tubing spooled onto a peel at the surface in order to fully calculate pressure losses of the system. In all of the 10,000 ft. drilling simulations, total coiled length of the system was set to 15,000 ft length on a 7 ft. spool diameter a with horizontal axle orientation. Results of the surface coil tubing losses are given in Appendix B.

Operational envelopes were created based on erosion velocity limit which is 1800 ft/min mixture velocity in the annulus. On the operational envelopes, a vertical erosion line was used to show the maximum injection flow rates for set erosion velocity. Therefore, the run points on the left of the vertical erosion line are the points which the maximum mixture velocity at the annulus does not exceed 1800 ft/min. Hydrate percentages were also shown on the graphs near the run points. It can be noted that, an estimation of less than 10 % hydrate formation can be chemically neutralized.

Fluids were injected into the coiled tubing with a 75 ^{o}F initial temperature. Pressure drop across the nozzle was fixed at 4000 psi, except the nitrogen only runs. In nitrogen only runs, 6000 psi pressure drop across the nozzle was needed to ensure liquid nitrogen phase in the tubing. Table 2 gives the input parameters for nitrogen and CO_2

with and without water injection cases. The input parameters for cases with water influxes are same with water addition cases given in Table 2.

Table 2: Input Parameters

	N_2 Only	**N_2 & Water**	**CO_2 Only**	**CO_2 & Water**
Depth (ft)	10,000	10,000	10,000	10,000
Formation	Sandstone	Sandstone	Sandstone	Sandstone
Geothermal Gradient (ºF/ft)	0.015	0.015	0.015	0.015
Surface Temperature (ºF)	60	60	60	60
Injected Fluid Temperature (ºF)	75	75	75	75
Return Choke Pressure (psia)	50	50	50	50
Nozzle Pressure Drop (psi)	6000	4000	4000	4000
Cutting Size (in)	0.001	0.001	0.001	0.001
ROP (ft/hour)	400	400	400	400

2. Nitrogen as Drilling Fluid

In this part, WellFlo simulation results are given for three different conditions in which supercritical nitrogen was used as a drilling fluid. In the first condition, only nitrogen was injected to the well. In the second condition, nitrogen was injected with different amount of water. For the third condition, nitrogen was injected with water and 5 gpm water influxes at the bottom of the well were allowed into the annulus.

Nitrogen runs were performed with different coiled tubing and hole sizes as previously shown in Table 1. Runs were started with 1.25” OD coiled tubing and 2.25” hole size. In this geometry, runs were performed for a wide range of flow rate conditions to create operational an envelope. In all runs, 4’’ surface pipe for the first 500 ft was used in order to prevent mixture velocity increase in the annulus.

2.1 Nitrogen without Water Addition Cases

Nitrogen runs started with the condition of injecting only nitrogen into the 10,000 ft deep vertical well. In these operations, significant temperature drop at the nozzle occurred due to the Joule Thompson effect. In this depth, since possible hydrate formation percentages were less than 1 % for all runs, they were not shown in the operational envelope graphs.

2.1.1 Nitrogen without Water Addition Cases (CT: 1.25” –H.S: 2.25”)

Figure 1 gives the operational envelope for nitrogen without water condition for the given tubing and hole size. In the graph, the vertical erosion line shows the maximum injection flow rates for the erosion velocity limit (1800 ft/min). Run points, left of the erosion line are for the conditions where the maximum mixture velocity of fluid in the annulus does not exceed erosion velocity limit. For nitrogen only cases, there is no liquid fraction after the nozzle which means all the liquid phase changed to gas phase after the pressure drop at the nozzle.

Figure 2 shows the change of injection pressure with flow rate. Increasing flow rate of the nitrogen to 10 gpm, increased the injected pressure to 5419 psia.

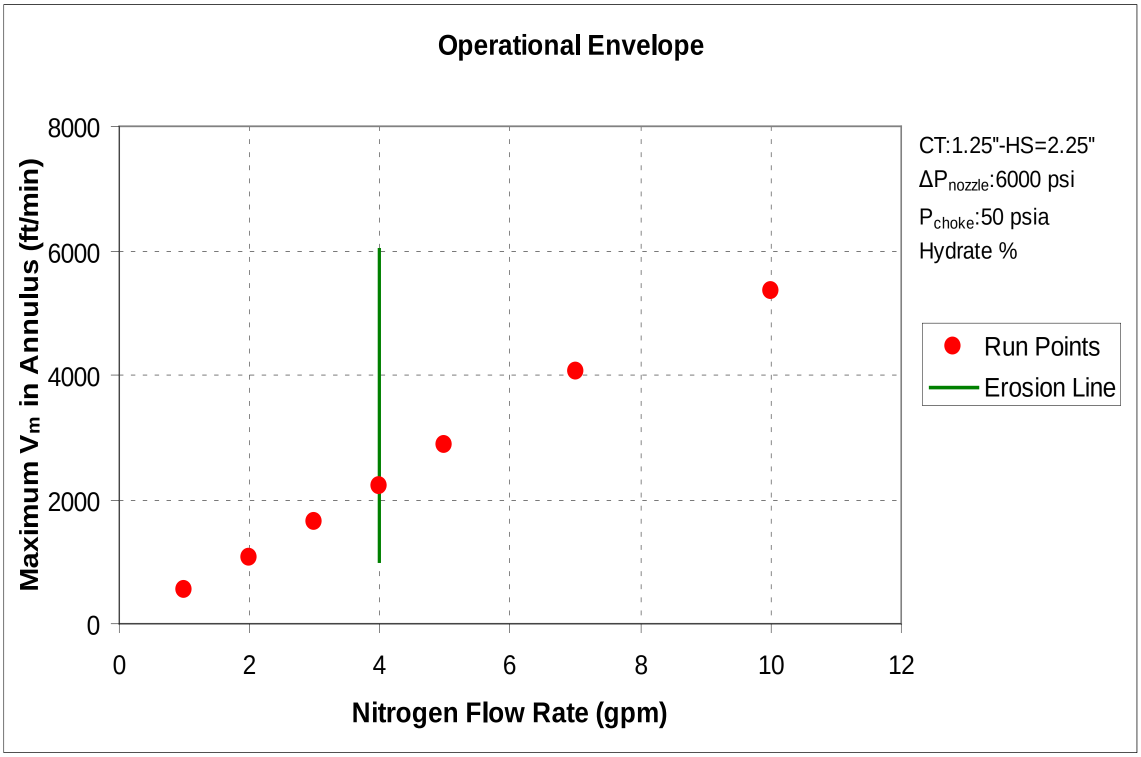


Figure 1: Operational Envelope for N_2 (CT:1.25”-HS:2.25”, Without Water)

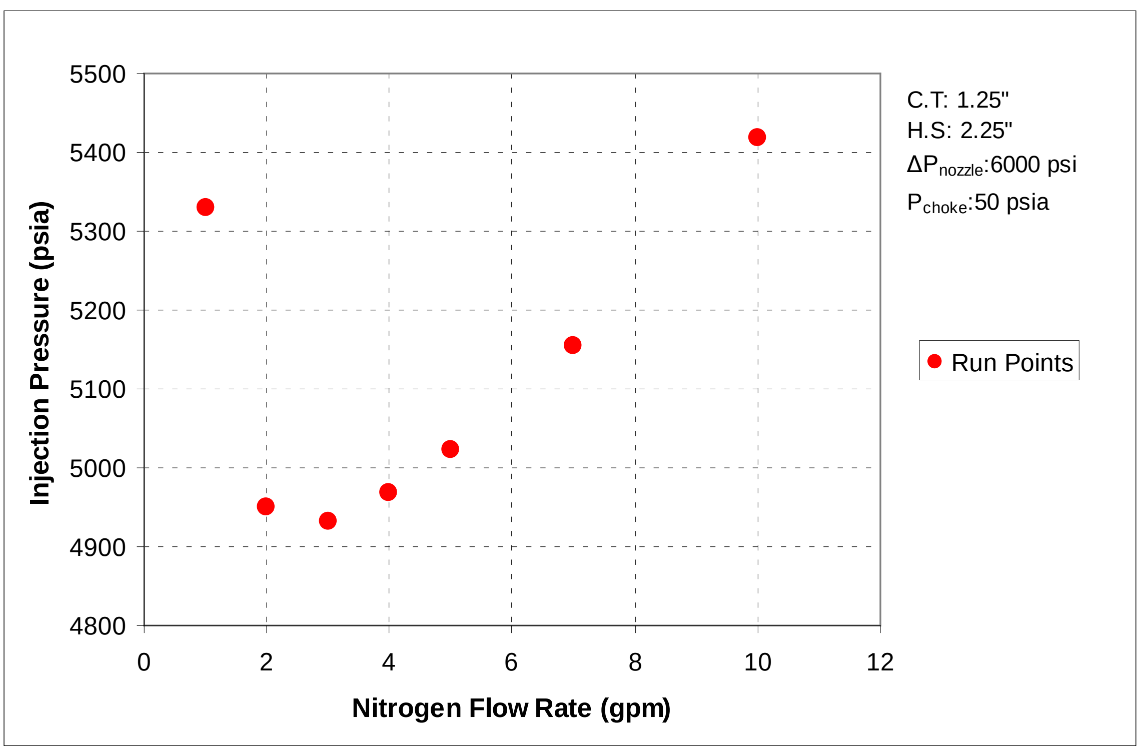


Figure 2: Flow Rate vs. Injection Pressure for N_2 (CT:1.25”-HS:2.25”, Without Water)

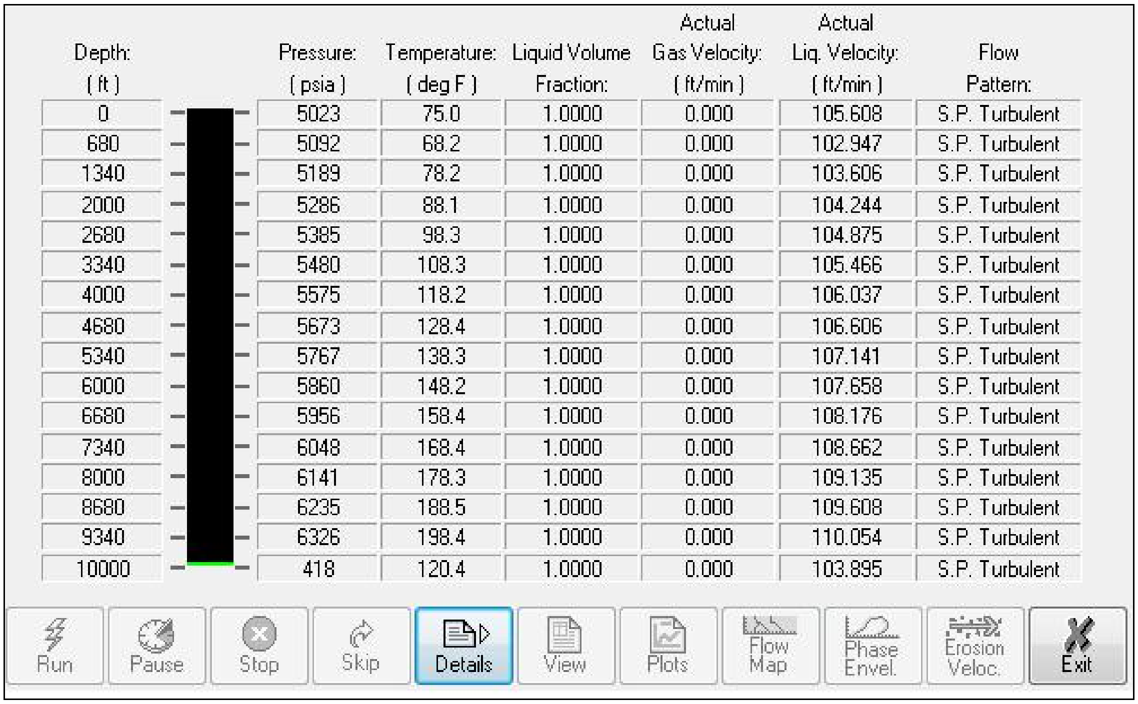
Example run monitors for tubing and annulus side of nitrogen only run with 5 gpm injection rate are given in Figure 3 and 4, respectively. As seen from the Figure 4, liquid fraction after the nozzle at the annulus becomes zero.

An example pressure and temperature profile graph for nitrogen only case is given for the flow rate of 5 gpm in Figures 5 and 6, respectively. As seen in Figure 5, the pressure drop of 6000 psi occurs at the nozzle. Pressure outputs for 5 gpm are given in Table 3.

Table 3: Output Pressure Values (N_2 without Water Addition, 5 gpm)

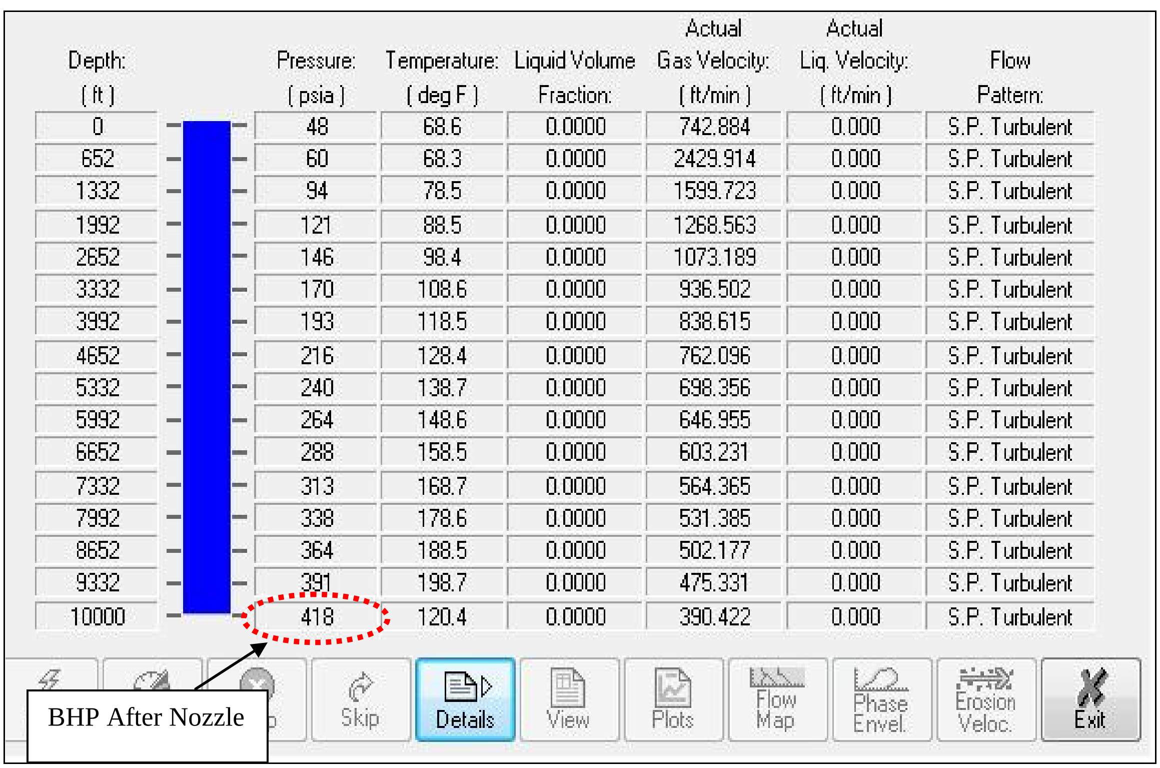
Injection Pressure (psia)	5023
BHP Upstream Nozzle (psia)	6417
BHP Downstream Nozzle (psi)	417

Figure 6 is the temperature profile of the fluid inside the coiled tubing and annulus with the formation temperature profile. The red line shows the temperature profile for fluid in the pipe and annulus and blue line shows the surrounding temperature profile. Temperature of the fluids followed the geothermal gradient until the nozzle, where significant pressure drop occurred and then followed the formation temperature profile as it moves up the annulus. Selected output results for all other flow rate data are given in Appendix A.



Depth: (ft)	Pressure: (psia)	Temperature: (deg F)	Liquid Volume Fraction:	Actual Gas Velocity: (ft/min)	Actual Liq. Velocity: (ft/min)	Flow Pattern:
0	5023	75.0	1.0000	0.000	105.608	S.P. Turbulent
680	5092	68.2	1.0000	0.000	102.947	S.P. Turbulent
1340	5189	78.2	1.0000	0.000	103.606	S.P. Turbulent
2000	5286	88.1	1.0000	0.000	104.244	S.P. Turbulent
2680	5385	98.3	1.0000	0.000	104.875	S.P. Turbulent
3340	5480	108.3	1.0000	0.000	105.466	S.P. Turbulent
4000	5575	118.2	1.0000	0.000	106.037	S.P. Turbulent
4680	5673	128.4	1.0000	0.000	106.606	S.P. Turbulent
5340	5767	138.3	1.0000	0.000	107.141	S.P. Turbulent
6000	5860	148.2	1.0000	0.000	107.658	S.P. Turbulent
6680	5956	158.4	1.0000	0.000	108.176	S.P. Turbulent
7340	6048	168.4	1.0000	0.000	108.662	S.P. Turbulent
8000	6141	178.3	1.0000	0.000	109.135	S.P. Turbulent
8680	6235	188.5	1.0000	0.000	109.608	S.P. Turbulent
9340	6326	198.4	1.0000	0.000	110.054	S.P. Turbulent
10000	418	120.4	1.0000	0.000	103.895	S.P. Turbulent

Figure 3: Tubing Side Run Monitor (N_2 without Water, CT:1.25", H.S:2.25", Q=5 gpm)



Depth: (ft)	Pressure: (psia)	Temperature: (deg F)	Liquid Volume Fraction:	Actual Gas Velocity: (ft/min)	Actual Liq. Velocity: (ft/min)	Flow Pattern:
0	48	68.6	0.0000	742.884	0.000	S.P. Turbulent
652	60	68.3	0.0000	2429.914	0.000	S.P. Turbulent
1332	94	78.5	0.0000	1599.723	0.000	S.P. Turbulent
1992	121	88.5	0.0000	1268.563	0.000	S.P. Turbulent
2652	146	98.4	0.0000	1073.189	0.000	S.P. Turbulent
3332	170	108.6	0.0000	936.502	0.000	S.P. Turbulent
3992	193	118.5	0.0000	838.615	0.000	S.P. Turbulent
4652	216	128.4	0.0000	762.096	0.000	S.P. Turbulent
5332	240	138.7	0.0000	698.356	0.000	S.P. Turbulent
5992	264	148.6	0.0000	646.955	0.000	S.P. Turbulent
6652	288	158.5	0.0000	603.231	0.000	S.P. Turbulent
7332	313	168.7	0.0000	564.365	0.000	S.P. Turbulent
7992	338	178.6	0.0000	531.385	0.000	S.P. Turbulent
8652	364	188.5	0.0000	502.177	0.000	S.P. Turbulent
9332	391	198.7	0.0000	475.331	0.000	S.P. Turbulent
10000	418	120.4	0.0000	390.422	0.000	S.P. Turbulent

Figure 4: Annulus Side Run Monitor (N_2 without Water, CT:1.25", H.S:2.25", Q=5 gpm)

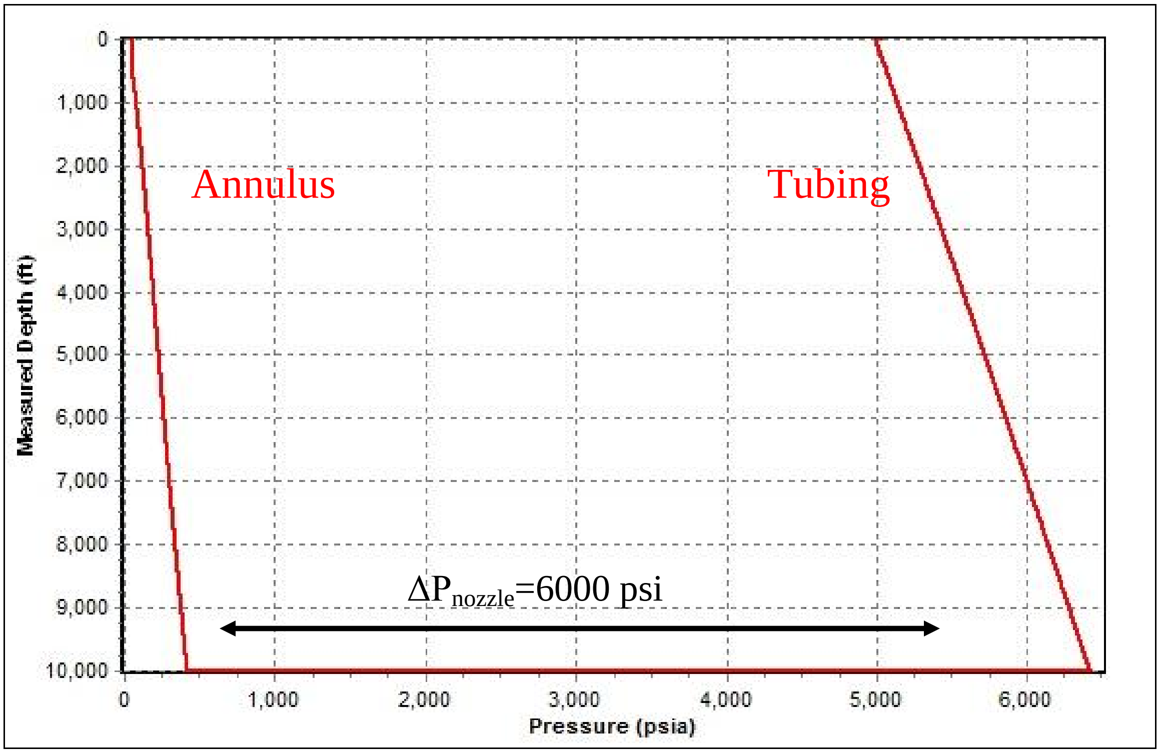


Figure 5: Pressure vs Depth (N_2 without Water, CT:1.25", H.S:2.25", Q=5 gpm)

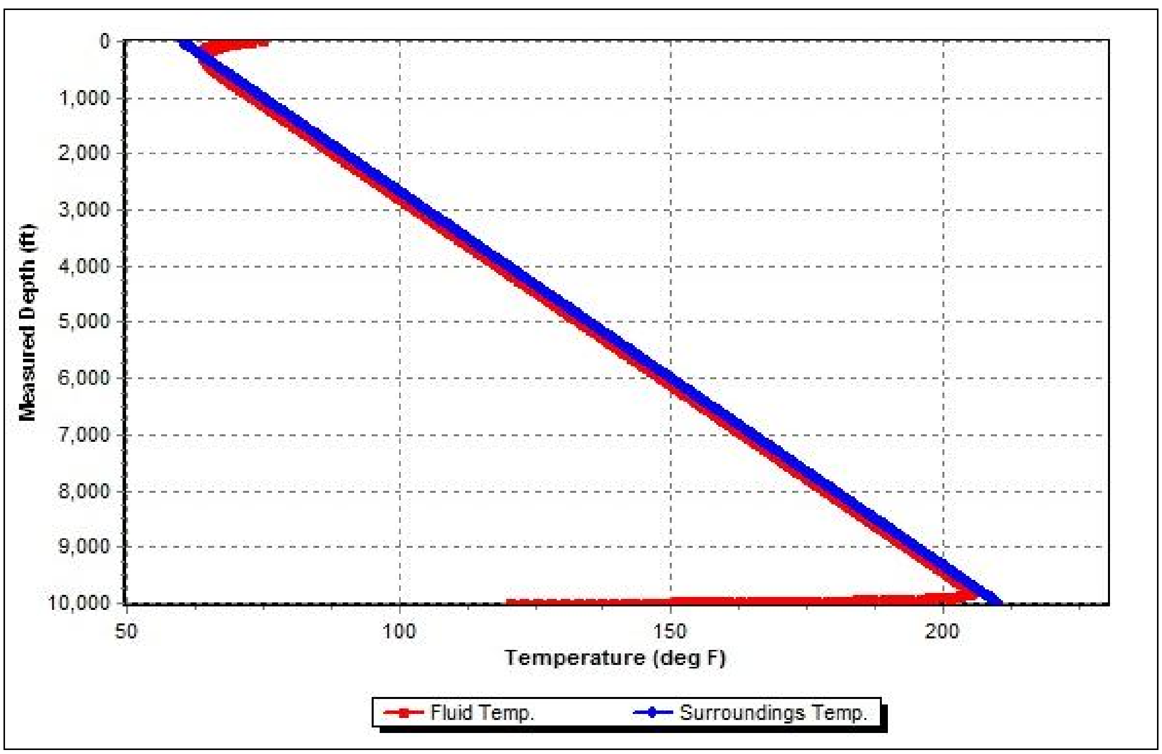


Figure 6: Temperature vs. Depth (N_2 without Water, CT:1.25", H.S:2.25", Q=5 gpm)

Figure 7 is the mixture velocity profile in annulus for 1.25" coiled tubing and 2.25'' hole size combination for all nitrogen flow rates. As can be seen from the graph, due to the expansion of gas phase nitrogen in the annulus, mixture velocity shows increase while reaching surface. Due to the 4'' surface pipe for the first 500 ft, mixture velocity decreases in the larger annulus.

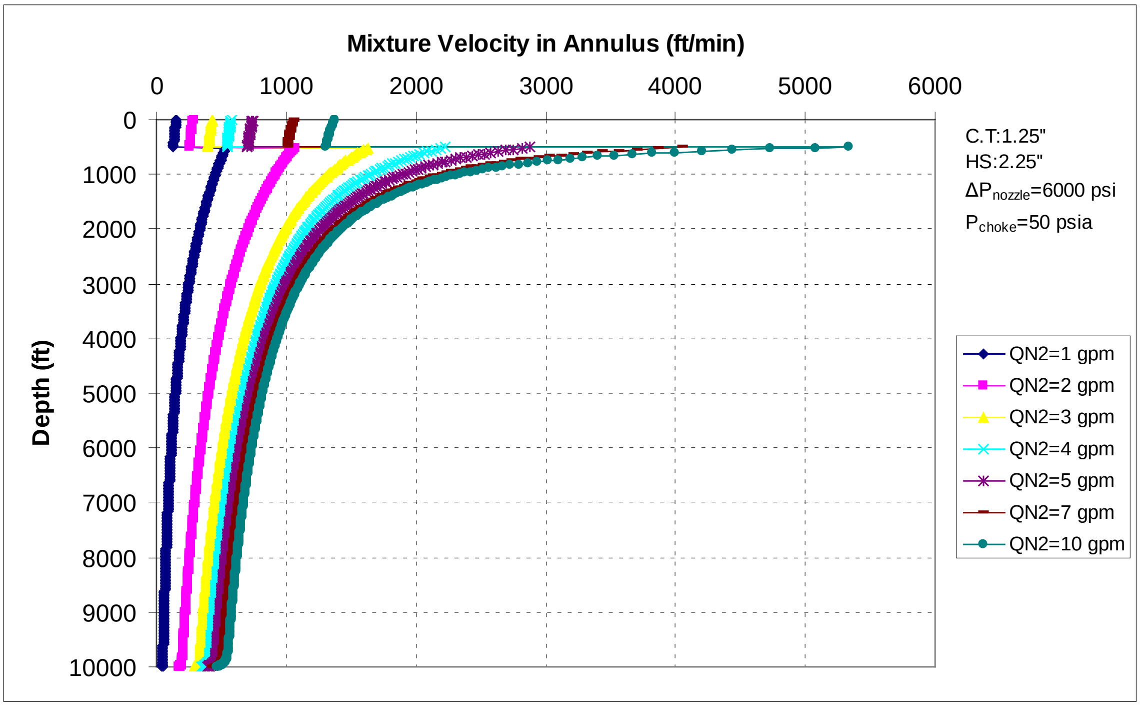


Figure 7: Mixture Velocity Profile for N_2 (CT:1.25"-HS:2.25", Without Water)

2.1.2 Nitrogen without Water Addition Cases for Different Coiled Tubing and Bore Hole Sizes

In this section, operational envelopes and injection pressure profiles are given for different coiled tubing and borehole size combinations. Also for these size combinations, possible hydrate formation percentages are zero for all flow rates.

In Figure 16 and 17, all the tubing and bore hole sizes combinations were plotted in the same graph to see the effect of hole size on erosion velocity and injection pressures. As seen from Figure 16, for the same coiled tubing size, increasing hole size (i.e. larger flow areas) decreases maximum mixture velocity in annulus. Therefore, operational envelopes become wider with increasing annulus size due to the lower velocity profile in the annulus but cutting transport efficiency decreases.

As seen from Figure 17, for the same coiled tubing size, increasing hole size decreases the needed injection pressure. Because, for smaller size annulus, due to the higher mixture velocity in the annulus, frictional losses are higher than that of larger size annulus. Therefore, when the mixture velocity increases in annulus, it increases the frictional losses and results in higher injection pressure. On the opposite, for lower velocity (due to either lower flow rates or larger annuli), cleaning the hole of solids and liquids can become a problem. However, this concern was not found in these runs. Also, increasing flow rate increases the needed injection pressure to ensure proper system operation.

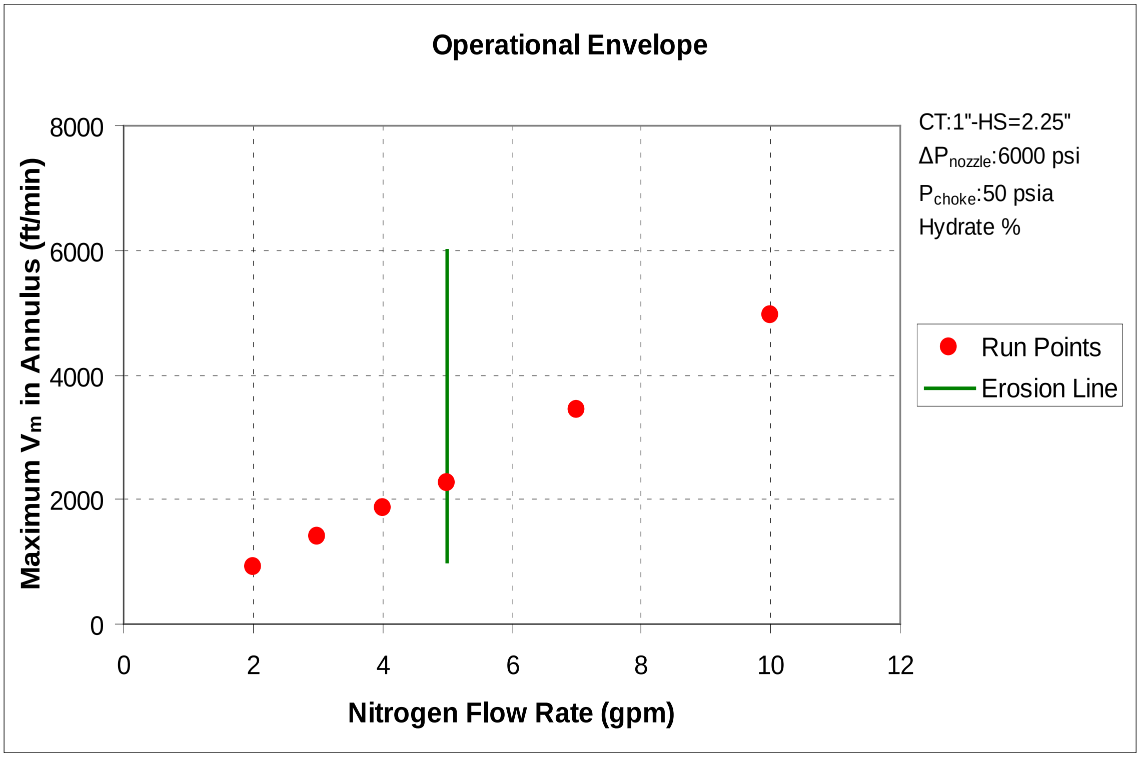


Figure 8: Operational Envelope for N_2 (CT:1”-HS:2.25”, Without Water)

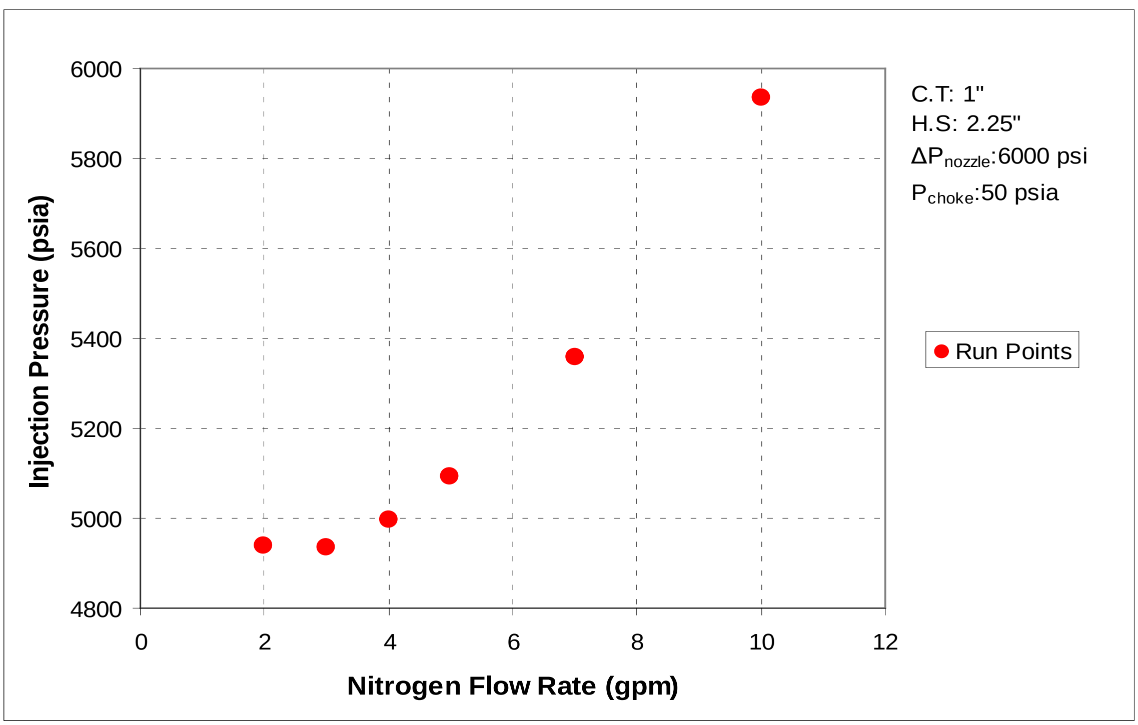


Figure 9: Flow Rate vs. Injection Pressure for N_2 (CT:1”-HS:2.25”, Without Water)

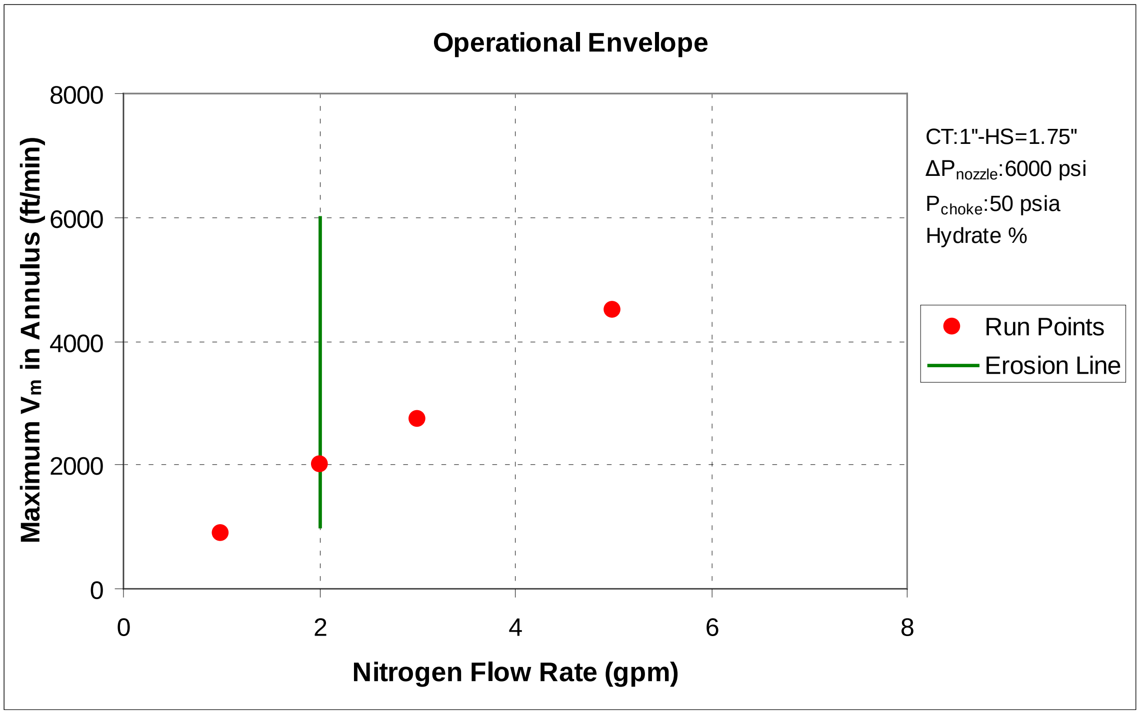


Figure 10: Operational Envelope for N_2 (CT:1”-HS:1.75”, Without Water)

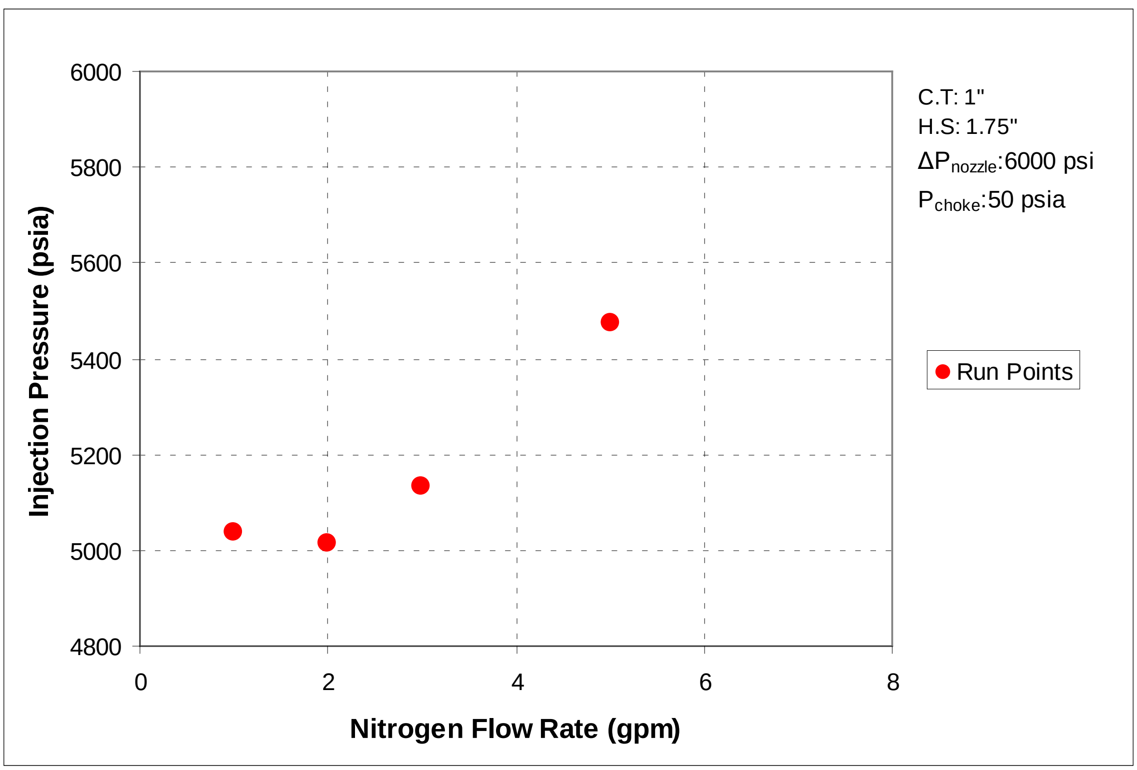


Figure 11: Flow Rate vs. Injection Pressure for N_2 (CT:1”-HS:1.75”, Without Water)

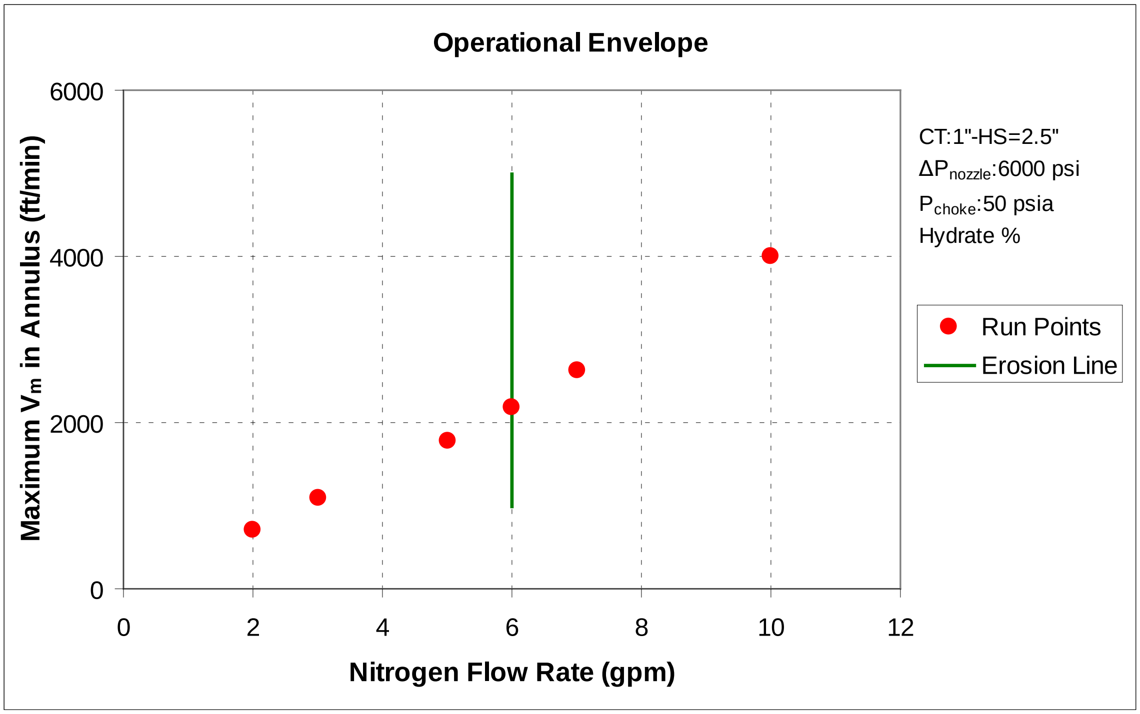


Figure 12: Operational Envelope for N_2 (CT: 1”-HS: 2.5”, Without Water)

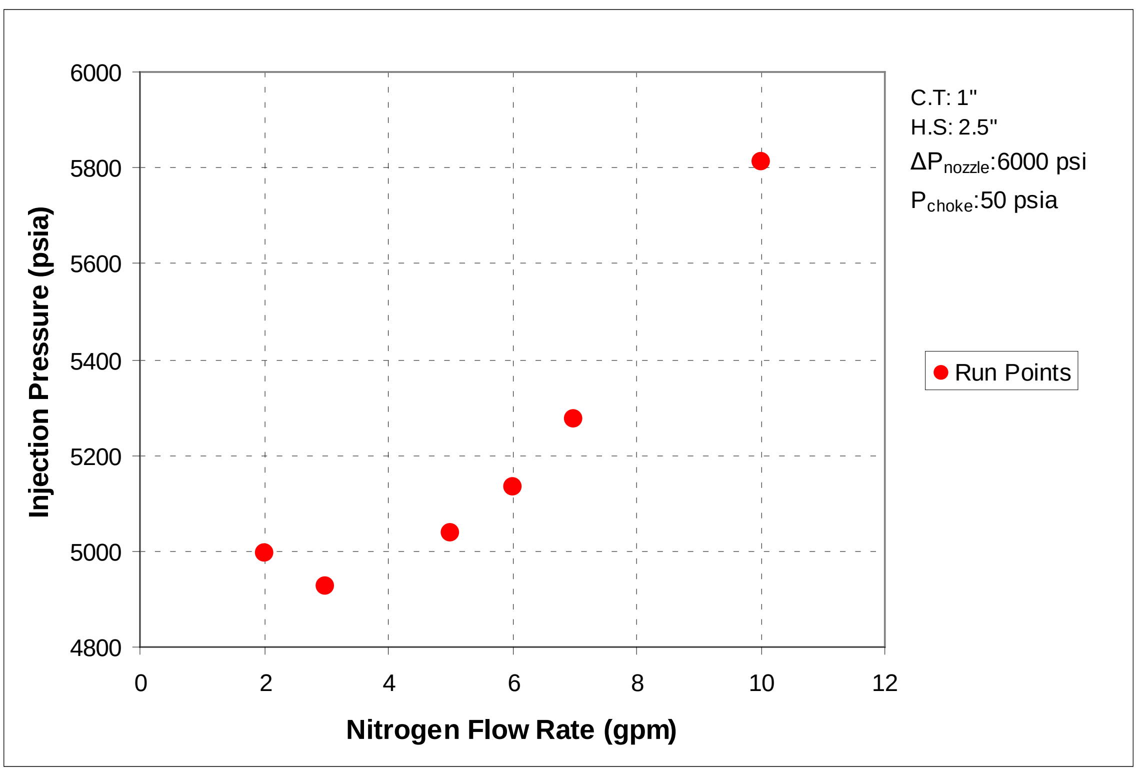


Figure 13: Flow Rate vs. Injection Pressure for N_2 (CT:1”-HS:2.5”, Without Water)

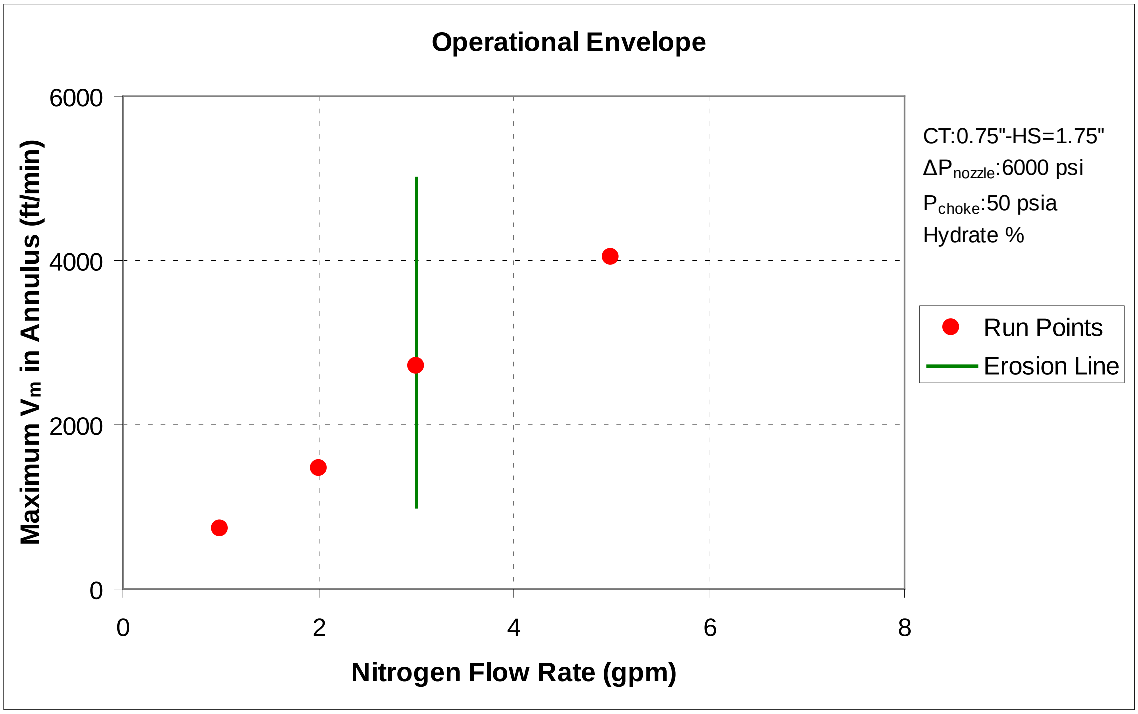


Figure 14: Operational Envelope for N_2 (CT: 0.75”-HS: 1.75”, Without Water)

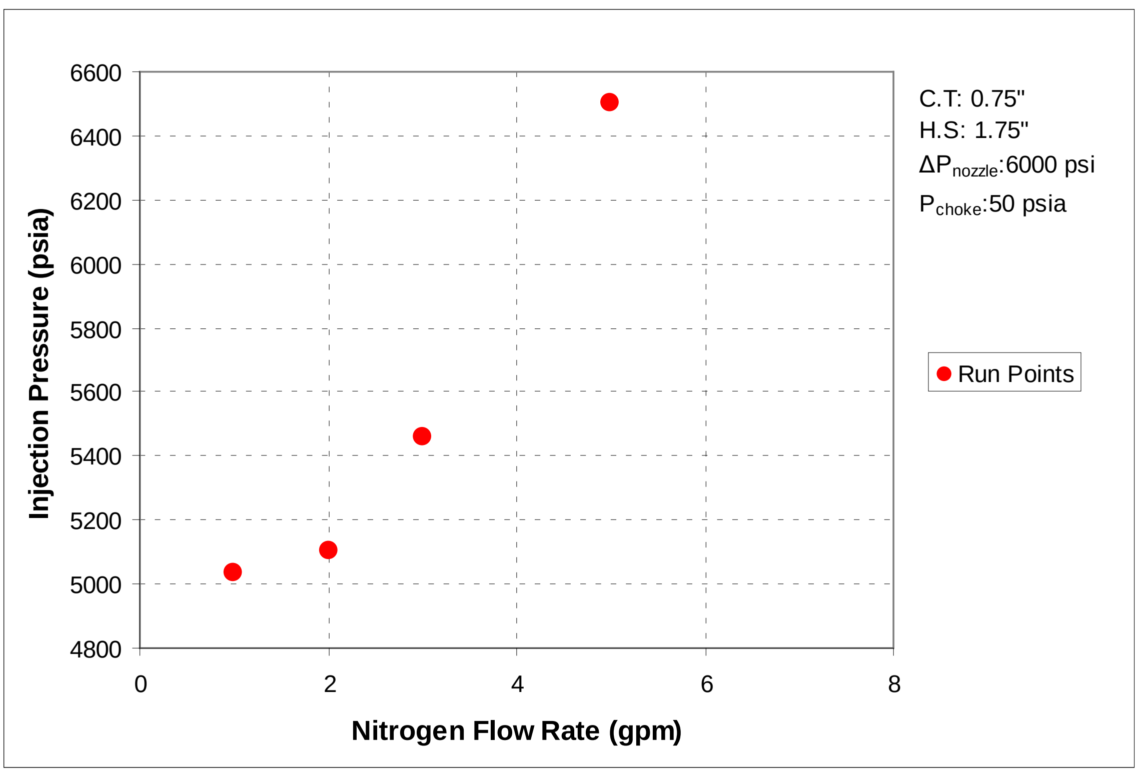


Figure 15: Flow Rate vs. Injection Pressure for N_2 (CT:0.75”-HS:1.75”, Without Water)

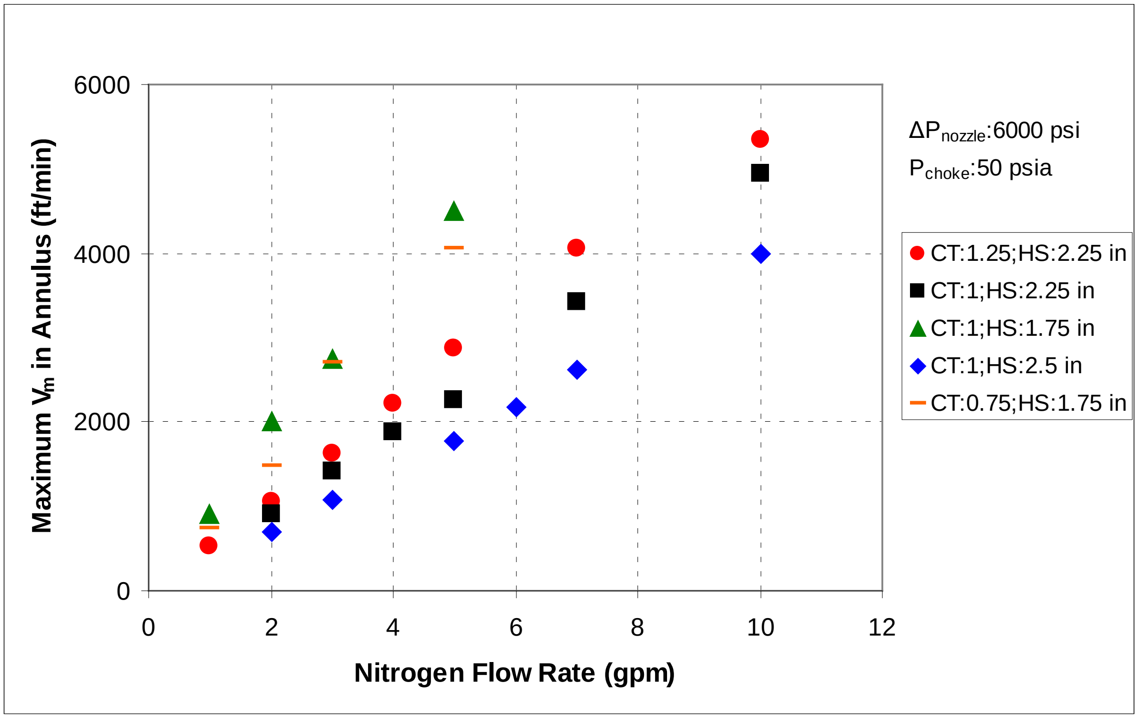


Figure 16: Flow Rate vs. Velocity for N_2 (Different Sizes, Without Water)

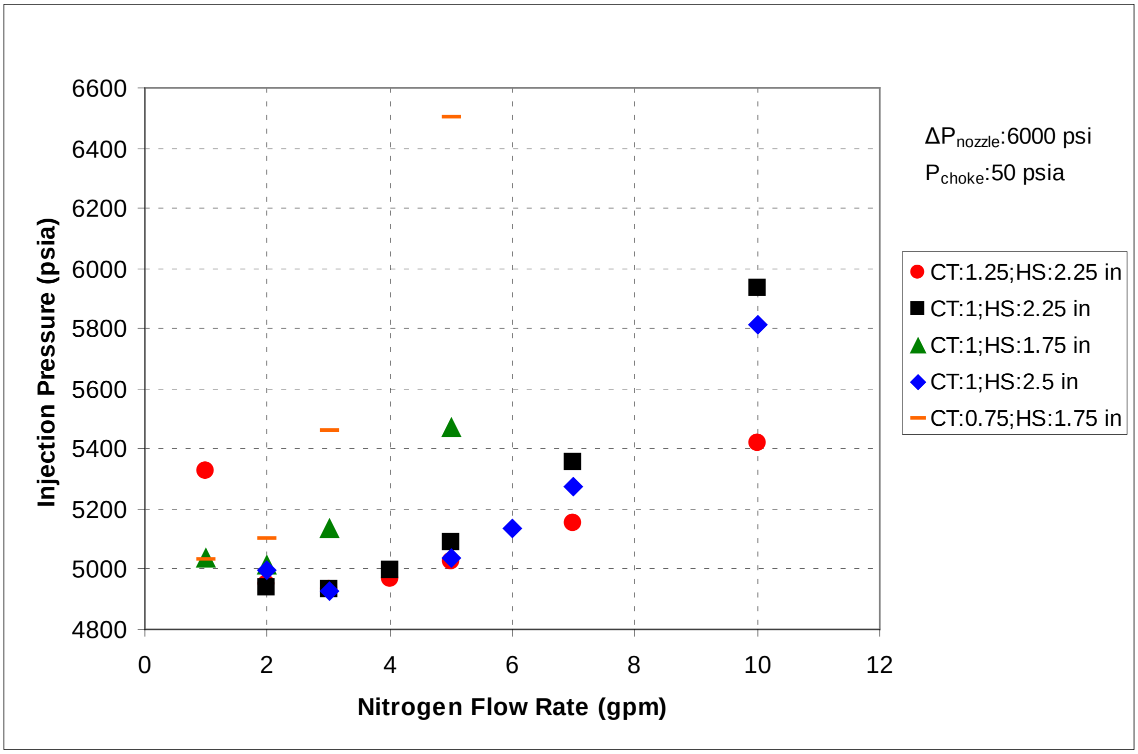


Figure 17: Flow Rate vs. Injection Pressure for N_2 (Different Sizes, Without Water)

2.2 Nitrogen with Water Addition Cases

In this part, results are given for nitrogen with water cases. Nitrogen was injected with different flow rates of water to create the operational envelope and to analyze the injection pressure profile for nitrogen. For nitrogen with water cases, input pressure drop at the nozzle was fixed to 4000 psi.

2.2.1 Nitrogen with Water Addition Cases (CT: 1.25” –H.S: 2.25”)

Figure 18 gives the operational envelope for nitrogen with water addition using 1.25” coiled tubing and a 2.25” bore hole size. As seen from the graph, there is not hydrate existence possibility for these conditions.

Run points at the right of the erosion line shows the conditions which maximum mixture velocity in the annulus exceeds the set erosion velocity (1800 ft/min). Also, only in one point, liquid fraction after the nozzle is higher than 0.25.

Figure 19 is the injection pressure profile of nitrogen with water addition runs. As can be seen from the graph, increasing nitrogen flow rate increased the needed injection pressure for the operation. Due to the density difference between nitrogen and water, significant amount of hydrostatic pressure losses were calculated at the surface coiled tubing facility. Amount of frictional and hydrostatic pressure losses are given in Appendix B.

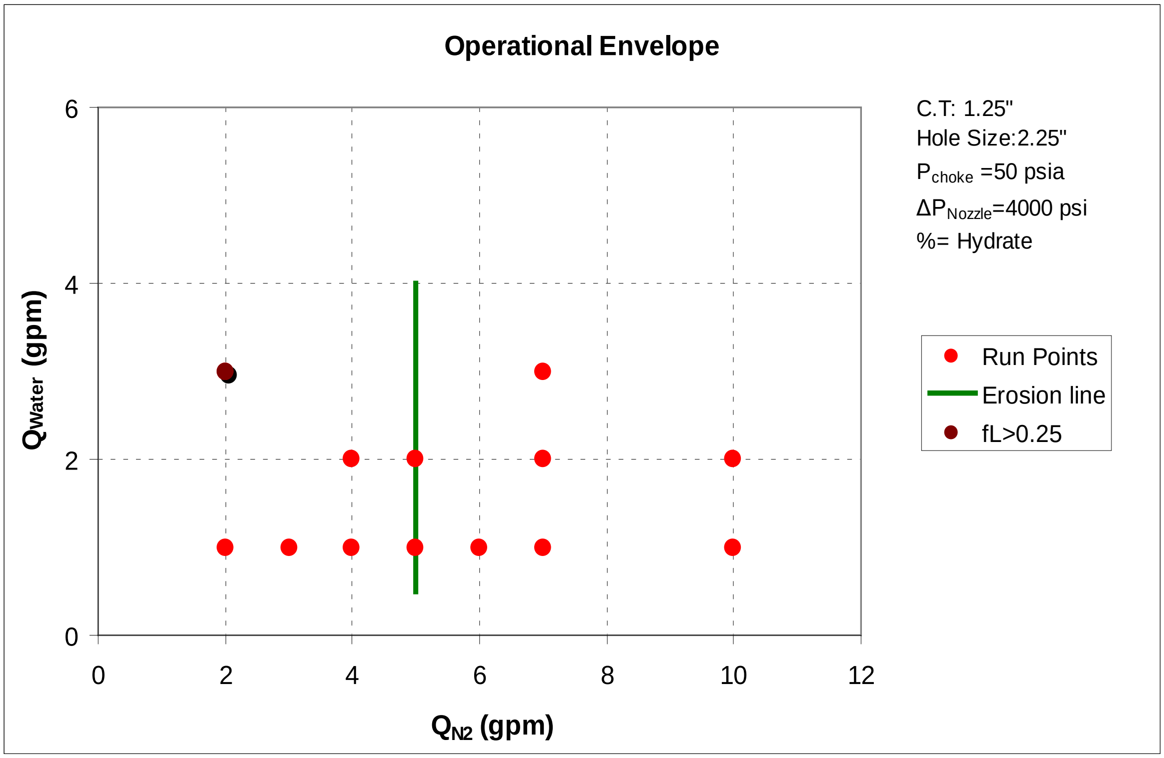


Figure 18: Operational Envelope for N_2 (CT:1.25”-HS:2.25”, With Water)

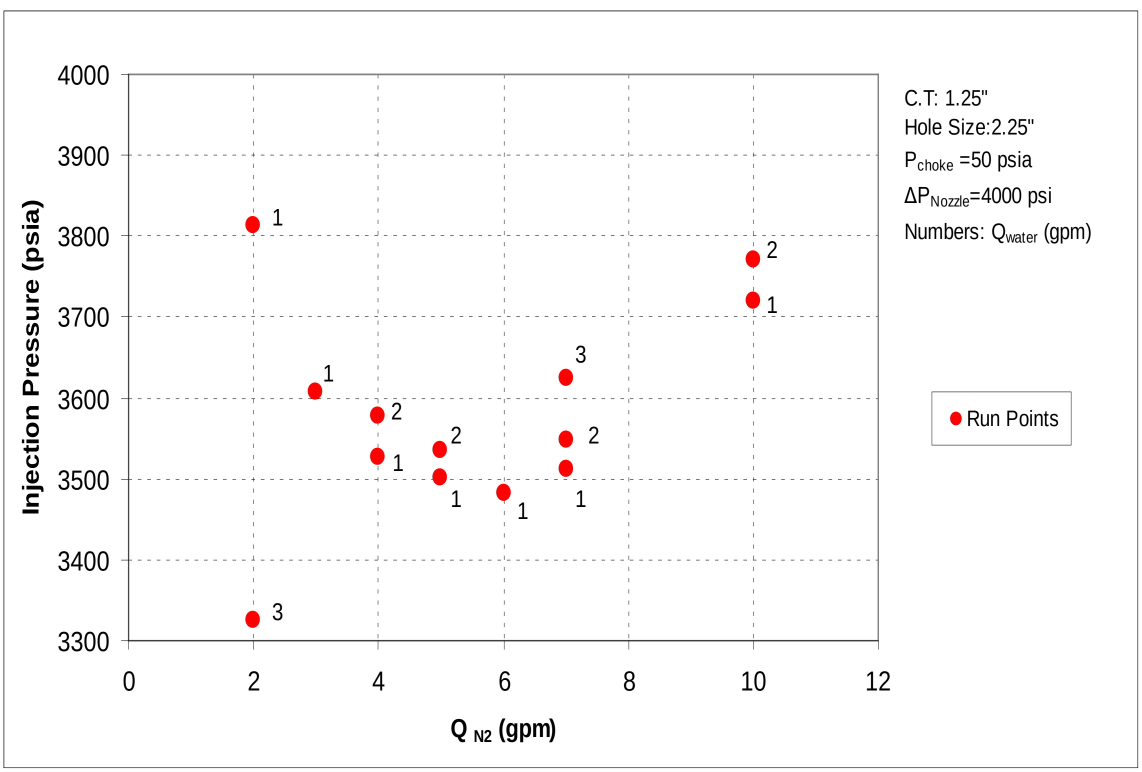


Figure 19: Flow Rate vs. Injection Pressure for N_2 (CT:1.25”-HS:2.25”, With Water)

Run monitors for the 5 gpm nitrogen and 1 gpm water are given for tubing and annulus sides in Figures 20 and 21, respectively. As can be seen from the Figure 20, amount of liquid fraction after the nozzle at the bottom of the well is 0.07.

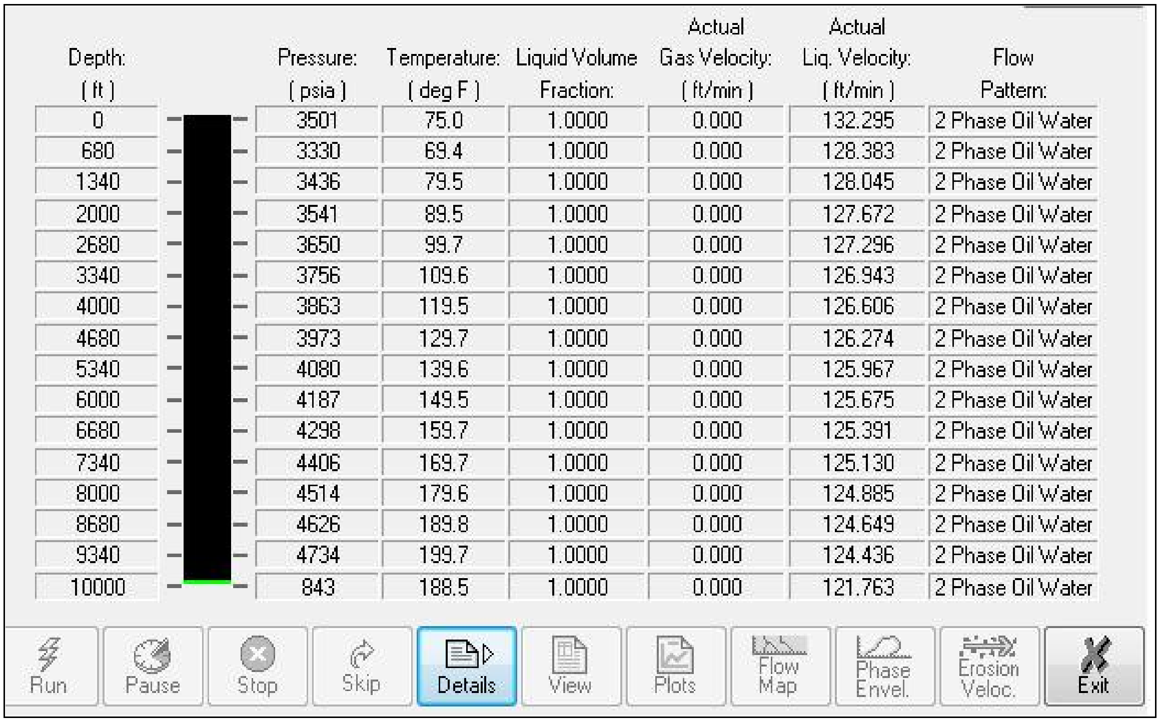
An example pressure and temperature profile graphs for nitrogen are given for the nitrogen flow rate of 5 gpm and water flow rate of 1 gpm in Figure 22 and 23, respectively. As can be seen in Figure 22, the pressure drop of 4000 psi occurs at the nozzle. Also due to the surface coiled tubing facility, 279 psi total pressure drop occurred at the surface. Pressure outputs are given in Table 4.

Table 4: Output Pressure Values (N_2 with Water Addition, Q_{N2}=5 gpm, Q_w= 1gpm)

Injection Pressure (psia)	3501
BHP Upstream Nozzle (psia)	4843
BHP Downstream Nozzle (psia)	843

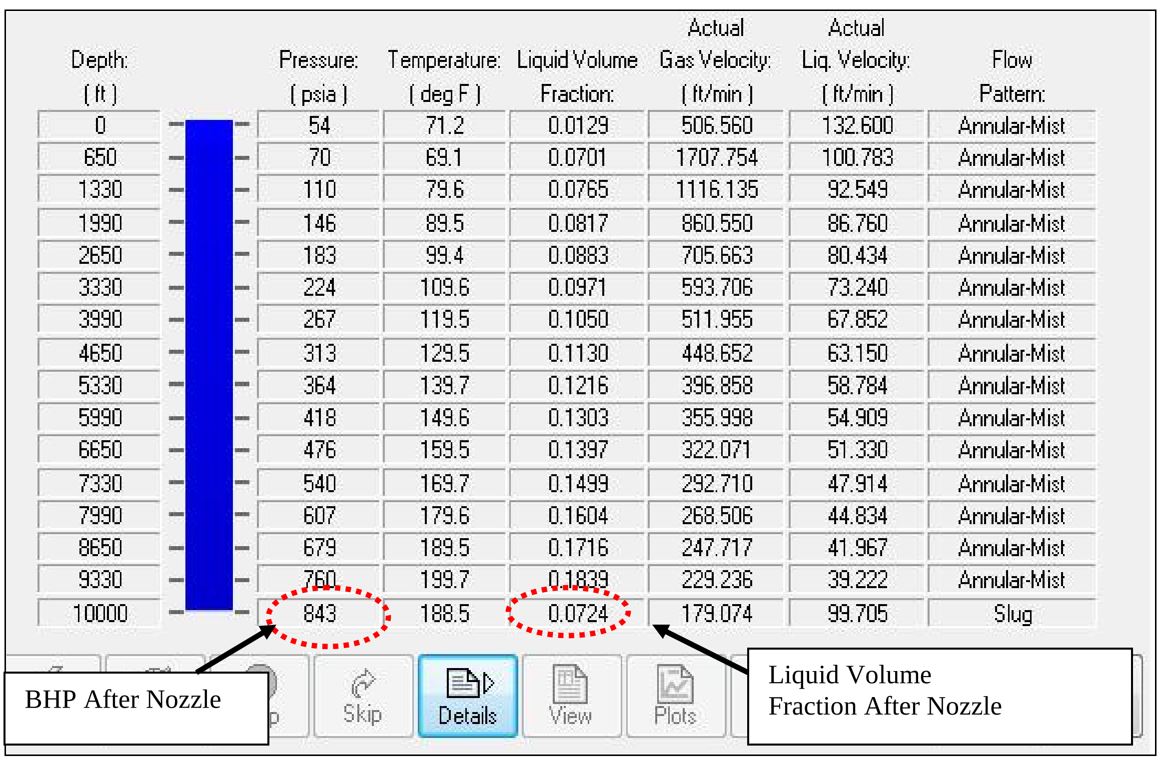
Figure 23 is the temperature profile of the fluid inside the tubing and annulus (red line) with the formation temperature profile (blue line). As can be seen from the figure, the temperature drop of the nitrogen decreases significantly with water addition condition. Selected output results for all flow rates are given in Appendix A.

Figure 24 shows mixture velocity profile in the tubing and annulus. As seen from the graph, mixture velocity increases while reaching surface due to the gas expansion and started to decline due to the surface pipe in the first 500 ft.



Depth: (ft)	Pressure: (psia)	Temperature: (deg F)	Liquid Volume Fraction:	Actual Gas Velocity: (ft/min)	Actual Liq. Velocity: (ft/min)	Flow Pattern:
0	3501	75.0	1.0000	0.000	132.295	2 Phase Oil Water
680	3330	69.4	1.0000	0.000	128.383	2 Phase Oil Water
1340	3436	79.5	1.0000	0.000	128.045	2 Phase Oil Water
2000	3541	89.5	1.0000	0.000	127.672	2 Phase Oil Water
2680	3650	99.7	1.0000	0.000	127.296	2 Phase Oil Water
3340	3756	109.6	1.0000	0.000	126.943	2 Phase Oil Water
4000	3863	119.5	1.0000	0.000	126.606	2 Phase Oil Water
4680	3973	129.7	1.0000	0.000	126.274	2 Phase Oil Water
5340	4080	139.6	1.0000	0.000	125.967	2 Phase Oil Water
6000	4187	149.5	1.0000	0.000	125.675	2 Phase Oil Water
6680	4298	159.7	1.0000	0.000	125.391	2 Phase Oil Water
7340	4406	169.7	1.0000	0.000	125.130	2 Phase Oil Water
8000	4514	179.6	1.0000	0.000	124.885	2 Phase Oil Water
8680	4626	189.8	1.0000	0.000	124.649	2 Phase Oil Water
9340	4734	199.7	1.0000	0.000	124.436	2 Phase Oil Water
10000	843	188.5	1.0000	0.000	121.763	2 Phase Oil Water

Figure 20: Tubing Run Monitor (N_2 with Water, CT:1.25”, H.S:2.25”, Q_{N2}=5,Q_w= 1gpm)



Depth: (ft)	Pressure: (psia)	Temperature: (deg F)	Liquid Volume Fraction:	Actual Gas Velocity: (ft/min)	Actual Liq. Velocity: (ft/min)	Flow Pattern:
0	54	71.2	0.0129	506.560	132.600	Annular-Mist
650	70	69.1	0.0701	1707.754	100.783	Annular-Mist
1330	110	79.6	0.0765	1116.135	92.549	Annular-Mist
1990	146	89.5	0.0817	860.550	86.760	Annular-Mist
2650	183	99.4	0.0883	705.663	80.434	Annular-Mist
3330	224	109.6	0.0971	593.706	73.240	Annular-Mist
3990	267	119.5	0.1050	511.955	67.852	Annular-Mist
4650	313	129.5	0.1130	448.652	63.150	Annular-Mist
5330	364	139.7	0.1216	396.858	58.784	Annular-Mist
5990	418	149.6	0.1303	355.998	54.909	Annular-Mist
6650	476	159.5	0.1397	322.071	51.330	Annular-Mist
7330	540	169.7	0.1499	292.710	47.914	Annular-Mist
7990	607	179.6	0.1604	268.506	44.834	Annular-Mist
8650	679	189.5	0.1716	247.717	41.967	Annular-Mist
9330	760	199.7	0.1839	229.236	39.222	Annular-Mist
10000	843	188.5	0.0724	179.074	99.705	Slug

Figure 21: Annulus Run Monitor (N_2 with Water, CT:1.25”,H.S:2.25”,Q_{N2}=5,Q_w= 1gpm)

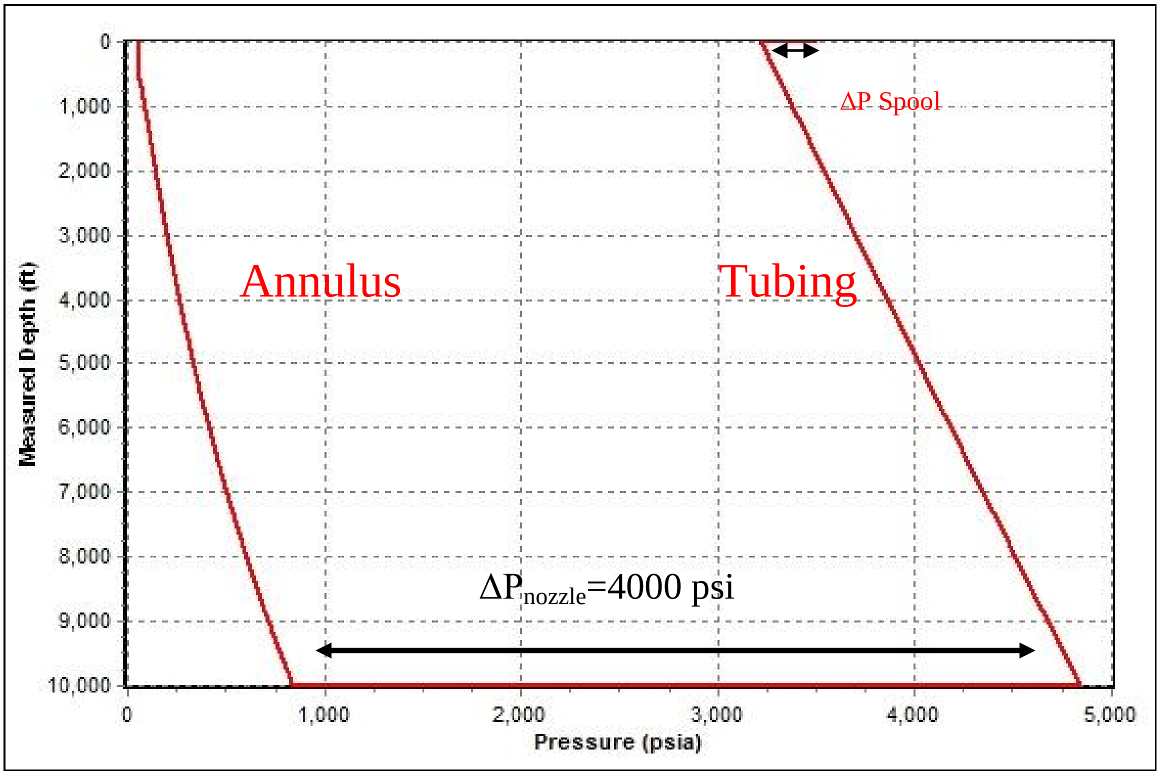


Figure 22: Pressure vs Depth (N_2 with Water, CT:1.25”, H.S:2.25”)

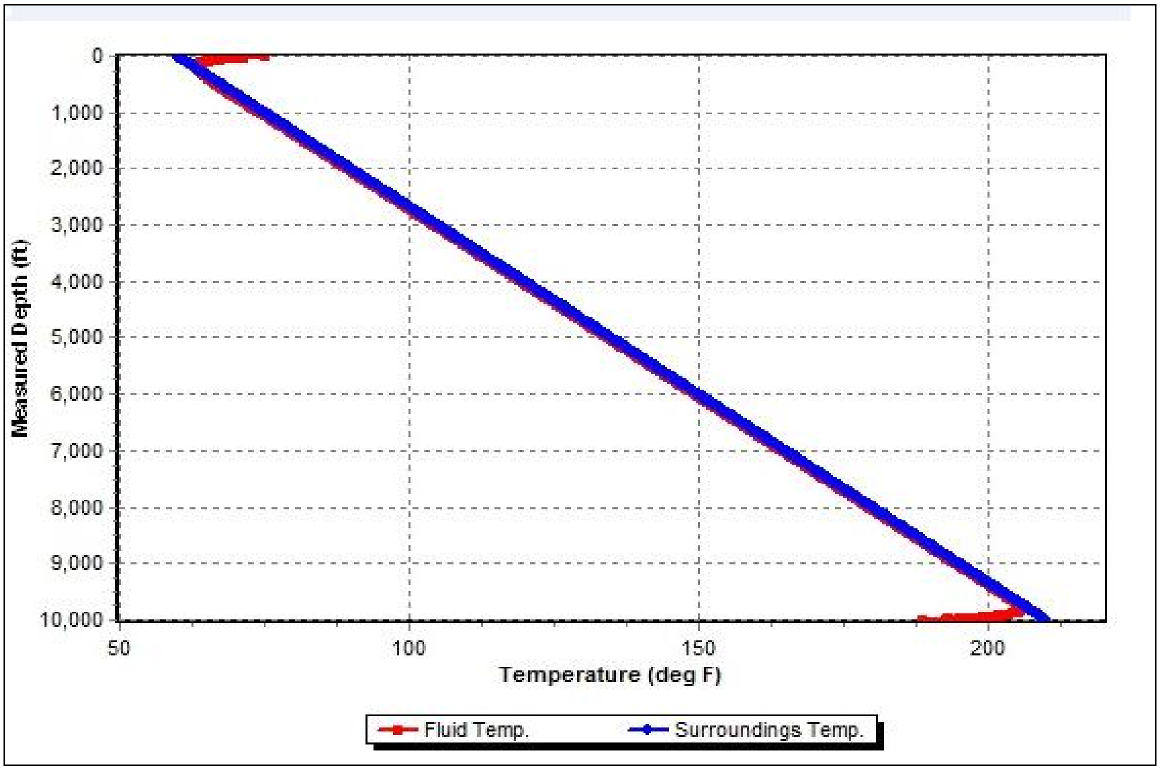


Figure 23: Temperature vs. Depth (N_2 With Water, CT:1.25”, H.S:2.25”)

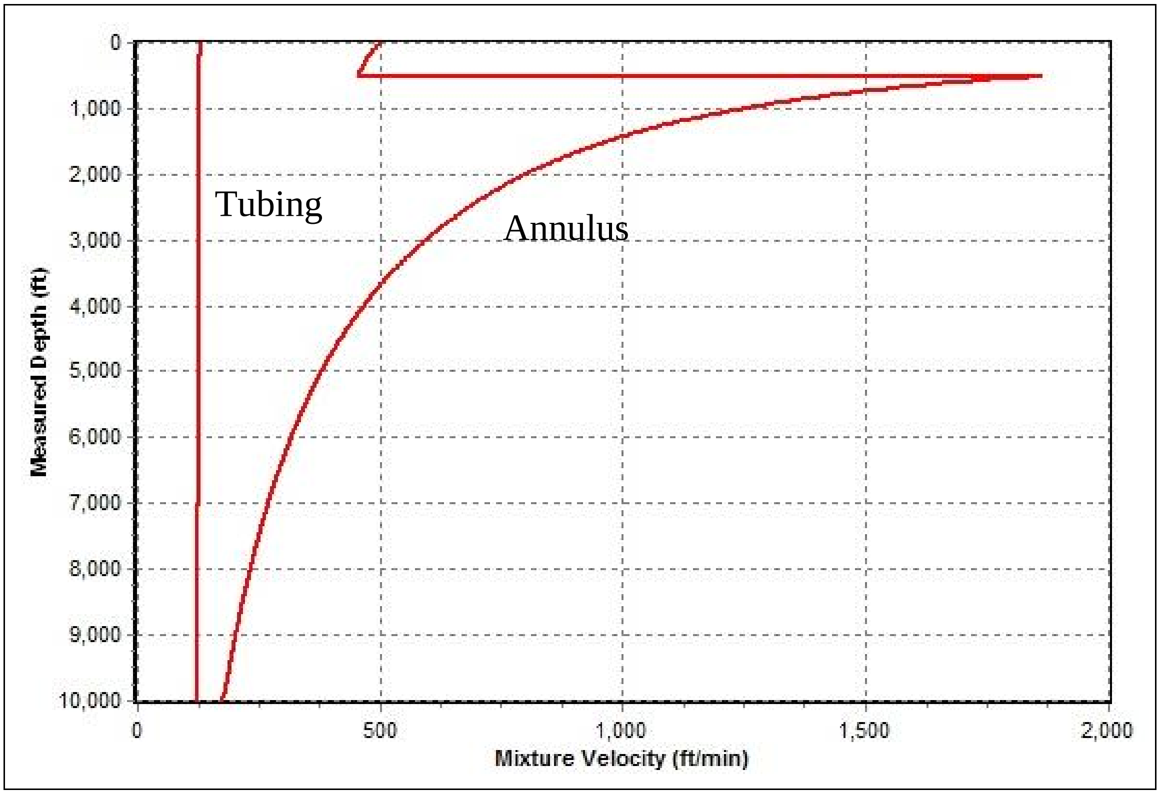


Figure 24: Velocity Profile (N_2 with Water, CT:1.25", H.S:2.25", Q_{N2}=5,Q_w=1gpm)

2.2.2 Nitrogen with Water Addition Cases for Different Coiled Tubing and Bore Hole Sizes

In this section, the operational envelopes and injection pressure profiles are given for different coiled tubing and borehole size combinations for nitrogen with water cases.

Hydrate formation is not a problem for these different size combinations. For a few run points, high liquid fraction occurred after the nozzle. Brown color was used on the operational envelope graphs in order to show run points which has liquid fraction more than 0.25 after the nozzle.

For injection pressure versus nitrogen graphs, water flow rates were written near the each run point on the graph. Injection pressure in the system increased with increasing injection flow rates.

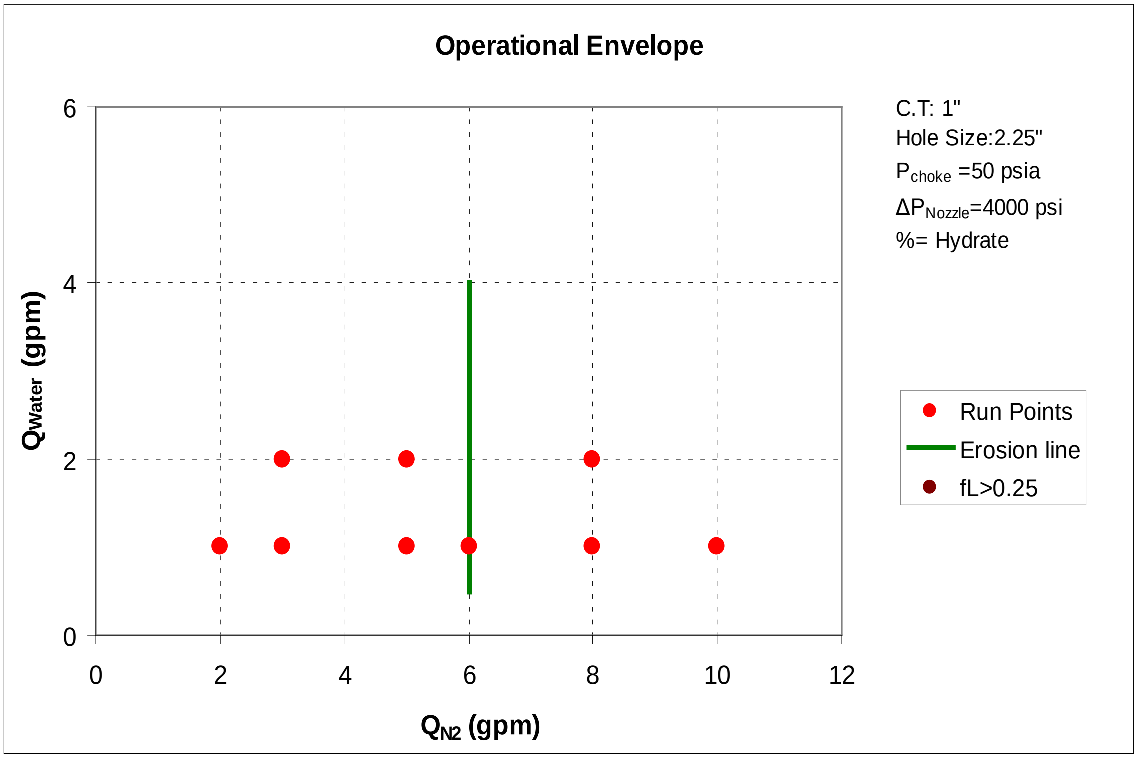


Figure 25: Operational Envelope for N_2 (CT:1”-HS:2.25”, With Water)

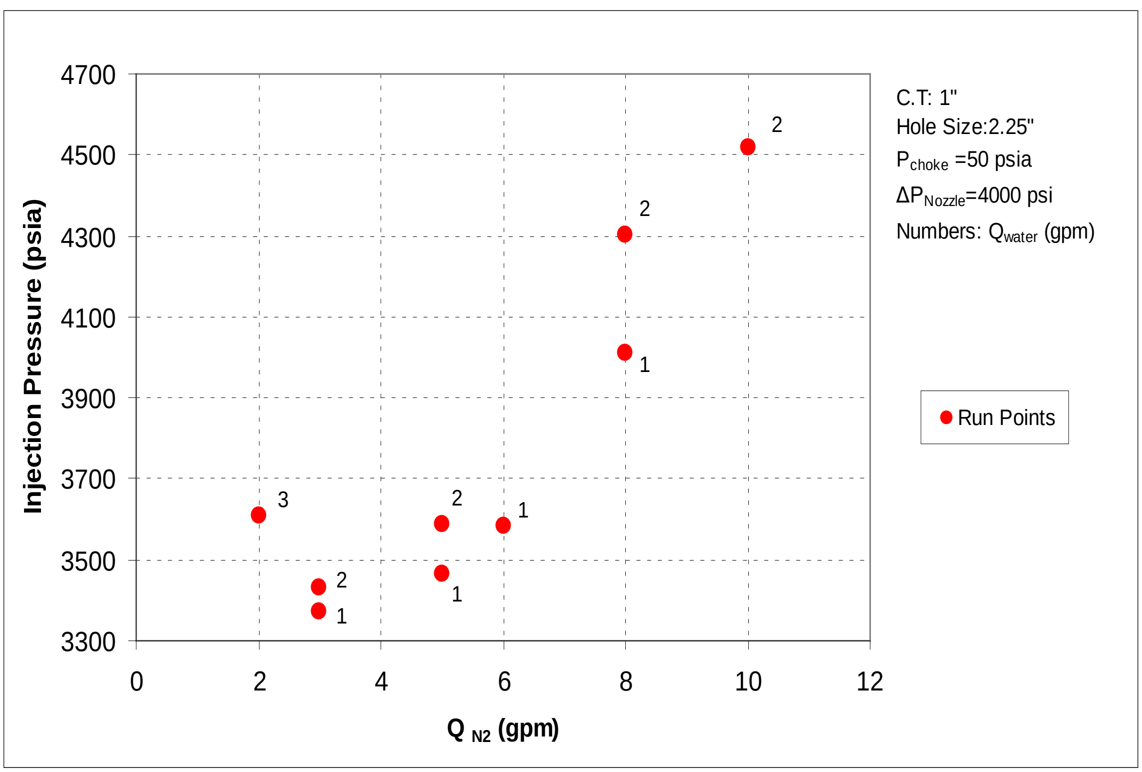


Figure 26: Flow Rate vs. Injection Pressure for N_2 (CT:1”-HS:2.25”, With Water)

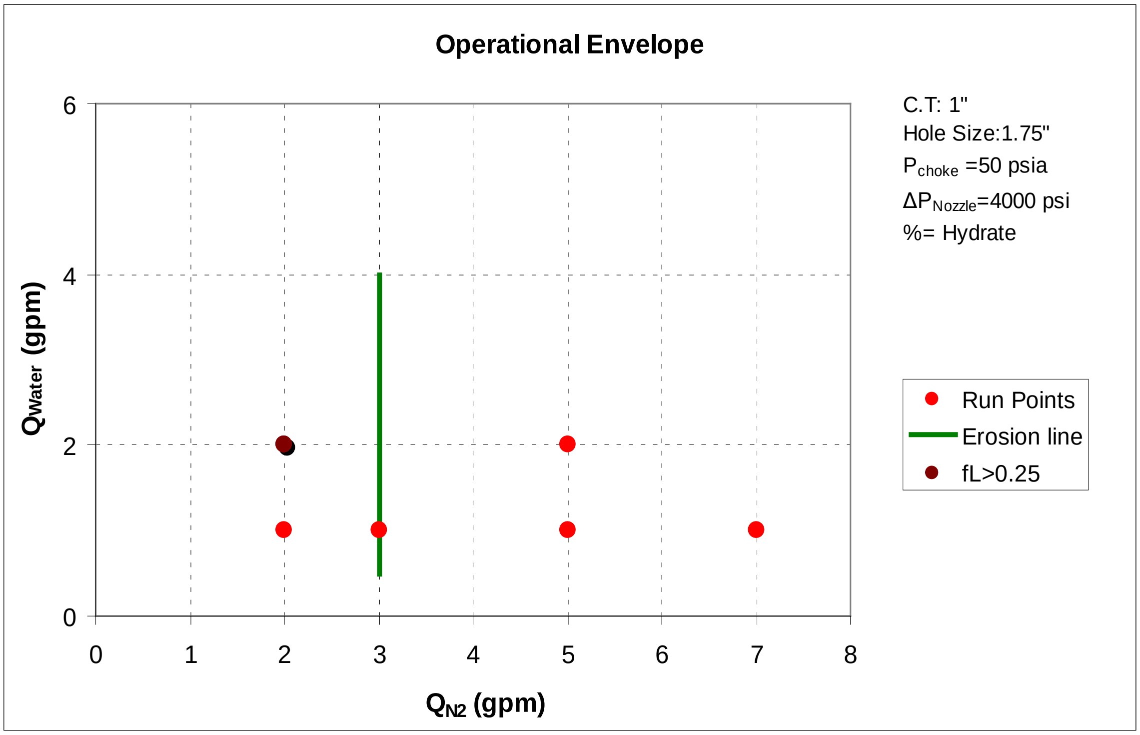


Figure 27: Operational Envelope for N_2 (CT:1”-HS:1.75”, With Water)

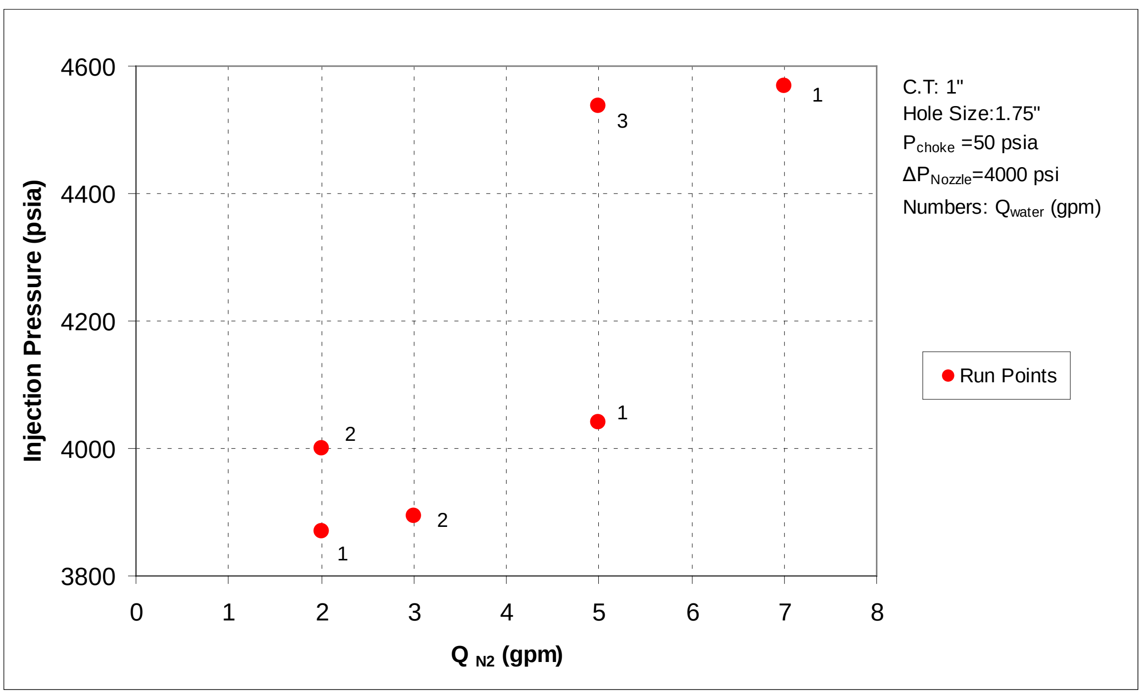


Figure 28: Flow Rate vs. Injection Pressure for N_2 (CT:1”-HS:1.75”, With Water)

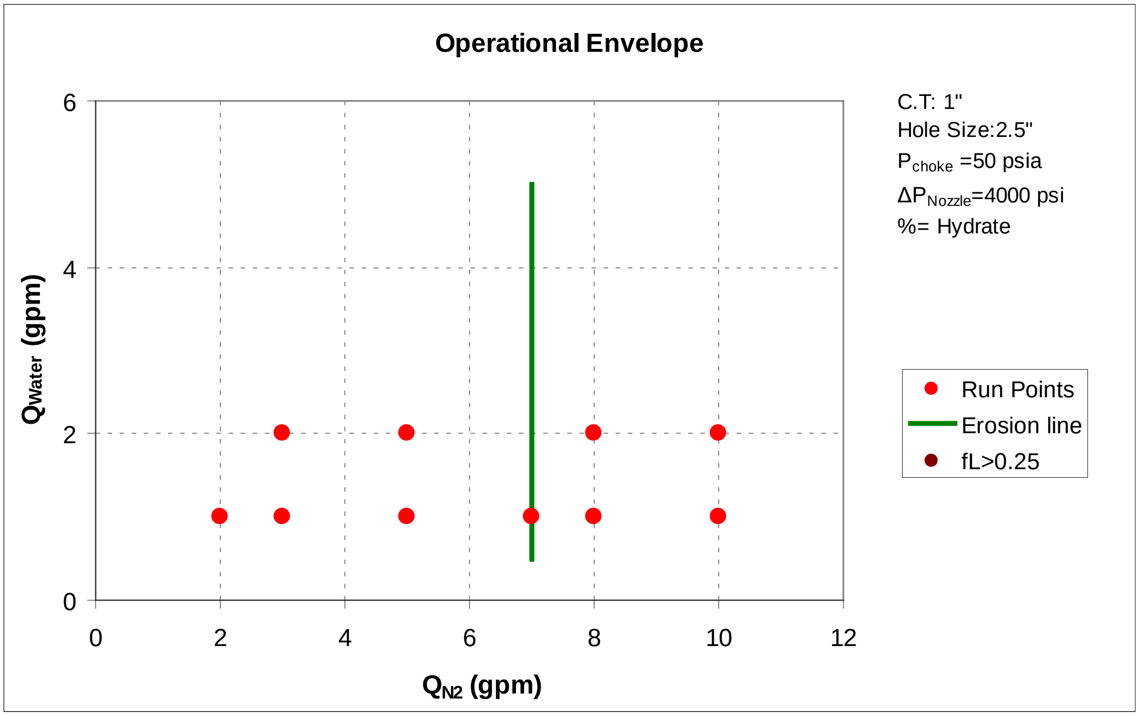


Figure 29: Operational Envelope for N_2 (CT:1”-HS:2.5”, With Water)

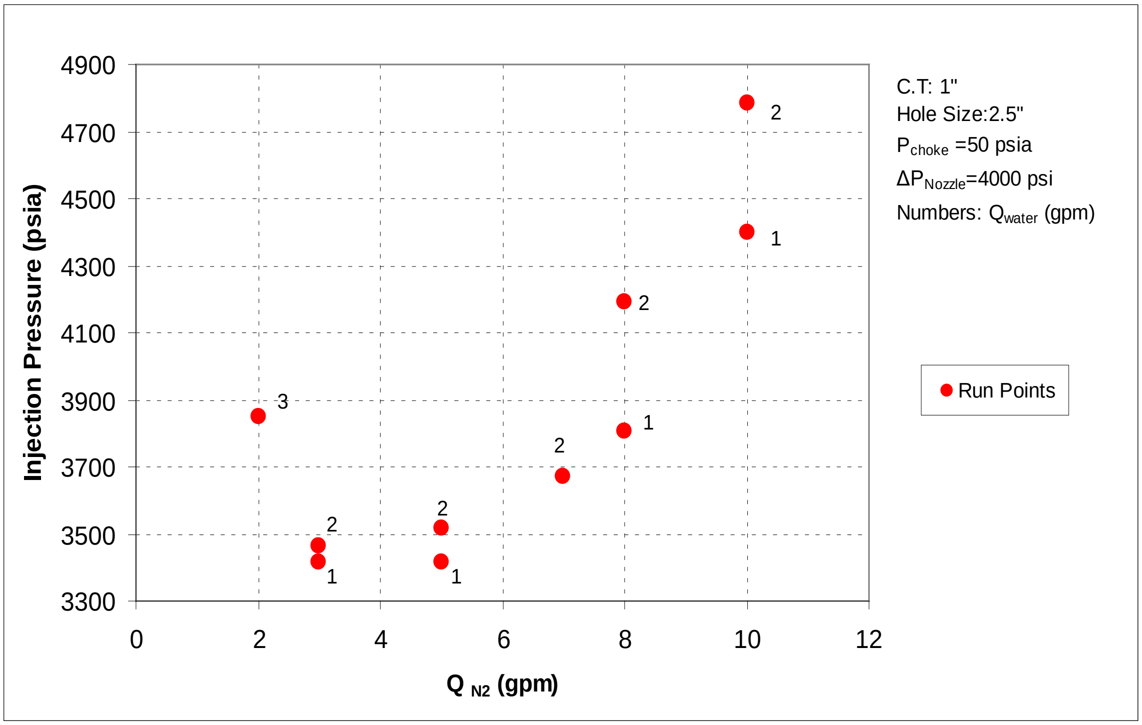


Figure 30: Flow Rate vs. Injection Pressure for N_2 (CT:1”-HS:2.5”, With Water)

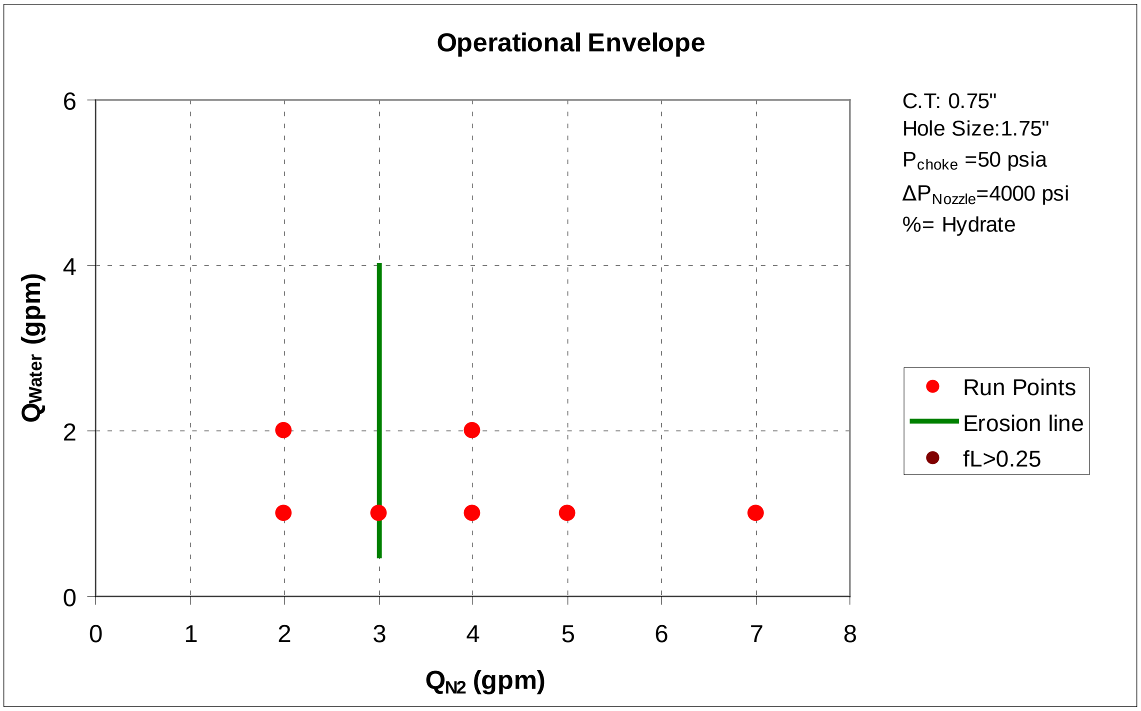


Figure 31: Operational Envelope for N_2 (CT:0.75”-HS:1.75”, With Water)

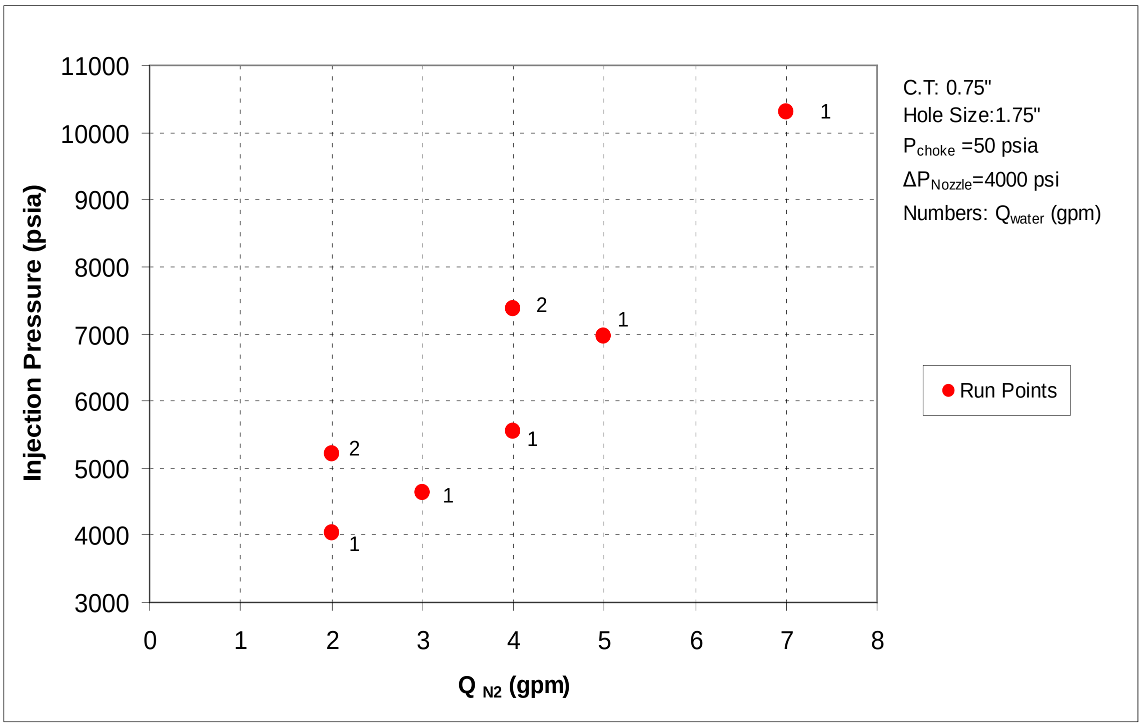


Figure 32: Flow Rate vs. Injection Pressure for N_2 (CT:0.75”-HS:1.75”, With Water)

2.3 Nitrogen with Water Influx Cases

In these simulations, nitrogen was injected with water and also 5 gpm water influx was allowed from the bottom of the well (at 10,000 ft) in the annulus. Runs were started with 1.25” coiled tubing and 2.25” bore hole size and performed also for other size combinations previously shown in Table 1.

5 gpm water influxes created significant amount of liquid fraction after the nozzle. Increasing nitrogen injecting rates decreased the liquid fraction after nozzle and for some cases liquid fraction became less than 0.25 after the nozzle.

2.3.1. Nitrogen with Water Influx (CT: 1.25” –H.S: 2.25”)

Figure 33 gives the operational envelope for nitrogen injecting with water and 5 gpm water influxes was allowed from bottom of the well. As seen from the graph, brown run points show the points which have more than 0.25 liquid fraction just after the nozzle.

Figure 34 gives the injection pressure profile of nitrogen with 5 gpm water influx at 10,000 ft. Numbers near the run points are amounts of water injected with nitrogen. As seen from the graph, with 5 gpm water influx, injection pressures increase up to 4940 psia.

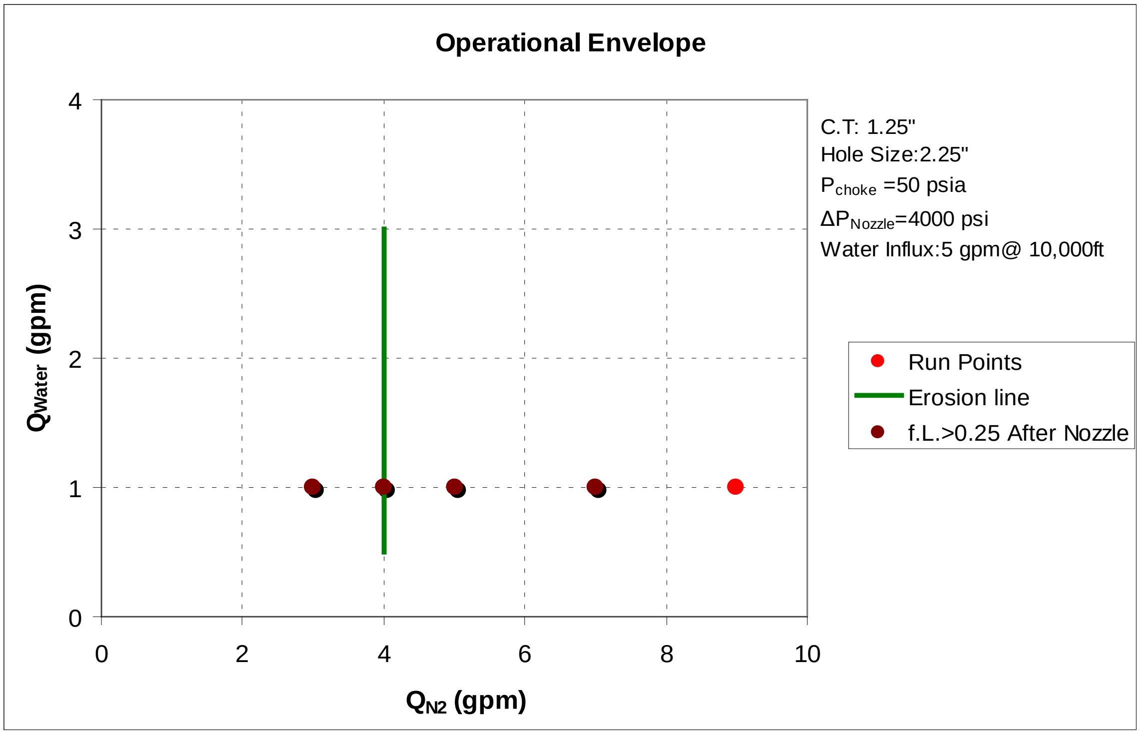


Figure 33: Operational Envelope for N_2 (CT:1.25”-HS:2.25”, With Water Influx)

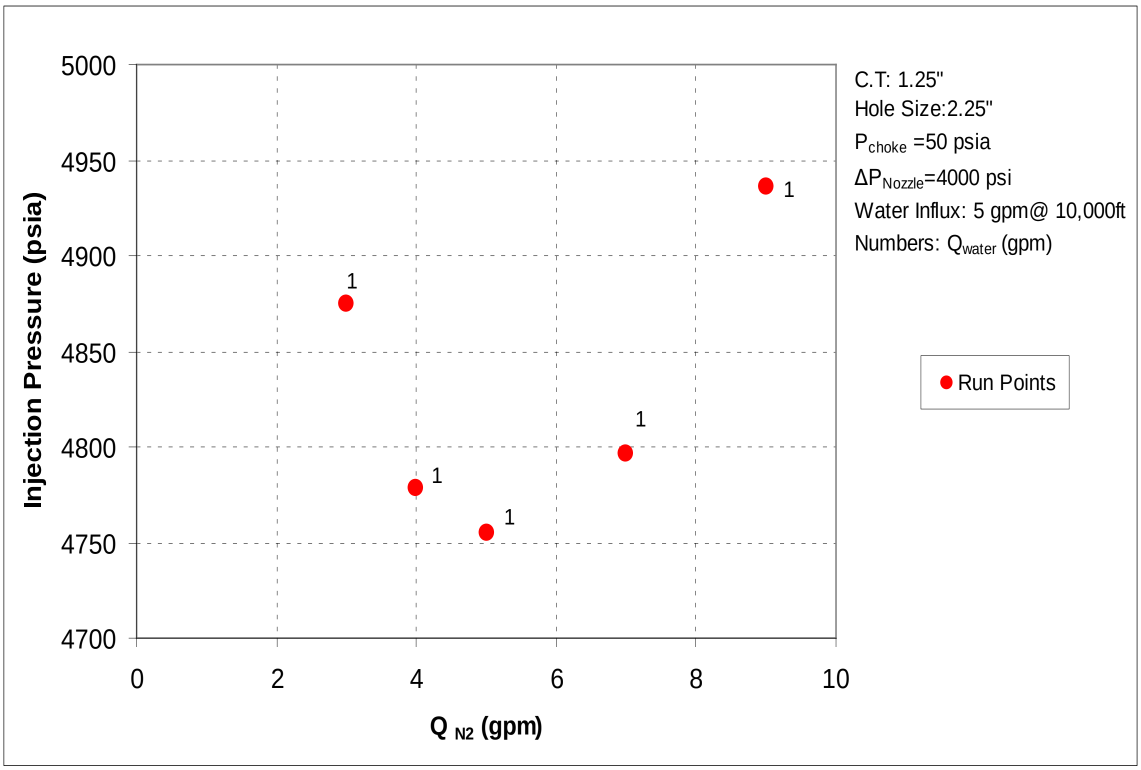


Figure 34: Flow Rate vs. Inj. Pressure for N_2 (CT:1.25”-HS:2.25”, With Water Influx)

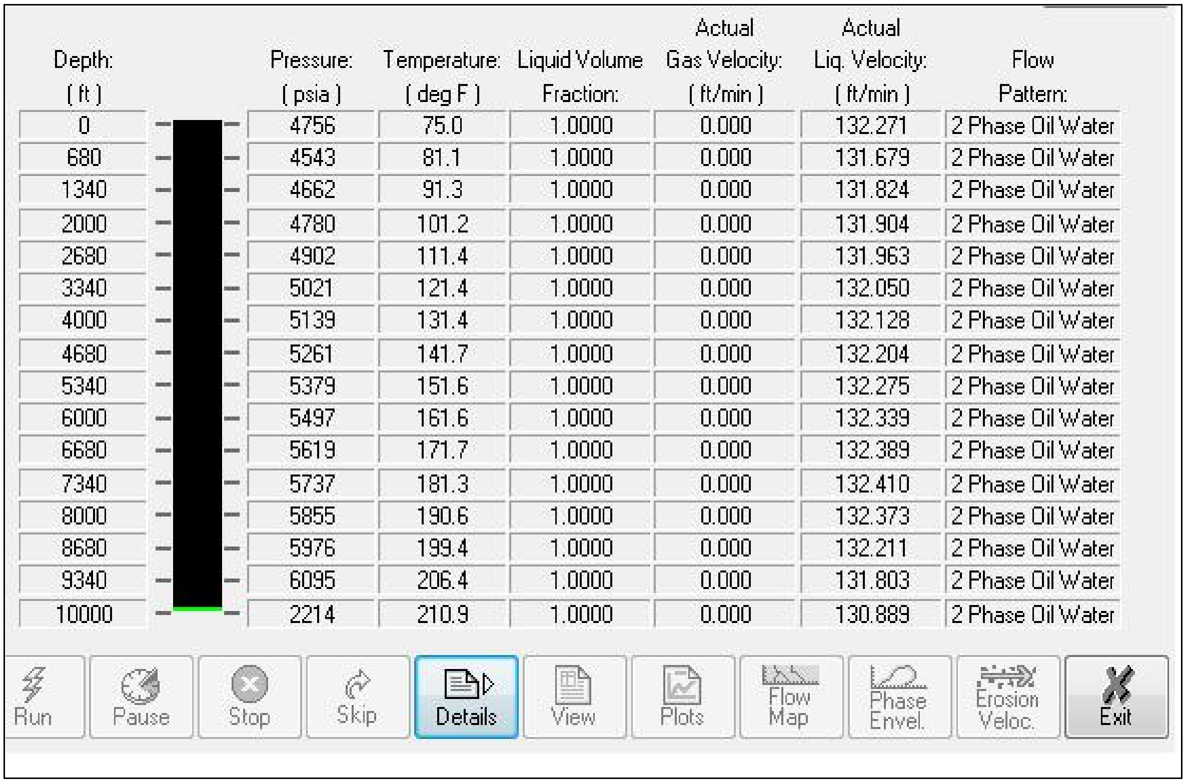
Run monitors for the nitrogen flow rate of 5 gpm, water flow rate of 1 gpm and water influx rate of 5 gpm are given for tubing and annulus sides in Figures 35 and 36, respectively. As can be seen from Figure 36, liquid fraction at the bottom of the well in the annulus is 0.34.

An example pressure and temperature profile graphs for same condition are given in Figure 37 and 38, respectively. As can be seen in Figure 37, the pressure drop of 4000 psi occurs at the nozzle. Also due to the surface coiled tubing facility, 334 psi total pressure drop occurred at the surface. Pressure outputs are given in Table 5.

Table 5: Output Pressure Values
(N_2, With Water Influx, Q_{N2}=5 gpm, Q_w= 1gpm, Q_{wi}=5 gpm)

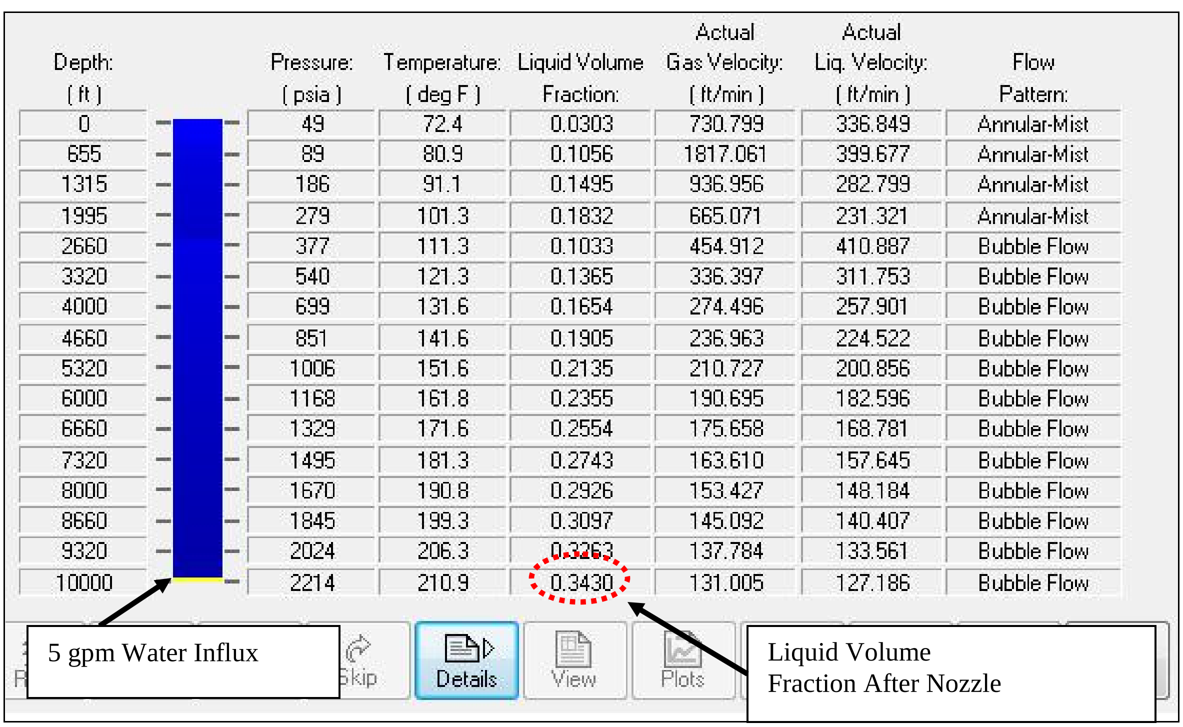
Injection Pressure (psia)	4755
BHP Upstream Nozzle (psia)	6213
BHP Downstream Nozzle (psia)	2213

Figure 38 is the temperature profile of the fluid inside the tubing and annulus (red line) with the formation temperature profile (blue line). Selected output results for all flow rates are given in Appendix A.



Depth: (ft)	Pressure: (psia)	Temperature: (deg F)	Liquid Volume Fraction:	Actual Gas Velocity: (ft/min)	Actual Liq. Velocity: (ft/min)	Flow Pattern:
0	4756	75.0	1.0000	0.000	132.271	2 Phase Oil Water
680	4543	81.1	1.0000	0.000	131.679	2 Phase Oil Water
1340	4662	91.3	1.0000	0.000	131.824	2 Phase Oil Water
2000	4780	101.2	1.0000	0.000	131.904	2 Phase Oil Water
2680	4902	111.4	1.0000	0.000	131.963	2 Phase Oil Water
3340	5021	121.4	1.0000	0.000	132.050	2 Phase Oil Water
4000	5139	131.4	1.0000	0.000	132.128	2 Phase Oil Water
4680	5261	141.7	1.0000	0.000	132.204	2 Phase Oil Water
5340	5379	151.6	1.0000	0.000	132.275	2 Phase Oil Water
6000	5497	161.6	1.0000	0.000	132.339	2 Phase Oil Water
6680	5619	171.7	1.0000	0.000	132.389	2 Phase Oil Water
7340	5737	181.3	1.0000	0.000	132.410	2 Phase Oil Water
8000	5855	190.6	1.0000	0.000	132.373	2 Phase Oil Water
8680	5976	199.4	1.0000	0.000	132.211	2 Phase Oil Water
9340	6095	206.4	1.0000	0.000	131.803	2 Phase Oil Water
10000	2214	210.9	1.0000	0.000	130.889	2 Phase Oil Water

Figure 35: Tubing Monitor (N_2, CT:1.25", H.S:2.25", Q_{N2}=5,Q_w= 1,Q_{wi}= 5 gpm)



Depth: (ft)	Pressure: (psia)	Temperature: (deg F)	Liquid Volume Fraction:	Actual Gas Velocity: (ft/min)	Actual Liq. Velocity: (ft/min)	Flow Pattern:
0	49	72.4	0.0303	730.799	336.849	Annular-Mist
655	89	80.9	0.1056	1817.061	399.677	Annular-Mist
1315	186	91.1	0.1495	936.956	282.799	Annular-Mist
1995	279	101.3	0.1832	665.071	231.321	Annular-Mist
2660	377	111.3	0.1033	454.912	410.887	Bubble Flow
3320	540	121.3	0.1365	336.397	311.753	Bubble Flow
4000	699	131.6	0.1654	274.496	257.901	Bubble Flow
4660	851	141.6	0.1905	236.963	224.522	Bubble Flow
5320	1006	151.6	0.2135	210.727	200.856	Bubble Flow
6000	1168	161.8	0.2355	190.695	182.596	Bubble Flow
6660	1329	171.6	0.2554	175.658	168.781	Bubble Flow
7320	1495	181.3	0.2743	163.610	157.645	Bubble Flow
8000	1670	190.8	0.2926	153.427	148.184	Bubble Flow
8660	1845	199.3	0.3097	145.092	140.407	Bubble Flow
9320	2024	206.3	0.3263	137.784	133.561	Bubble Flow
10000	2214	210.9	0.3430	131.005	127.186	Bubble Flow

Figure 36: Annulus Monitor (N_2, CT:1.25",H.S:2.25", Q_{N2}=5,Q_w= 1,Q_{wi}= 5 gpm)

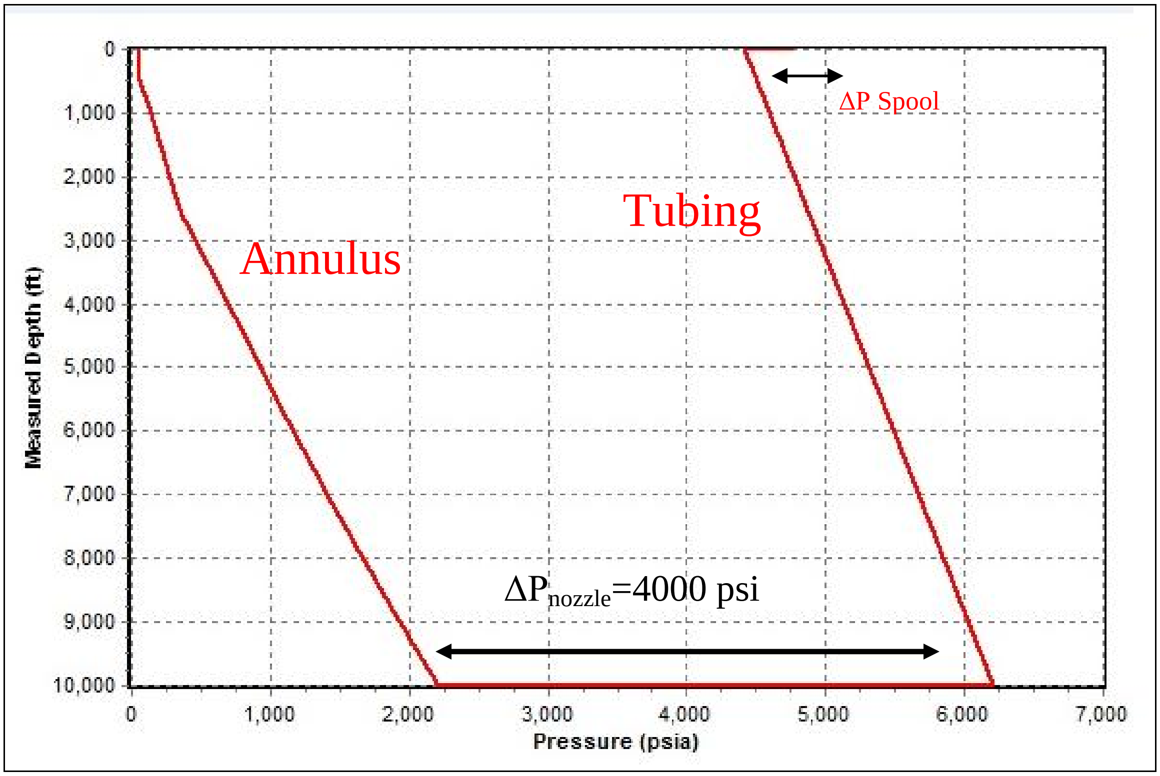


Figure 37: Pressure vs Depth (N_2 with Water Influx, CT:1.25”, H.S:2.25”)

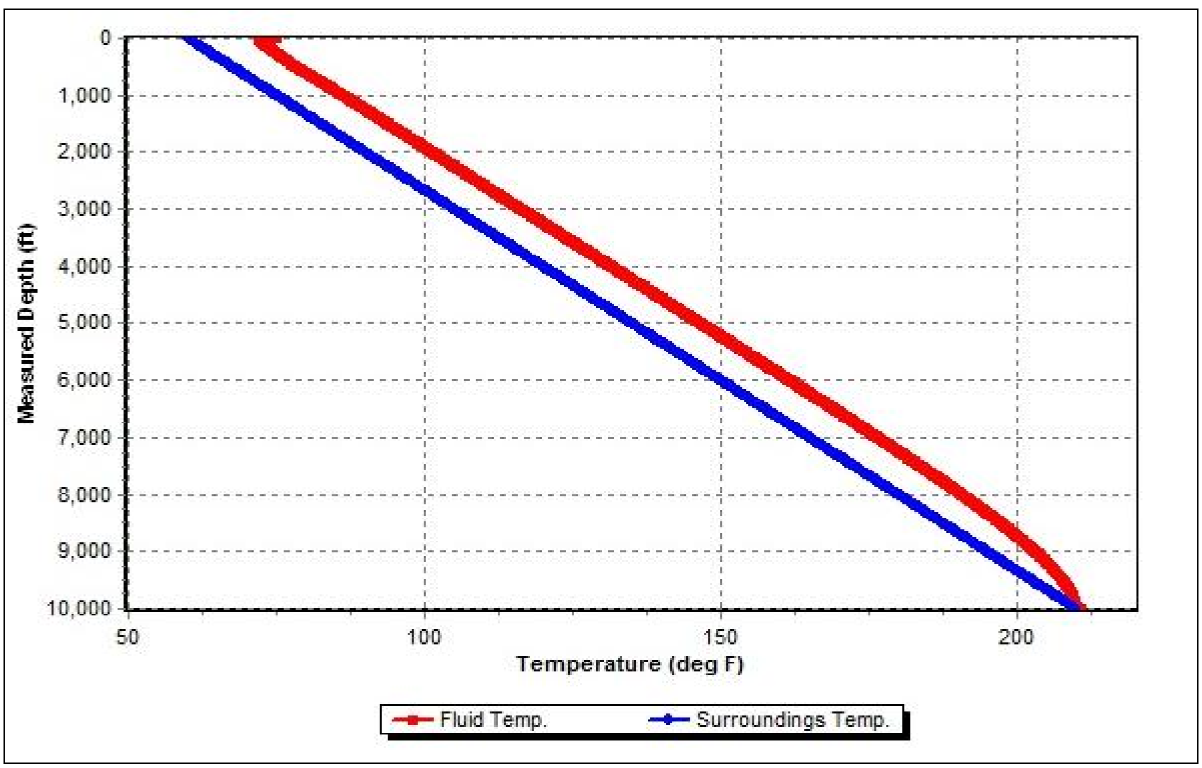


Figure 38: Temperature vs Depth (N_2 With Water Influx, CT:1.25”, H.S:2.25”)

2.3.2 Nitrogen with Water Influx for Different Coiled Tubing and Bore Hole Sizes

In this section, operational envelopes and injection pressure profiles are given for different coiled tubing and borehole size combinations for nitrogen with water influx cases. Nitrogen was injected to the tubing with water for all the conditions.

As seen on the operational envelope graphs, due to the 5 gpm water influx from the bottom of the well, liquid fraction after the nozzle are high for almost all different coiled tubing sizes.

Hydrate formation is not a problem for also different size combinations. Most of the cases hydrate does not occur in the system.

For injection pressure versus nitrogen graphs, water flow rates were written near the each run points on the graph. Injection pressures in the system increased with increasing injection flow rates.

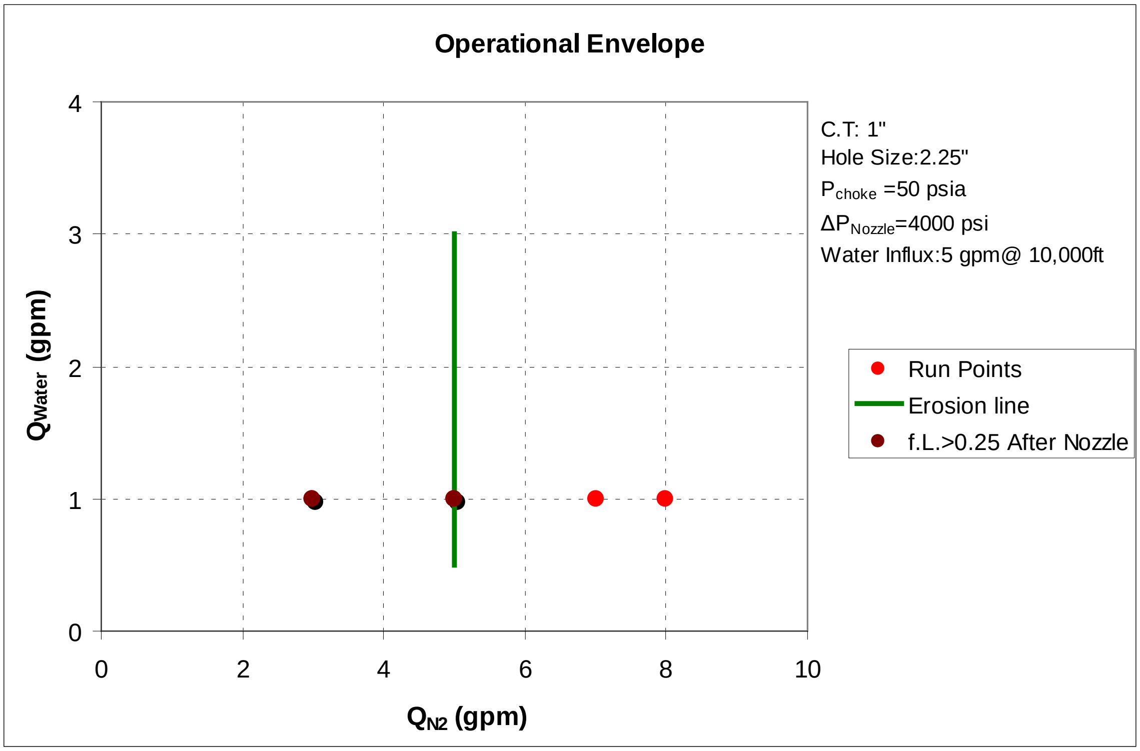


Figure 39: Operational Envelope for N_2 (CT:1”-HS:2.25”, With Water Influx)

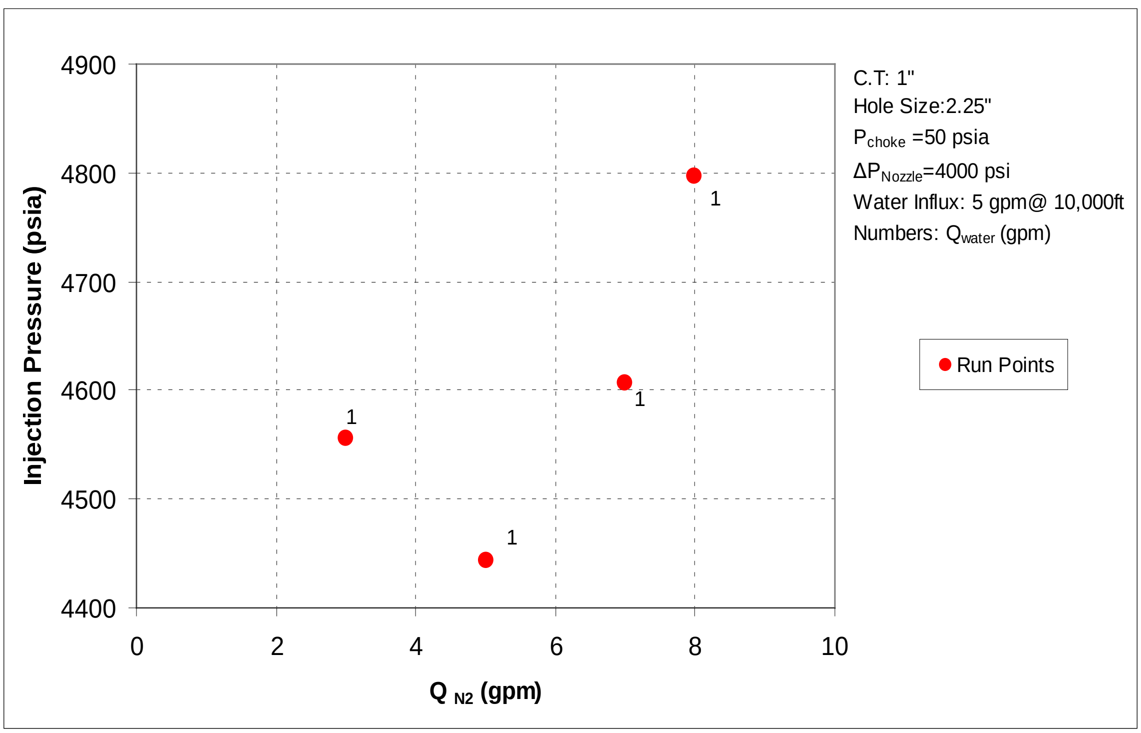


Figure 40: Flow Rate vs. Inj. Pressure for N_2 (CT:1”-HS:2.25”, With Water Influx)

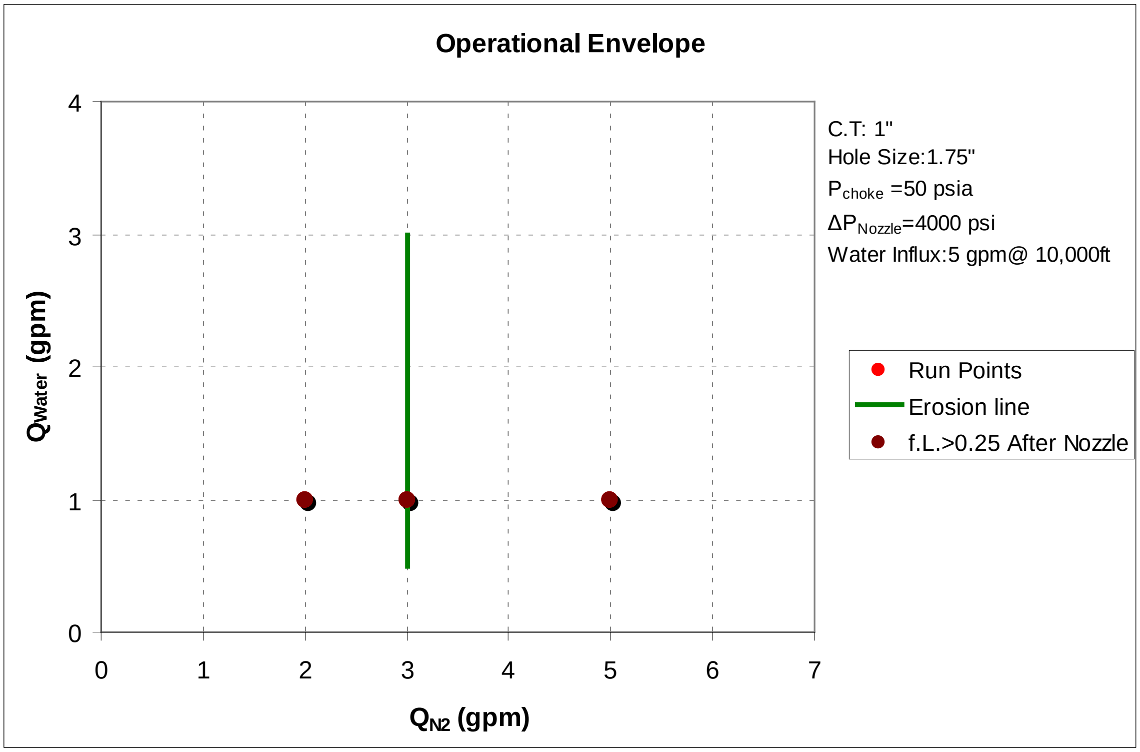


Figure 41: Operational Envelope for N_2 (CT:1”-HS:1.75”, With Water Influx)

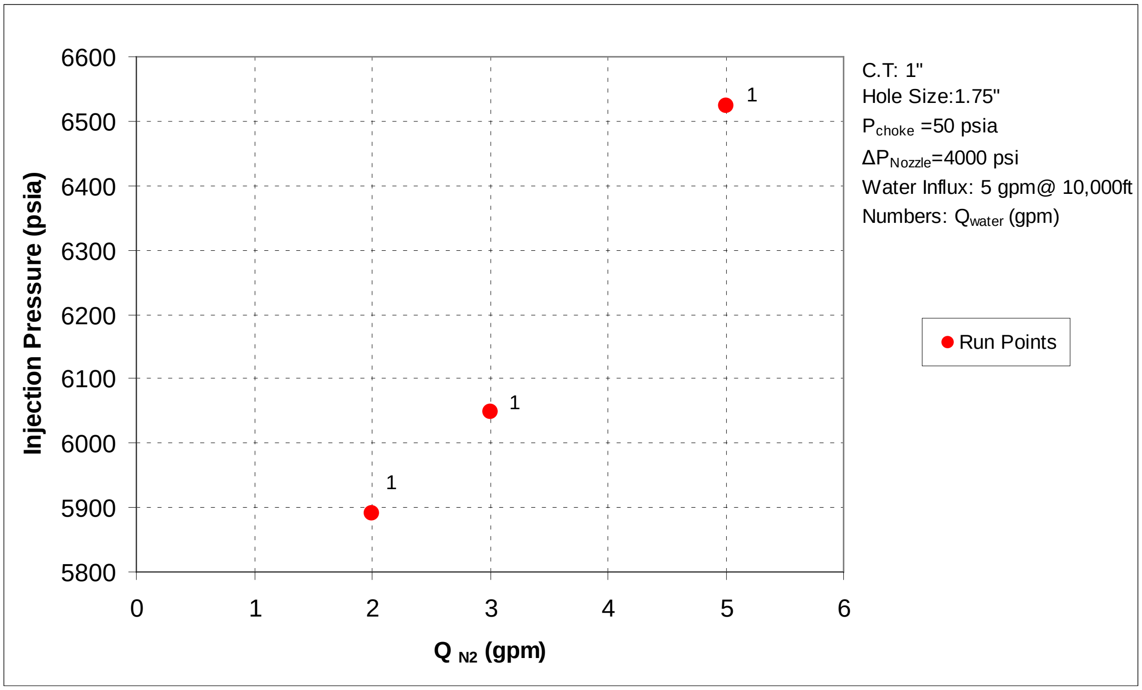


Figure 42: Flow Rate vs. Inj. Pressure for N_2 (CT:1”-HS:1.75”, With Water Influx)

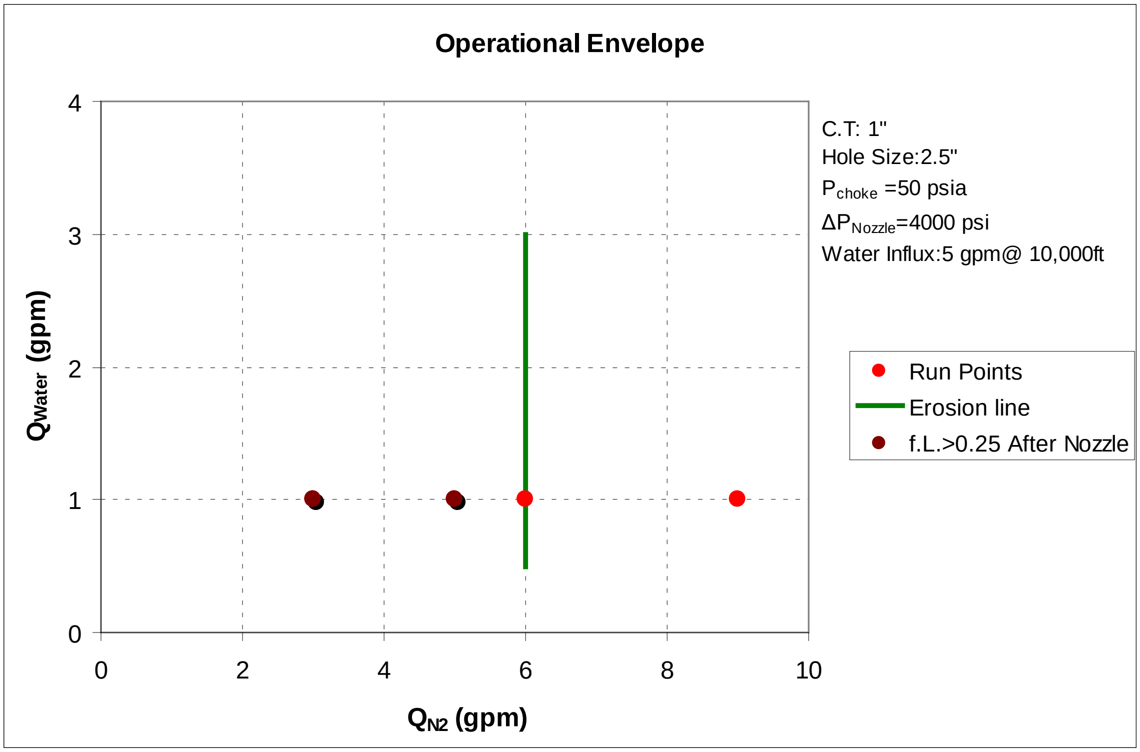


Figure 43: Operational Envelope for N_2 (CT:1"-HS:2.5", With Water Influx)

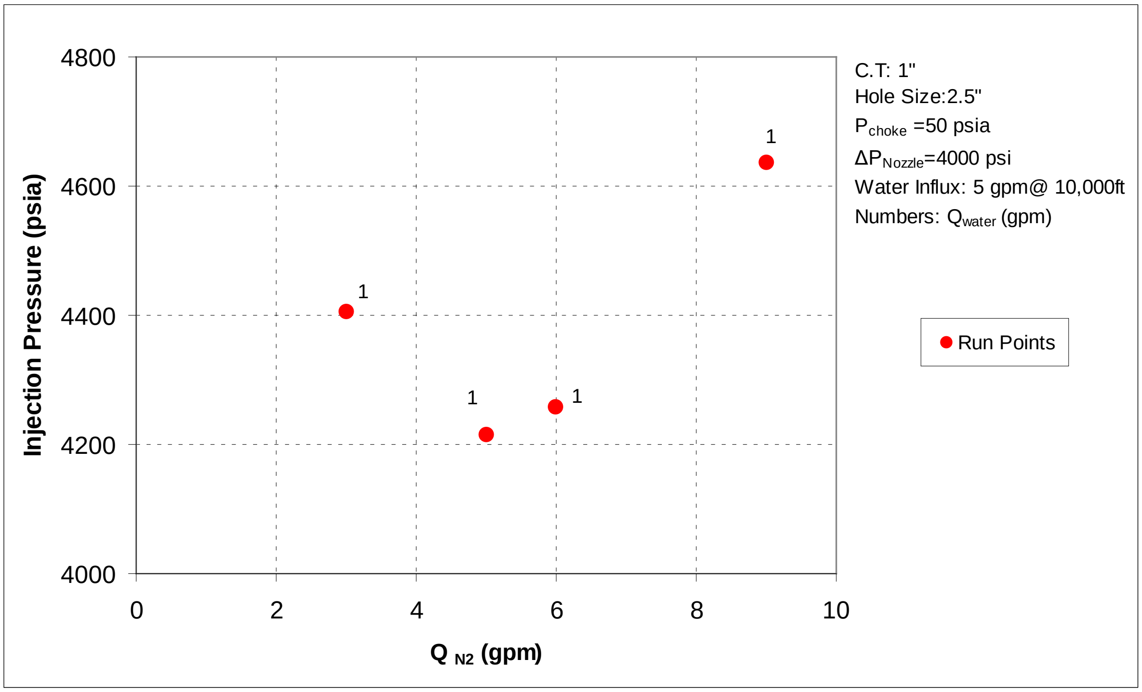


Figure 44: Flow Rate vs. Inj. Pressure for N_2 (CT:1"-HS:2.5", With Water Influx)

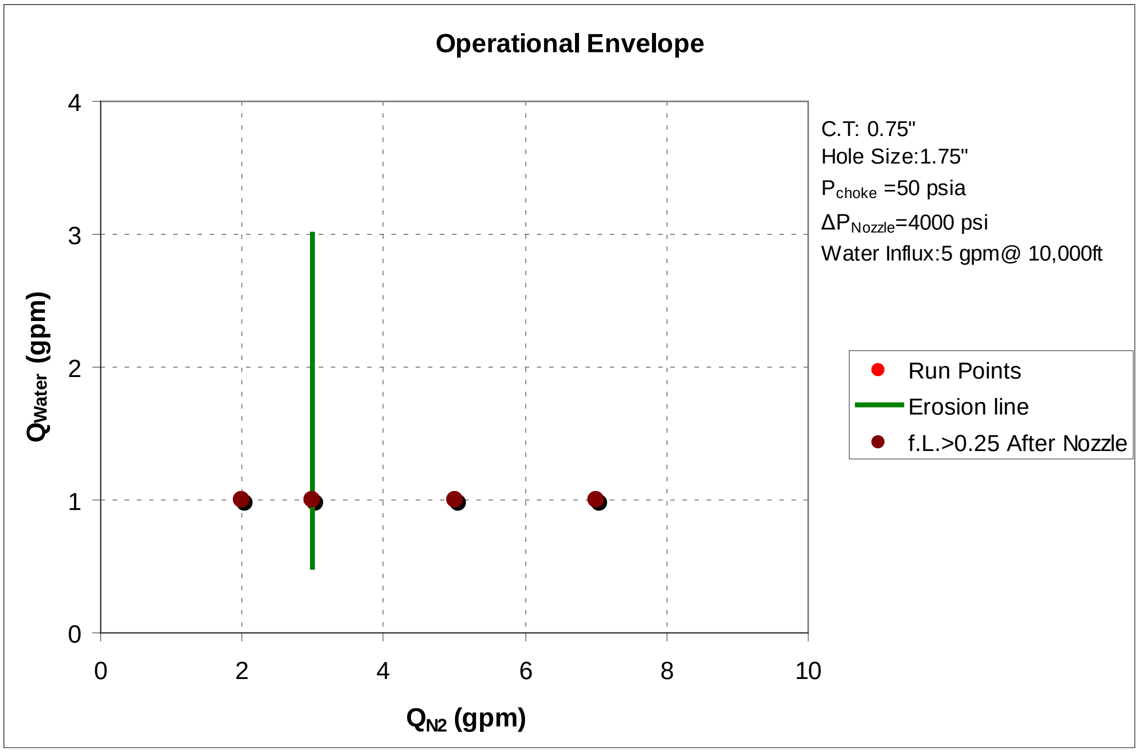


Figure 45: Operational Envelope for N_2 (CT:0.75"-HS:1.75", With Water Influx)

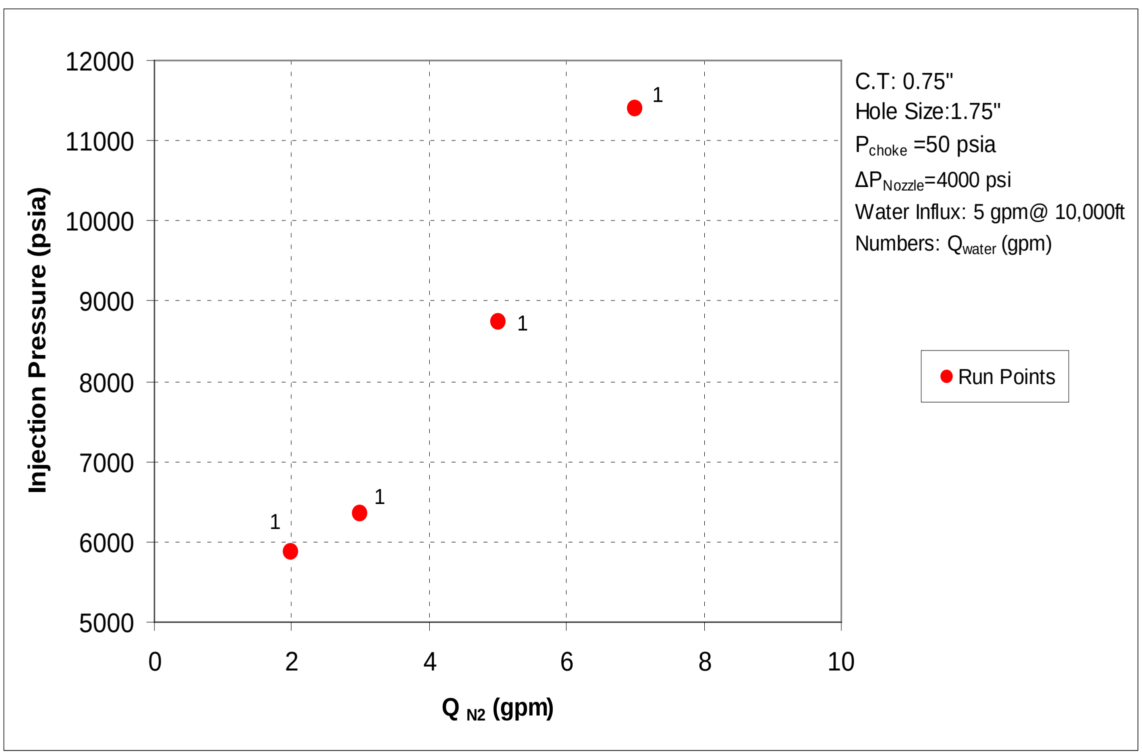


Figure 46: Flow Rate vs. Inj. Pressure for N_2 (CT:0.75"-HS:1.75", With Water Influx)

3. Carbon dioxide as Drilling Fluid

In this part, WellFlo simulation results are given for three different conditions in which supercritical CO_2 was used as a drilling fluid. In the first condition, only CO_2 was injected to the well. In the second condition, CO_2 was injected with different amount of water. For the third condition, CO_2 was injected with water and 5 gpm water influxes at the bottom of the well into the annulus after nozzle.

CO_2 runs were performed with different coiled tubing and hole sizes as previously shown in Table 1. Runs were started with 1.25” OD coiled tubing and 2.25” hole size. In this geometry, runs were performed for a wide range of flow rate conditions to create an operational envelope. Similar to N_2 runs, 4” surface pipe was used for the first 500 ft for all CO_2 runs.

3.1 CO_2 without Water Addition Cases

CO_2 runs started with the condition of injecting only CO_2 into the 10,000 ft deep vertical well. In these operations, temperature drop was occurred due to the Joule Thompson effect. Possible hydrate formation percentages are shown in the operational envelope graphs near the run points.

3.1.1 CO_2 without Water Addition Cases (CT: 1.25” –H.S: 2.25”)

Figure 47 gives operational envelope for CO_2 without water condition for given tubing and hole sizes. In the graph, again the erosion line shows the maximum injection flow rates for the erosion velocity limit (1800 ft/min). As can be seen from Figure 47, maximum CO_2 injection flow rate needs to be less than 3 gpm in order not to exceed erosion velocity in the annulus.

As seen from the graph, for CO_2 without water cases, more than 0.25 liquid fraction was occurred after nozzle in the system for the run points shown by the brown color. Pressure and temperature values after the nozzle should have proper values to provide gas phase CO_2.

Figure 48 shows the change of injection pressure for different CO_2 flow rates. High hydrostatic head in the tubing resulted in lower needed injection pressures for CO_2 runs.

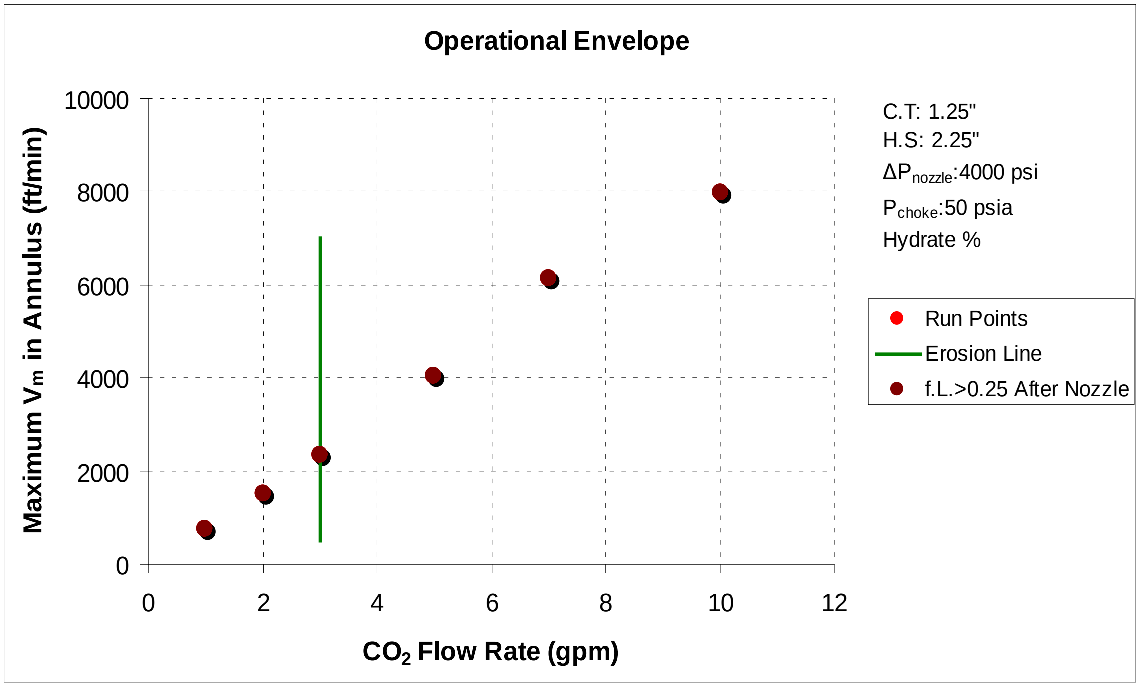


Figure 47: Operational Envelope for CO_2 (CT:1.25”-HS:2.25”, Without Water)

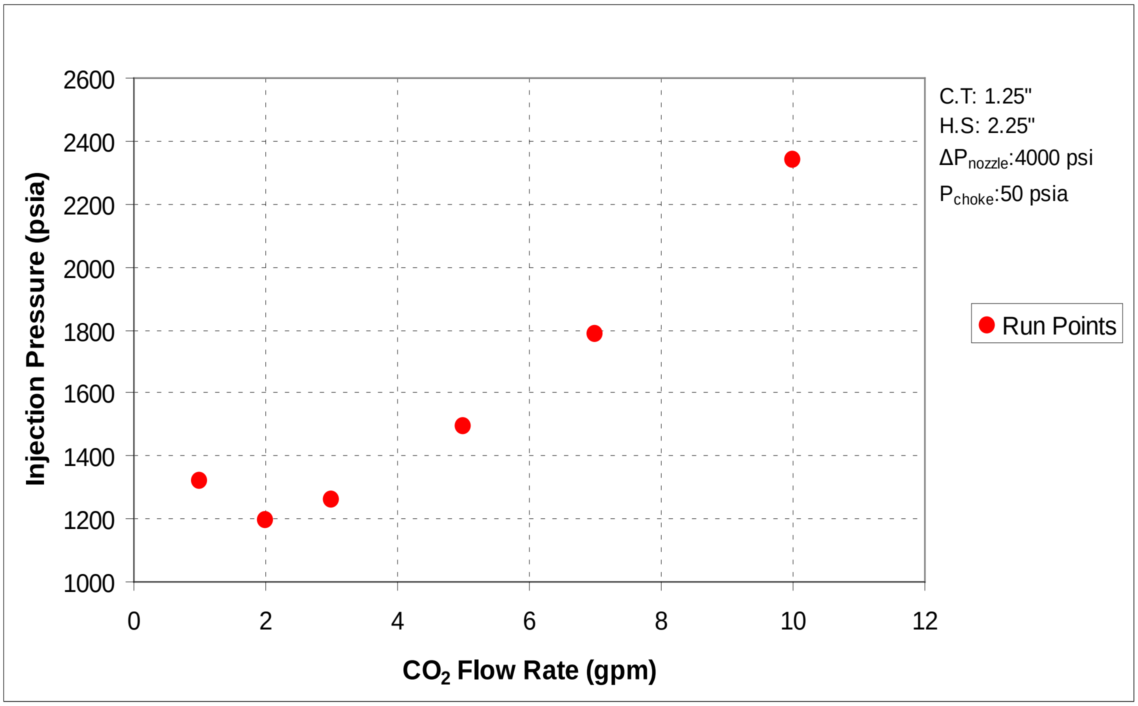


Figure 48: Flow Rate vs. Injection Pressure for CO_2 (CT:1.25”-HS:2.25”, Without Water)

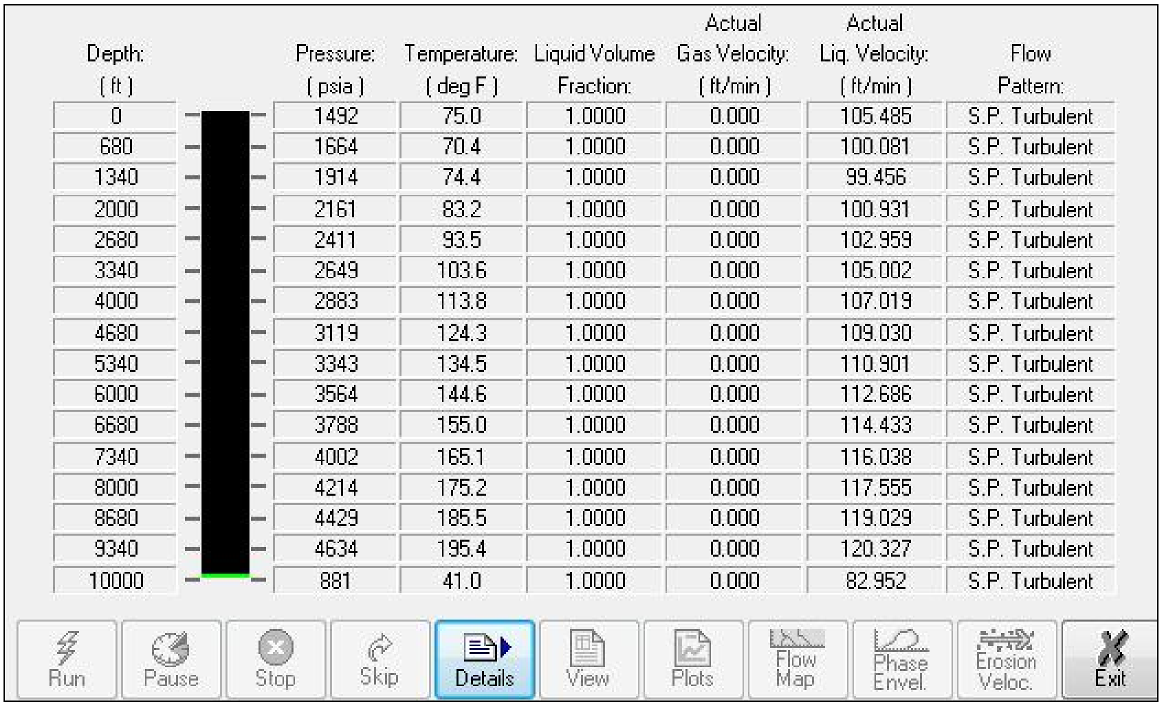
Example run monitors for tubing and annulus side of CO_2 only run with 5 gpm injection rate are given in Figure 49 and 50, respectively. As can be seen from Figure 50, liquid fraction after the nozzle is 1. Pressure and temperature combination after the nozzle caused high liquid fraction.

An example pressure and temperature profile graph for CO_2 only case is given for the flow rate of 5 gpm in Figures 51 and 52, respectively. As seen in Figure 51, the pressure drop of 4000 psi occurs at the nozzle. Pressure outputs for 5 gpm are given in Table 6.

Table 6: Output Pressure Values (CO_2 without Water Addition, 5 gpm)

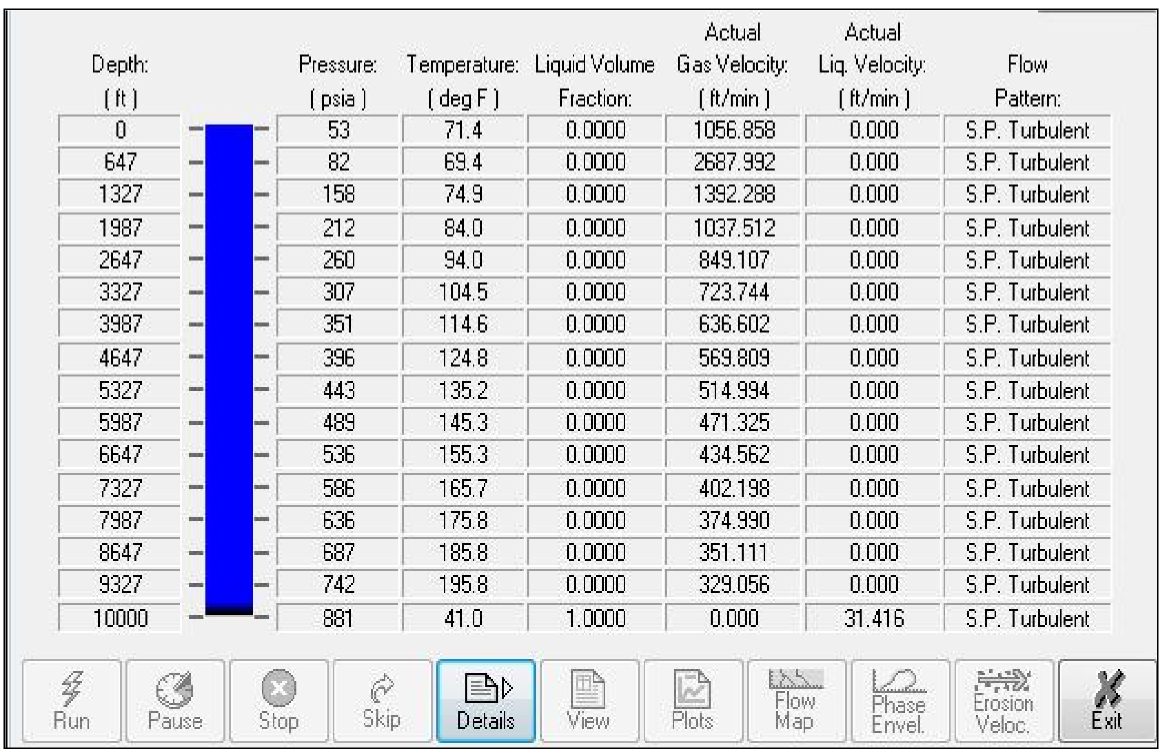
Injection Pressure (psia)	1492
BHP Upstream Nozzle (psia)	4880
BHP Downstream Nozzle (psia)	880

Figure 52 is the temperature profile of the fluid inside the coiled tubing and annulus with the formation temperature profile. The red line shows the temperature profile for fluid in the pipe and annulus and blue line shows the surrounding temperature profile. Temperature of the fluids followed the geothermal gradient until the nozzle, where significant pressure drop occurred and then followed the formation temperature profile as it moves up the annulus. Selected output results for all other flow rate data are given in Appendix A.



Depth: (ft)	Pressure: (psia)	Temperature: (deg F)	Liquid Volume Fraction:	Actual Gas Velocity: (ft/min)	Actual Liq. Velocity: (ft/min)	Flow Pattern:
0	1492	75.0	1.0000	0.000	105.485	S.P. Turbulent
680	1664	70.4	1.0000	0.000	100.081	S.P. Turbulent
1340	1914	74.4	1.0000	0.000	99.456	S.P. Turbulent
2000	2161	83.2	1.0000	0.000	100.931	S.P. Turbulent
2680	2411	93.5	1.0000	0.000	102.959	S.P. Turbulent
3340	2649	103.6	1.0000	0.000	105.002	S.P. Turbulent
4000	2883	113.8	1.0000	0.000	107.019	S.P. Turbulent
4680	3119	124.3	1.0000	0.000	109.030	S.P. Turbulent
5340	3343	134.5	1.0000	0.000	110.901	S.P. Turbulent
6000	3564	144.6	1.0000	0.000	112.686	S.P. Turbulent
6680	3788	155.0	1.0000	0.000	114.433	S.P. Turbulent
7340	4002	165.1	1.0000	0.000	116.038	S.P. Turbulent
8000	4214	175.2	1.0000	0.000	117.555	S.P. Turbulent
8680	4429	185.5	1.0000	0.000	119.029	S.P. Turbulent
9340	4634	195.4	1.0000	0.000	120.327	S.P. Turbulent
10000	881	41.0	1.0000	0.000	82.952	S.P. Turbulent

Figure 49: Tubing Side Run Monitor (CO_2 without Water,CT:1.25, H.S:2.25", Q=5 gpm)



Depth: (ft)	Pressure: (psia)	Temperature: (deg F)	Liquid Volume Fraction:	Actual Gas Velocity: (ft/min)	Actual Liq. Velocity: (ft/min)	Flow Pattern:
0	53	71.4	0.0000	1056.858	0.000	S.P. Turbulent
647	82	69.4	0.0000	2687.992	0.000	S.P. Turbulent
1327	158	74.9	0.0000	1392.288	0.000	S.P. Turbulent
1987	212	84.0	0.0000	1037.512	0.000	S.P. Turbulent
2647	260	94.0	0.0000	849.107	0.000	S.P. Turbulent
3327	307	104.5	0.0000	723.744	0.000	S.P. Turbulent
3987	351	114.6	0.0000	636.602	0.000	S.P. Turbulent
4647	396	124.8	0.0000	569.809	0.000	S.P. Turbulent
5327	443	135.2	0.0000	514.994	0.000	S.P. Turbulent
5987	489	145.3	0.0000	471.325	0.000	S.P. Turbulent
6647	536	155.3	0.0000	434.562	0.000	S.P. Turbulent
7327	586	165.7	0.0000	402.198	0.000	S.P. Turbulent
7987	636	175.8	0.0000	374.990	0.000	S.P. Turbulent
8647	687	185.8	0.0000	351.111	0.000	S.P. Turbulent
9327	742	195.8	0.0000	329.056	0.000	S.P. Turbulent
10000	881	41.0	1.0000	0.000	31.416	S.P. Turbulent

Figure 50: Annulus Side Run Monitor (CO_2 without Water,CT:1.25,H.S:2.25",Q=5 gpm)

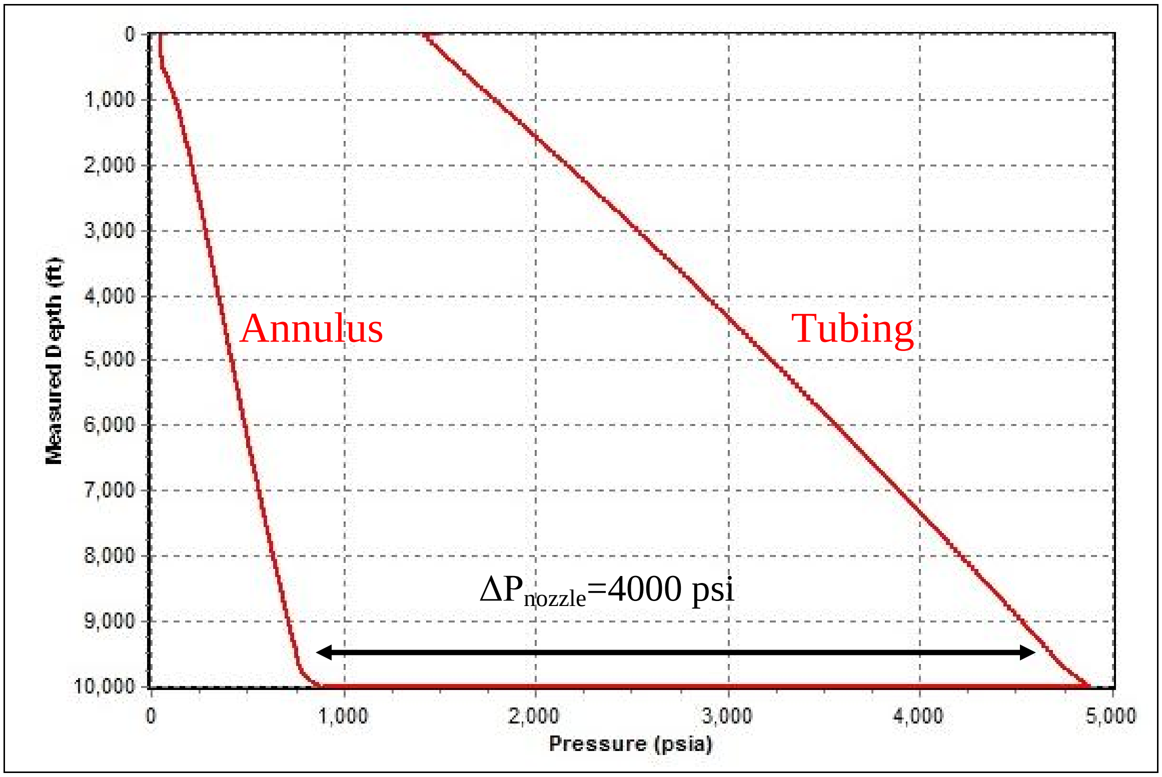


Figure 51: Pressure vs Depth (CO_2 without Water, CT:1.25”, H.S:2.25”, Q=5 gpm)

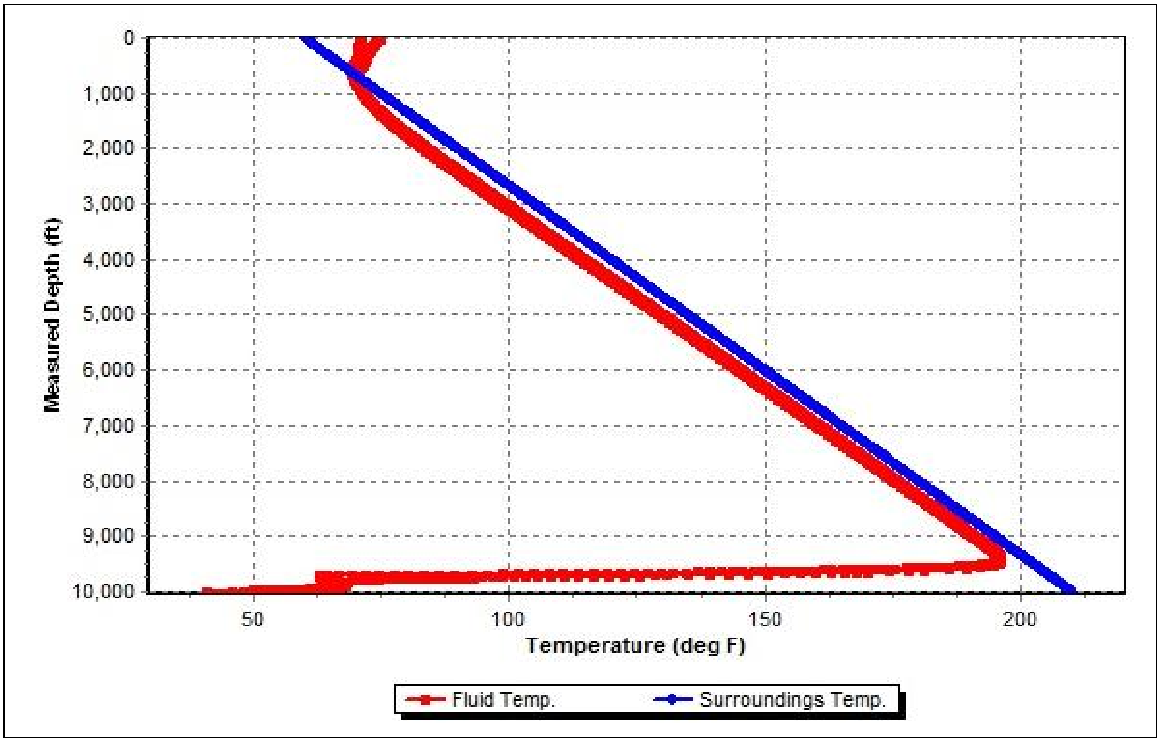


Figure 52: Temperature vs. Depth (CO_2 without Water, CT:1.25”,H.S:2.25”, Q=5 gpm)

Figure 53 is the mixture velocity profile in annulus for 1.25”-2.25’’ size combination for different CO_2 flow rates. As can be seen from the graph, due to the expansion of gas phase CO_2 in the annulus, mixture velocity shows significant increase while reaching surface.

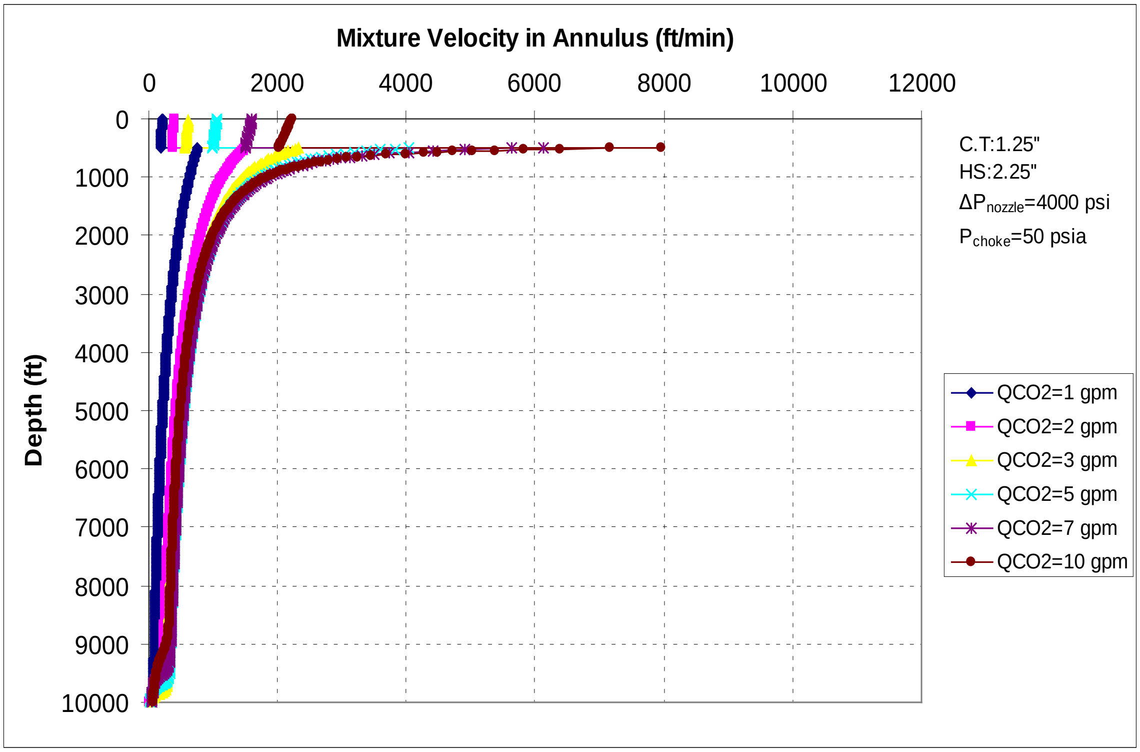


Figure 53: Mixture Velocity Profile for CO_2 (CT:1.25”-HS:2.25”, Without Water)

3.1.2 CO_2 without Water Addition Cases for Different Coiled Tubing and Bore Hole Sizes

In this section, operational envelopes and injection pressure profiles are given for different coiled tubing and borehole size combinations. For all the run points, liquid fraction of the CO_2 is more than 0.25 after the nozzle. Possible hydrate formation percentages are given on the operational envelope graphs near the run points.

In Figure 62 and 63, all the tubing and bore hole sizes combinations are plotted in the same graph to see the effect of hole size on erosion velocity and injection pressures. As seen from Figure 62, for the same coiled tubing size, increasing hole size decreases maximum mixture velocity in annulus. Because, for the same flow rate, larger annulus creates lower velocity in annulus as expected. Therefore, operational envelopes become wider with increasing annulus size due to the lower velocity profile in the annulus. As seen on Figure 63, for the same coiled tubing size, increasing hole size decreases the needed injection pressure. Because, for small size annulus, due to the high mixture velocity in annulus, frictional losses are higher than that of larger size annulus. Also, increasing flow rate, increases the needed injection pressure to ensure the operation in the system.

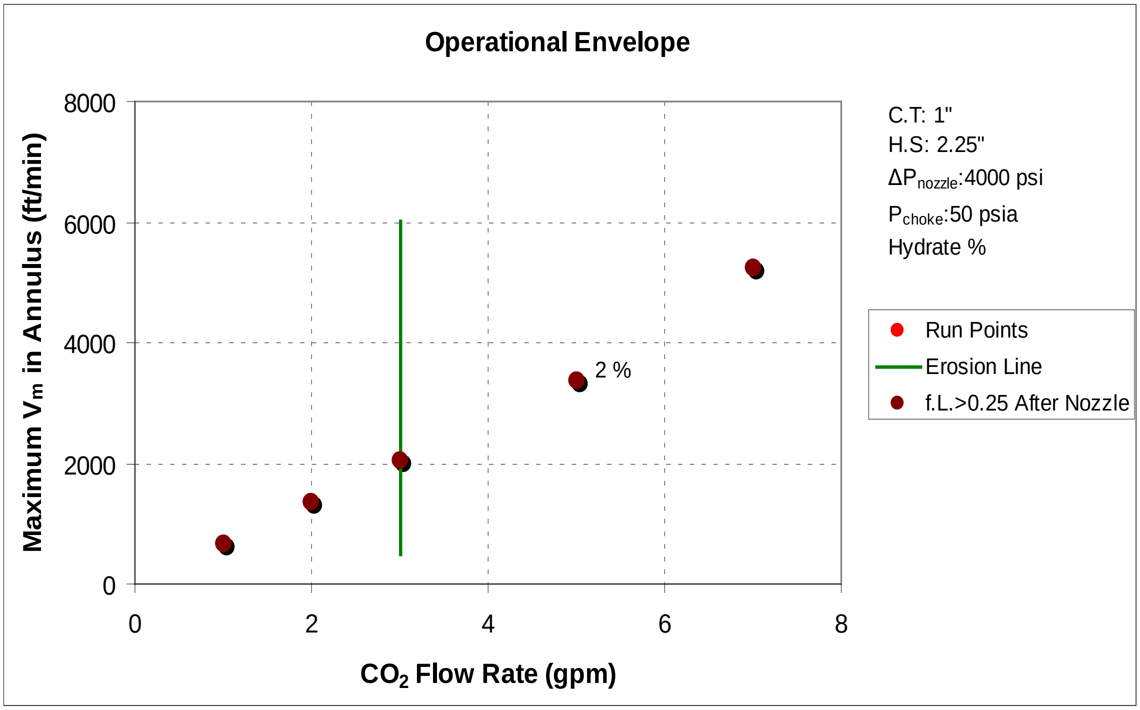


Figure 54: Operational Envelope for CO_2 (CT:1”-HS:2.25”, Without Water)

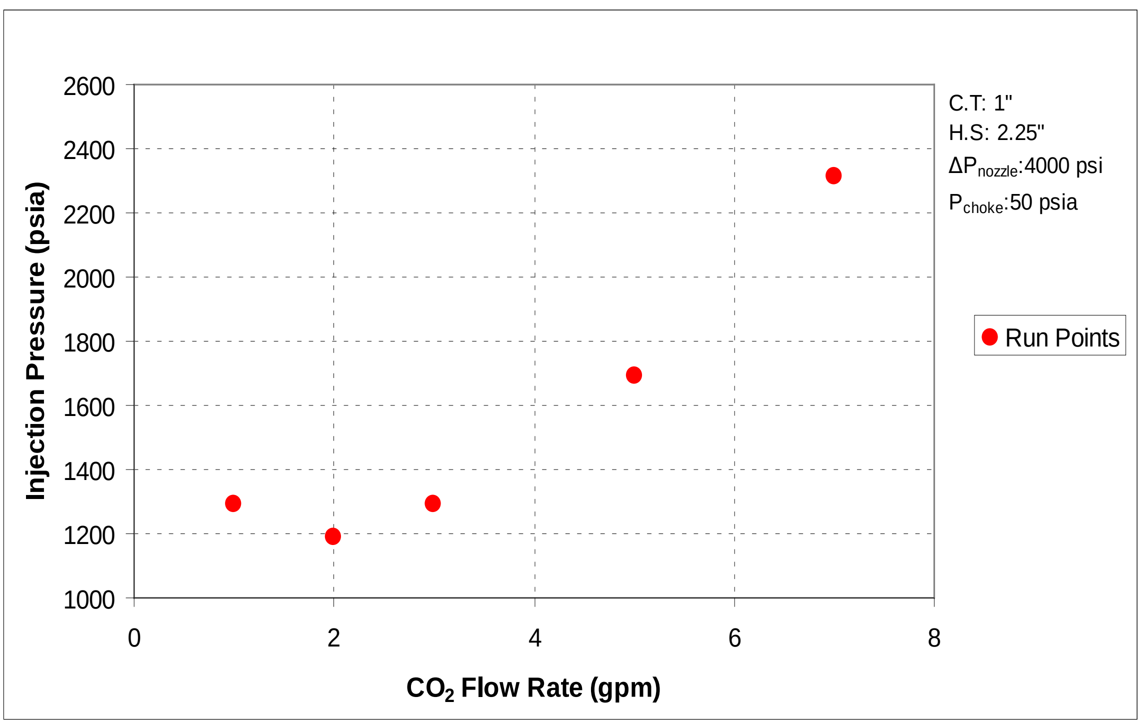


Figure 55: Flow Rate vs. Injection Pressure for CO_2 (CT:1”-HS:2.25”, Without Water)

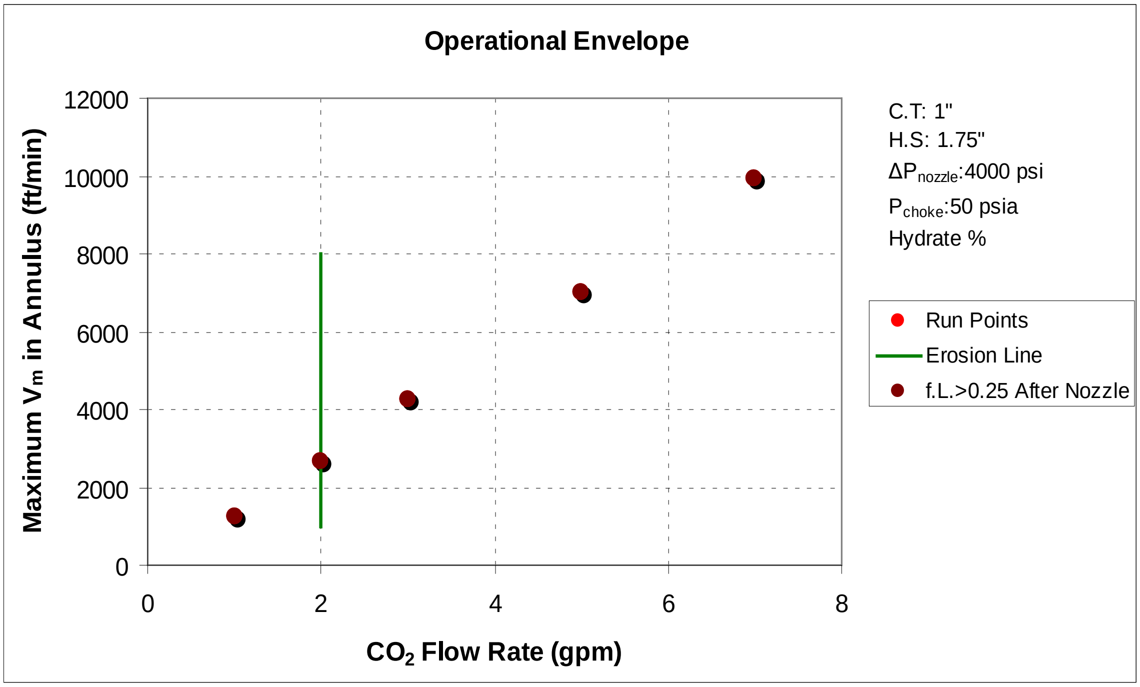


Figure 56: Operational Envelope for CO_2 (CT:1”-HS:1.75”, Without Water)

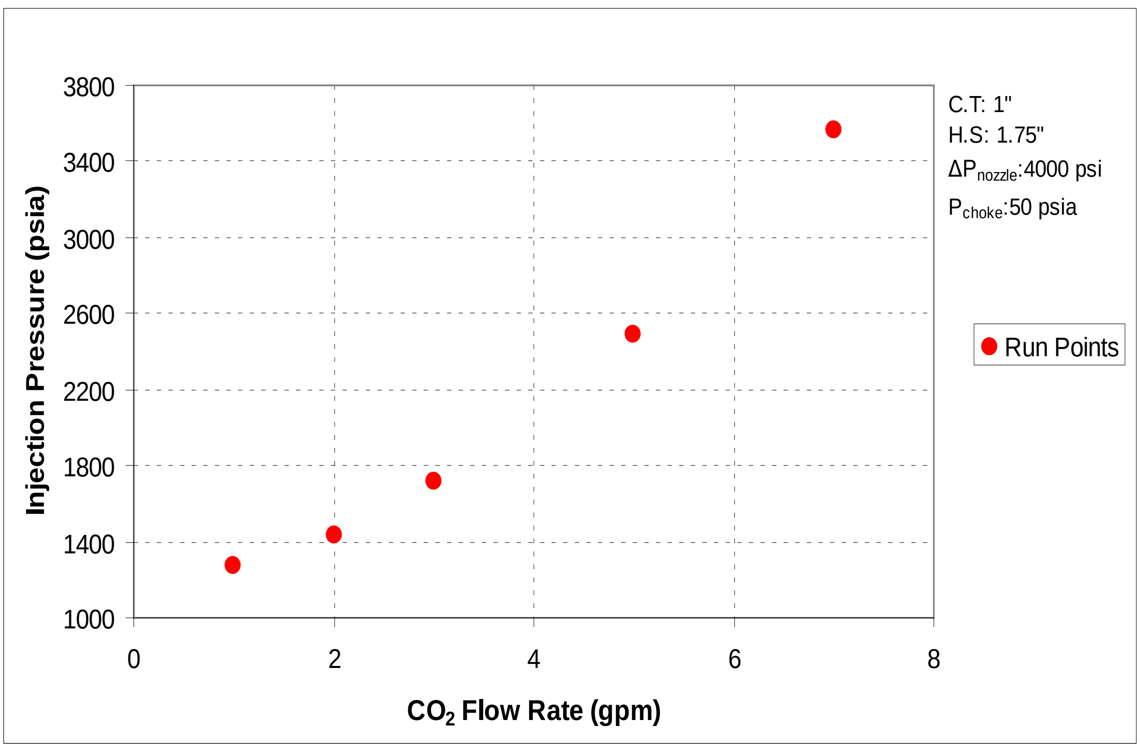


Figure 57: Flow Rate vs. Injection Pressure for CO_2 (CT:1”-HS:1.75”, Without Water)

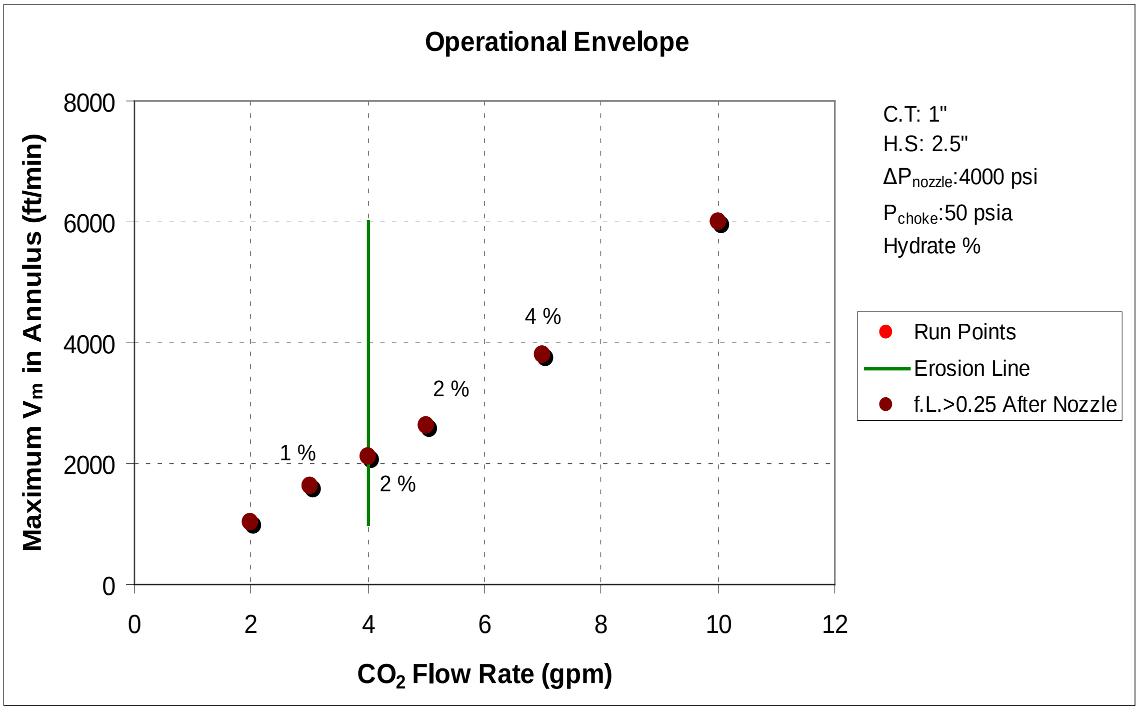


Figure 58: Operational Envelope for CO_2 (CT:1”-HS:2.5”, Without Water)

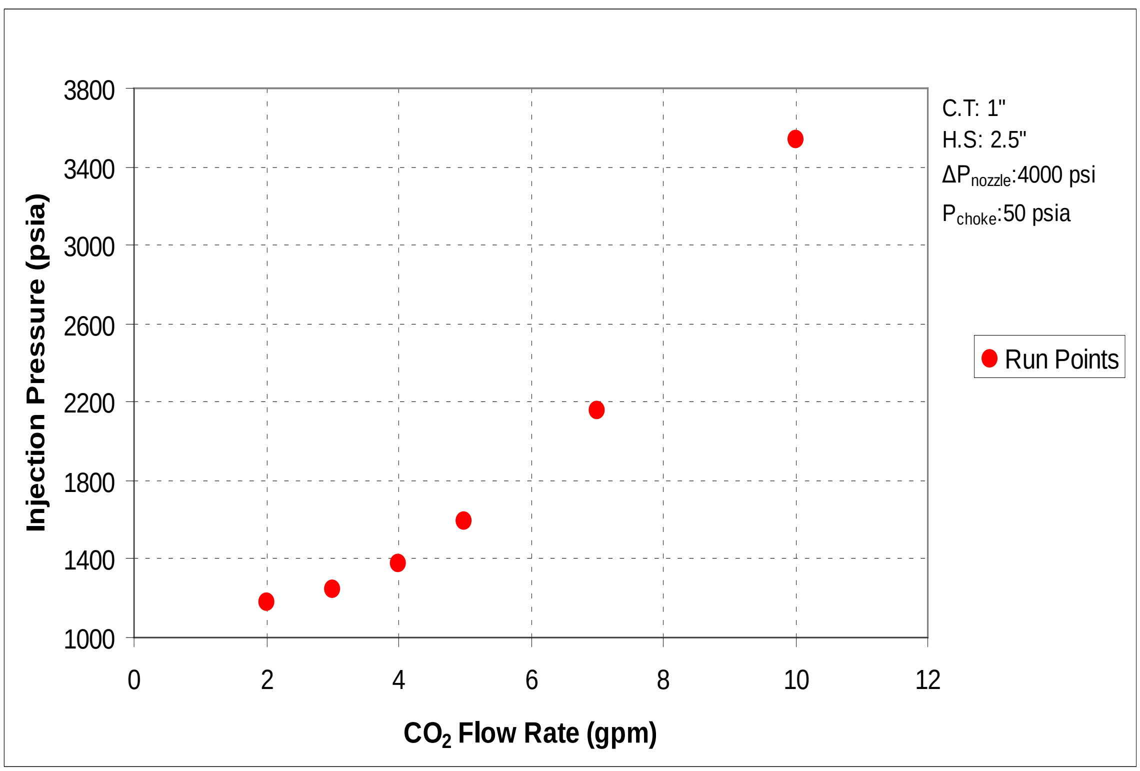


Figure 59: Flow Rate vs. Injection Pressure for CO_2 (CT:1”-HS:2.5”, Without Water)

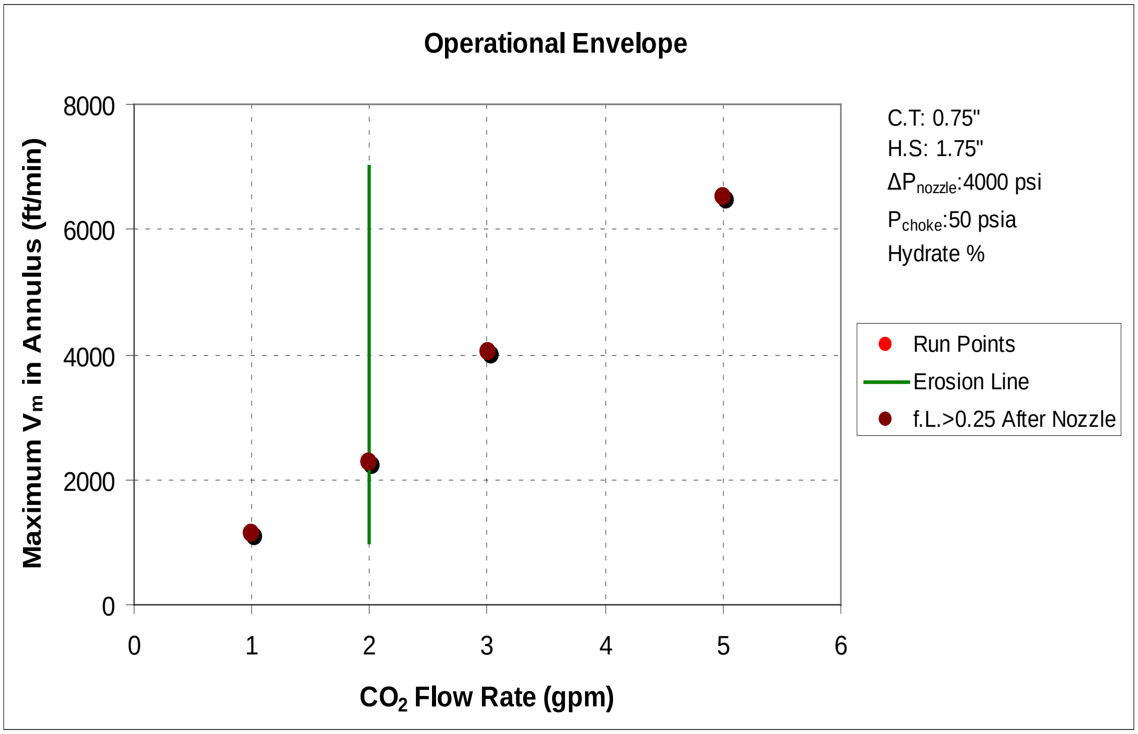


Figure 60: Operational Envelope for CO_2 (CT: 0.75”-HS: 1.75”, Without Water)

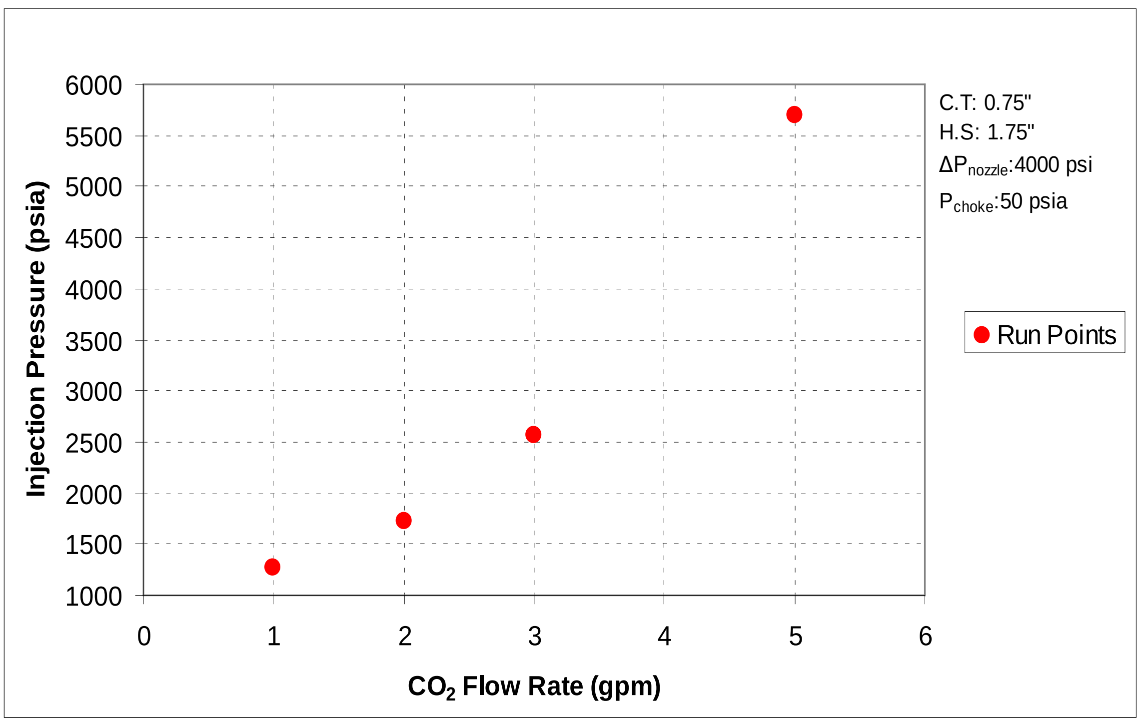


Figure 61: Flow Rate vs. Injection Pressure for CO_2 (CT:0.75”-HS:1.75”, Without Water)

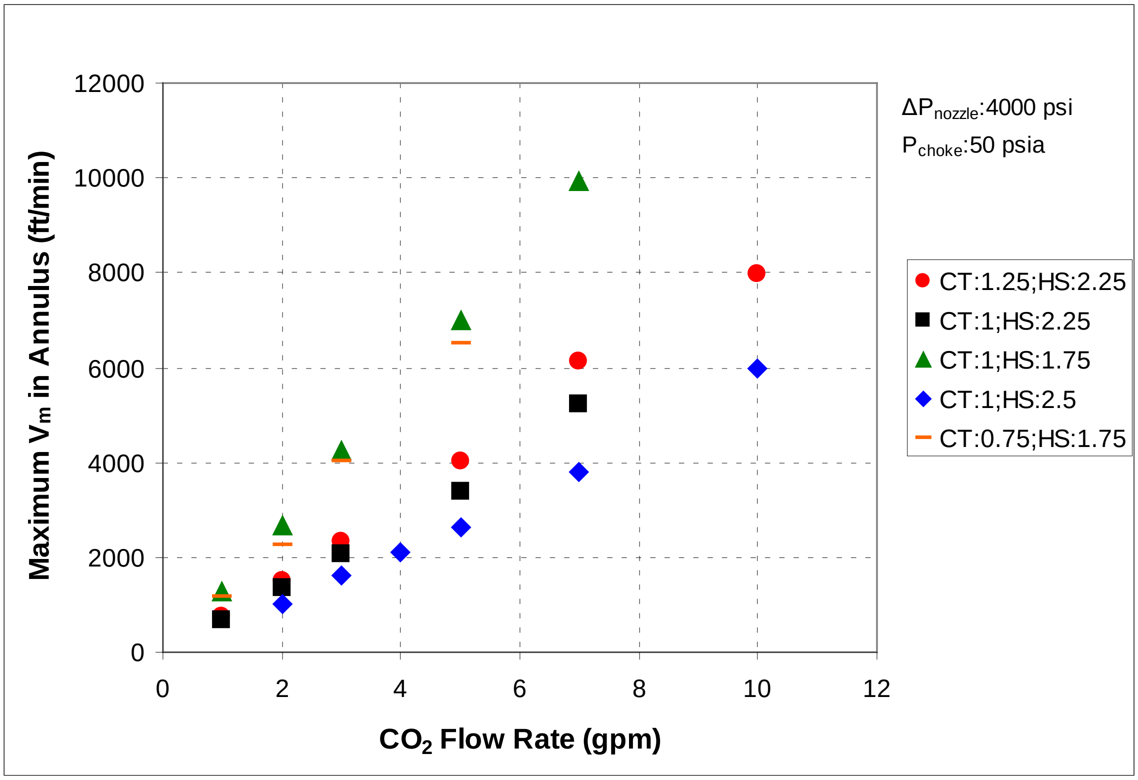


Figure 62: Flow Rate vs Velocity for CO_2 (Different Sizes, Without Water)

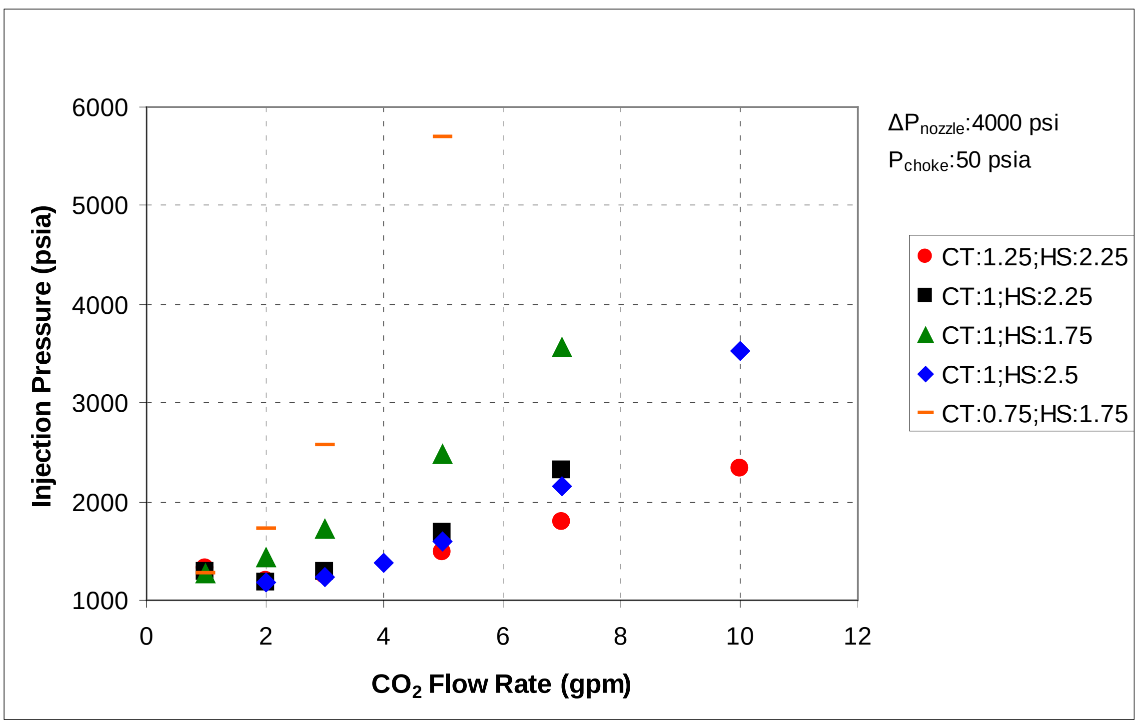


Figure 63: Flow Rate vs. Injection Pressure for CO_2 (Different Sizes, Without Water)

3.2 CO_2 with Water Addition Cases

In this part, results for CO_2 with water cases are given. Water was injected with different flow rates to create the operational envelope and to analyze the injection pressure profile for CO_2. Injecting water in the CO_2 drilling operation decreased the temperature drop of CO_2. Also, brown color was used to show run points which has liquid fraction more than 0.25. Almost for most of the CO2 with water addition runs, liquid fraction has high values.

3.2.1 CO_2 with Water Addition Cases (CT: 1.25" –H.S: 2.25")

Figure 64 gives the operational envelope for CO_2 with water additions using 1.25" coiled tubing and a 2.25" bore hole size. Run points at the right of the erosion line shows the conditions for a given injection flow rate, which maximum mixture velocity in the annulus exceeds the set erosion velocity. For all the cases hydrate percentages are less than 1.

Figure 65 gives the injection pressure versus CO_2 flow rate. Numbers near the run points indicate the amount of water flow rate (gpm) at that condition. Increased injection rates increased the needed injection pressure to ensure the operation.

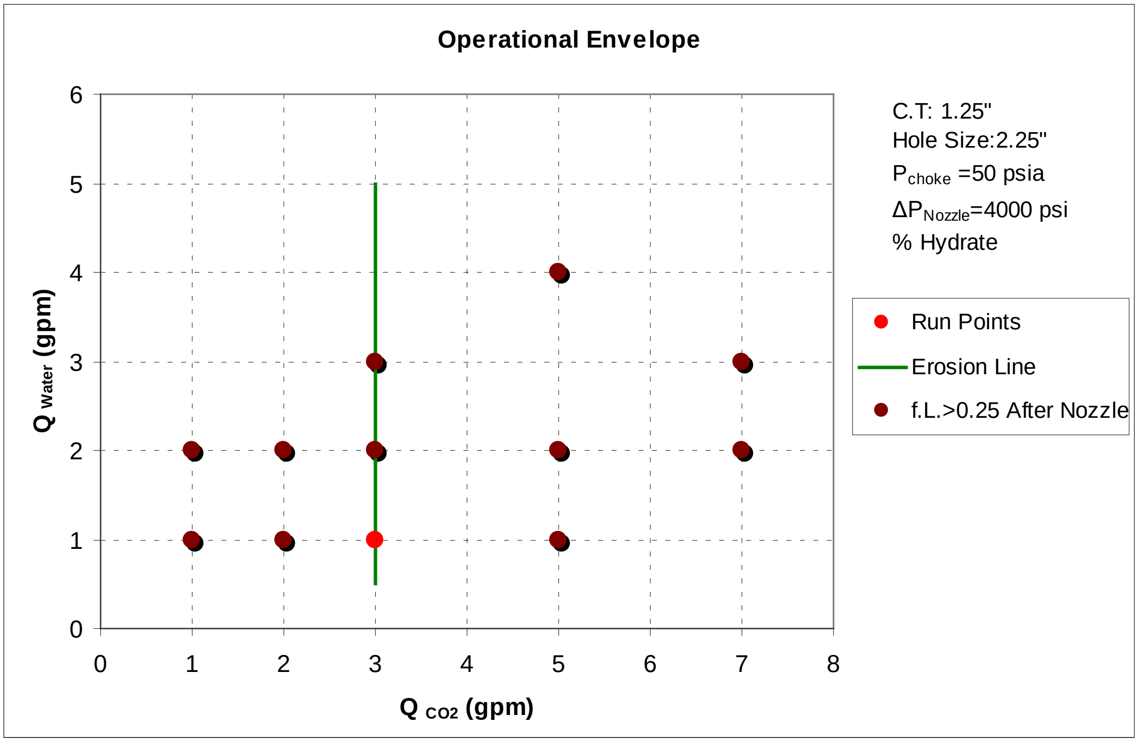


Figure 64: Operational Envelope for CO_2 (CT:1.25”-HS:2.25”, With Water)

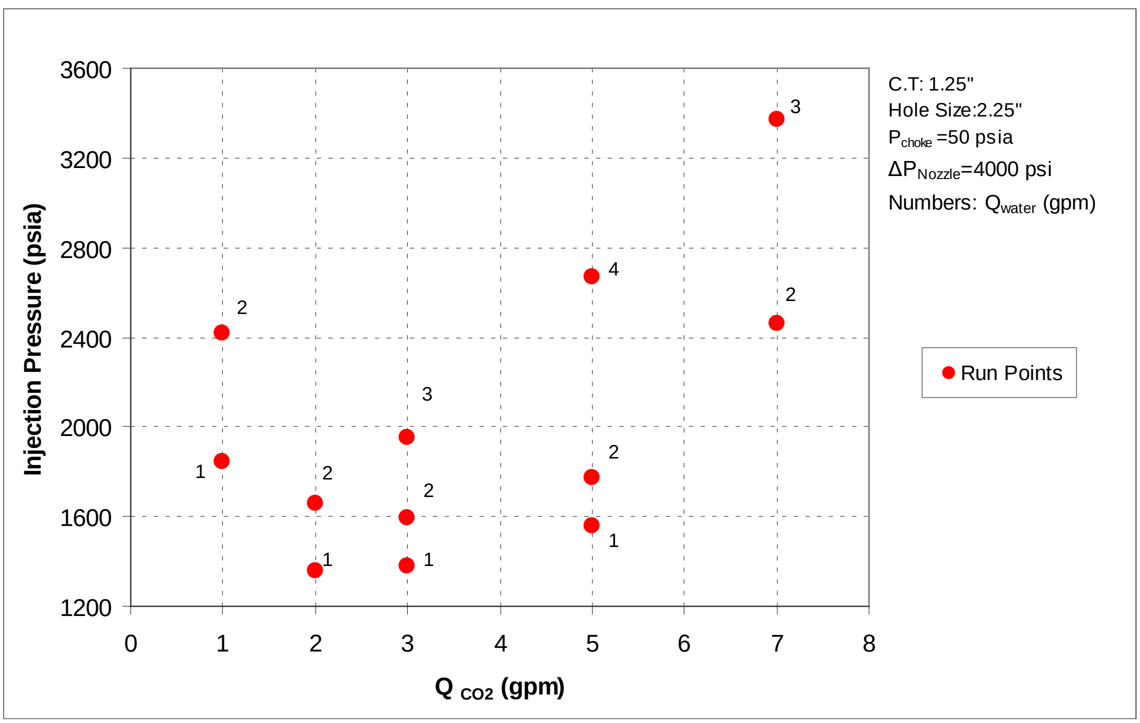


Figure 65: Flow Rate vs. Inj. Pressure for CO_2 (CT:1.25”-HS:2.25”, With Water)

Run monitors for the 5 gpm CO_2 and 1 gpm water are given for tubing and annulus sides in Figures 66 and 67, respectively.

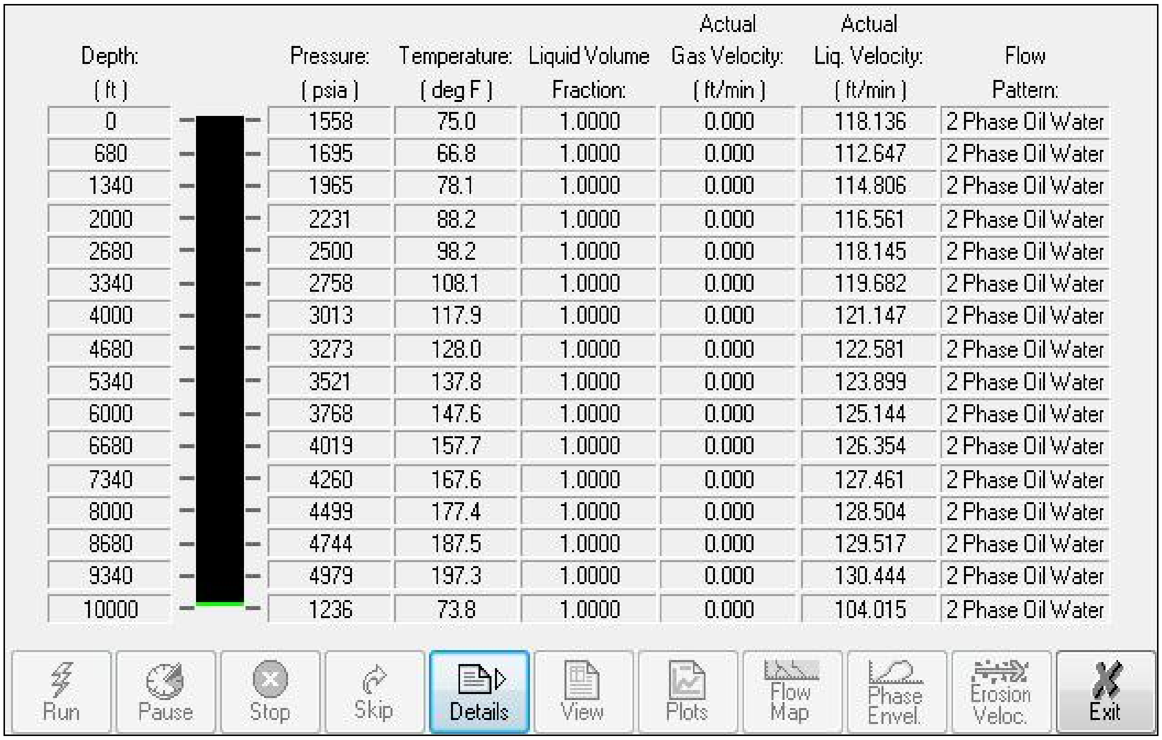
An example pressure and temperature profile graph for CO_2 is given for the CO_2 flow rate of 5 gpm and water flow rate of 1 gpm in Figure 68 and 69, respectively. As can be seen in Figure 68, pressure drop of 4000 psi occurs at the nozzle. Pressure outputs are given in Table 7.

Table 7: Output Pressure Values (CO_2 with Water Addition, Q_{CO2}=5 gpm, Q_w= 1gpm)

Injection Pressure (psia)	1558
BHP Upstream Nozzle (psia)	5236
BHP Downstream Nozzle (psia)	1236

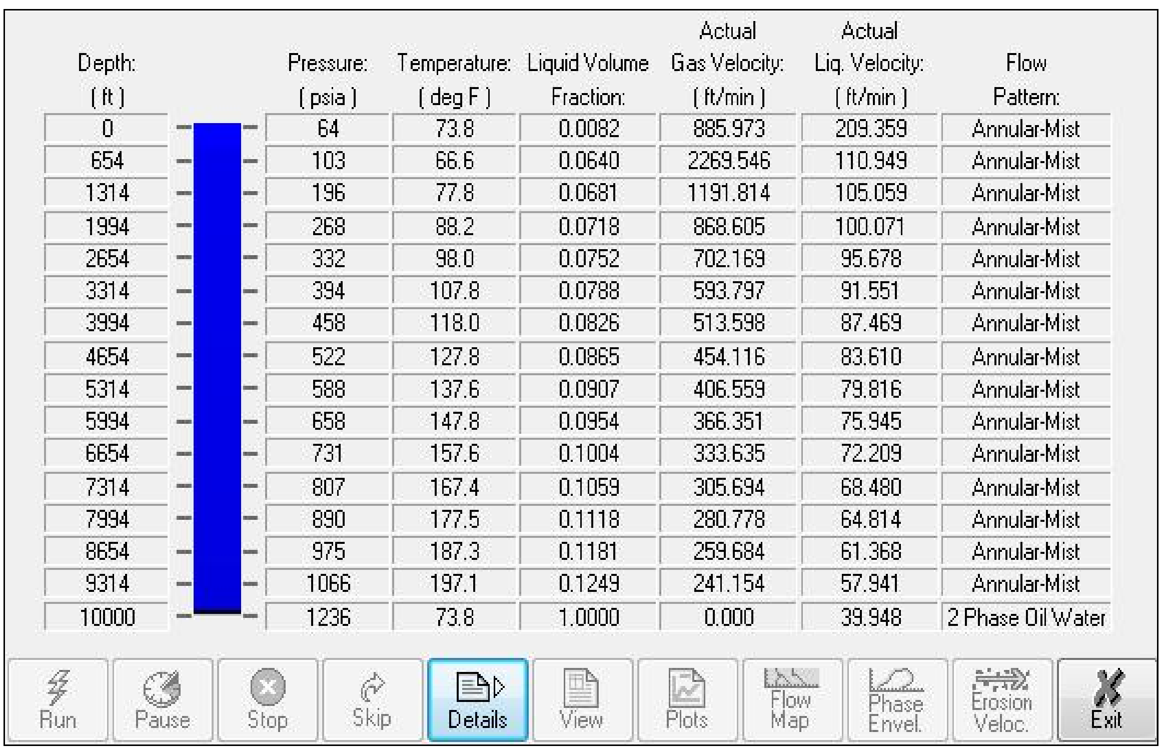
Figure 69 is the temperature profile of the fluid inside the pipe and annulus with formation temperature profile. As can be seen from the figure, temperature drop of the CO_2 decreases compare with the conditions for without water.

Figure 70 shows mixture velocity profile in the tubing and annulus. As seen from the graph, mixture velocity increases while reaching surface due to the gas expansion.



Depth: (ft)	Pressure: (psia)	Temperature: (deg F)	Liquid Volume Fraction:	Actual Gas Velocity: (ft/min)	Actual Liq. Velocity: (ft/min)	Flow Pattern:
0	1558	75.0	1.0000	0.000	118.136	2 Phase Oil Water
680	1695	66.8	1.0000	0.000	112.647	2 Phase Oil Water
1340	1965	78.1	1.0000	0.000	114.806	2 Phase Oil Water
2000	2231	88.2	1.0000	0.000	116.561	2 Phase Oil Water
2680	2500	98.2	1.0000	0.000	118.145	2 Phase Oil Water
3340	2758	108.1	1.0000	0.000	119.682	2 Phase Oil Water
4000	3013	117.9	1.0000	0.000	121.147	2 Phase Oil Water
4680	3273	128.0	1.0000	0.000	122.581	2 Phase Oil Water
5340	3521	137.8	1.0000	0.000	123.899	2 Phase Oil Water
6000	3768	147.6	1.0000	0.000	125.144	2 Phase Oil Water
6680	4019	157.7	1.0000	0.000	126.354	2 Phase Oil Water
7340	4260	167.6	1.0000	0.000	127.461	2 Phase Oil Water
8000	4499	177.4	1.0000	0.000	128.504	2 Phase Oil Water
8680	4744	187.5	1.0000	0.000	129.517	2 Phase Oil Water
9340	4979	197.3	1.0000	0.000	130.444	2 Phase Oil Water
10000	1236	73.8	1.0000	0.000	104.015	2 Phase Oil Water

Figure 66: Tubing Monitor (CO_2 with Water, CT:1.25”, H.S:2.25”, Q_{CO2}=5,Q_w= 1gpm)



Depth: (ft)	Pressure: (psia)	Temperature: (deg F)	Liquid Volume Fraction:	Actual Gas Velocity: (ft/min)	Actual Liq. Velocity: (ft/min)	Flow Pattern:
0	64	73.8	0.0082	885.973	209.359	Annular-Mist
654	103	66.6	0.0640	2269.546	110.949	Annular-Mist
1314	196	77.8	0.0681	1191.814	105.059	Annular-Mist
1994	268	88.2	0.0718	868.605	100.071	Annular-Mist
2654	332	98.0	0.0752	702.169	95.678	Annular-Mist
3314	394	107.8	0.0788	593.797	91.551	Annular-Mist
3994	458	118.0	0.0826	513.598	87.469	Annular-Mist
4654	522	127.8	0.0865	454.116	83.610	Annular-Mist
5314	588	137.6	0.0907	406.559	79.816	Annular-Mist
5994	658	147.8	0.0954	366.351	75.945	Annular-Mist
6654	731	157.6	0.1004	333.635	72.209	Annular-Mist
7314	807	167.4	0.1059	305.694	68.480	Annular-Mist
7994	890	177.5	0.1118	280.778	64.814	Annular-Mist
8654	975	187.3	0.1181	259.684	61.368	Annular-Mist
9314	1066	197.1	0.1249	241.154	57.941	Annular-Mist
10000	1236	73.8	1.0000	0.000	39.948	2 Phase Oil Water

Figure 67: Annulus Monitor (CO_2 with Water, CT:1.25”,H.S:2.25”,Q_{CO2}=5,Q_w= 1gpm)

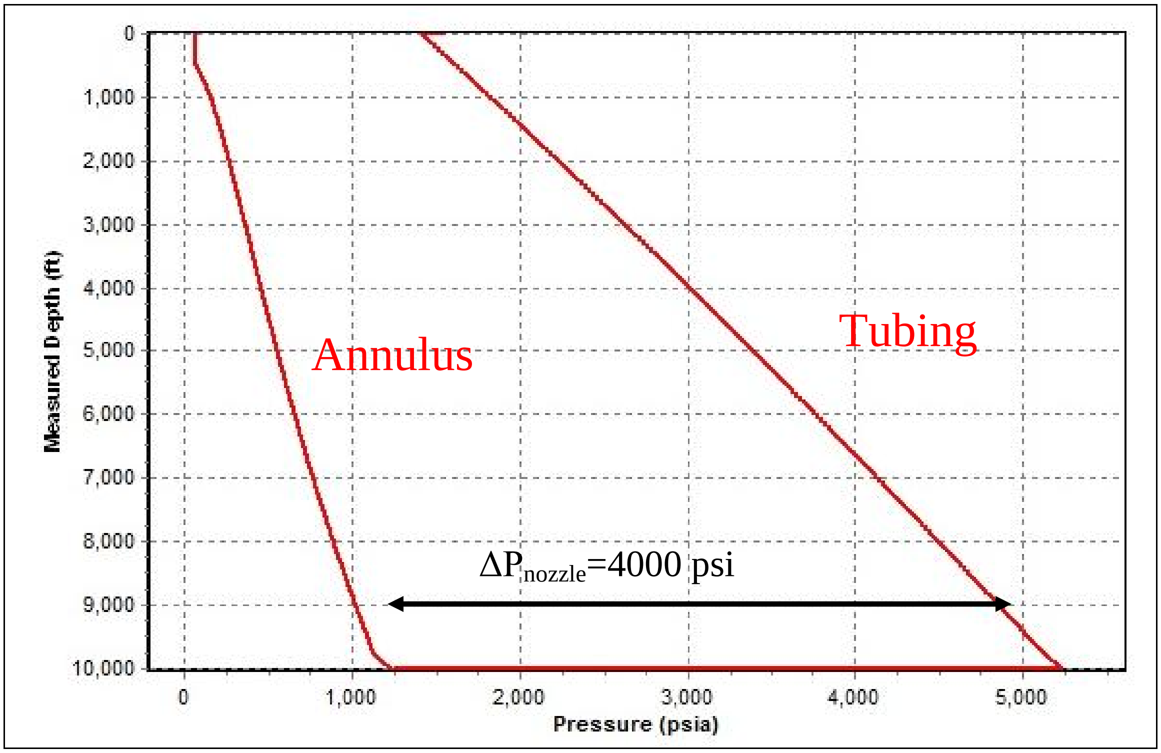


Figure 68: Pressure vs. Depth (CO_2 with Water, CT:1.25”, H.S:2.25”)

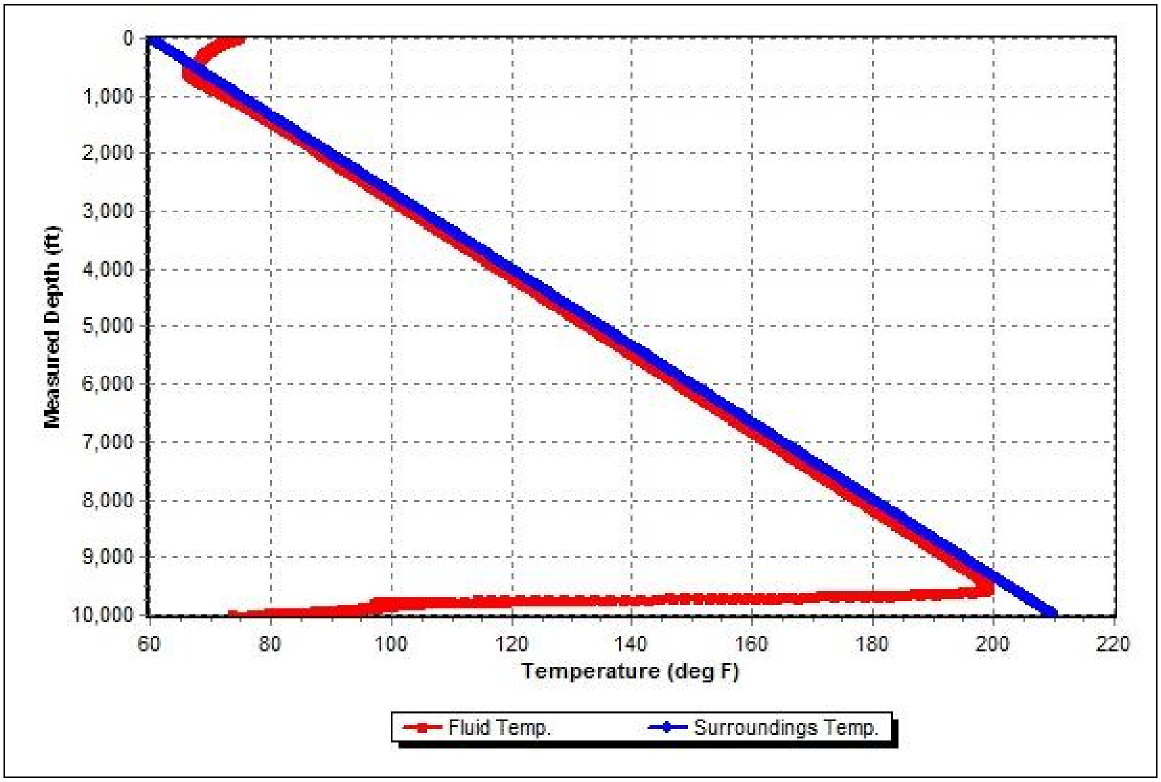


Figure 69: Temperature vs. Depth (CO_2 With Water, CT:1.25”, H.S:2.25”)

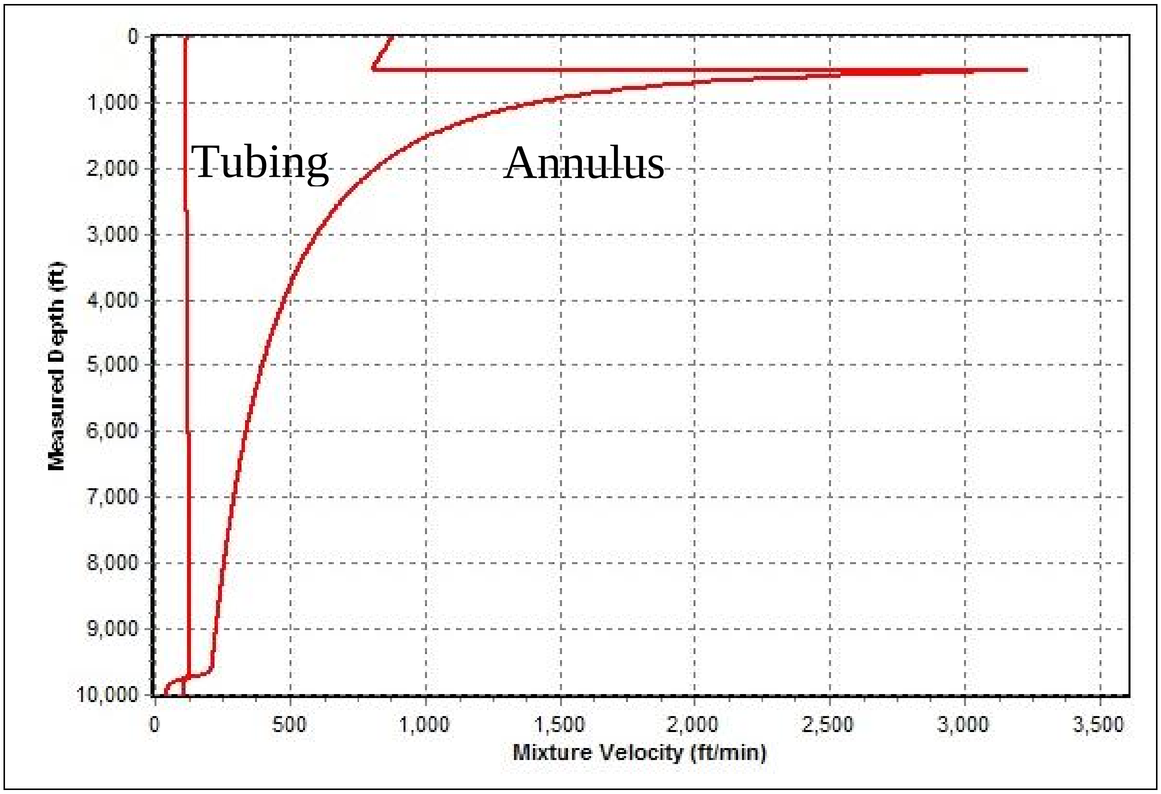


Figure 70: Velocity Profile (CO_2 with Water, CT:1.25", H.S:2.25", Q_{CO2}=5,Q_w=1gpm)

3.2.2 CO_2 with Water Addition Cases for Different Coiled Tubing and Bore Hole Sizes

In this section, the operational envelopes and injection pressure profiles are given for different coiled tubing and borehole size combinations for CO_2 with water cases.

Hydrate formation is also not a problem for these different size combinations. Brown color was used on the operational envelope graphs in order to show run points which has liquid fraction more than 0.25.

For injection pressure versus CO_2 flow rate graphs, water flow rates were written near the each run point on the graph. Injection pressure in the system increased with increasing injection flow rates.

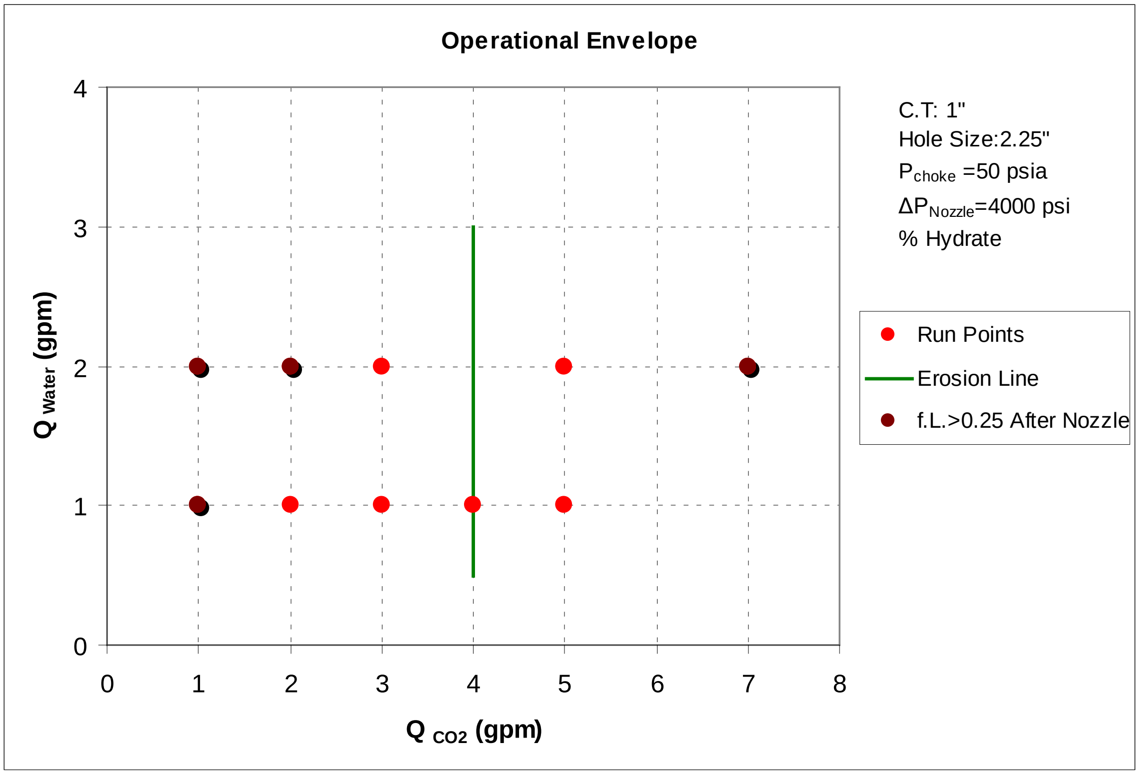


Figure 71: Operational Envelope for CO_2 (CT:1"-HS:2.25", With Water)

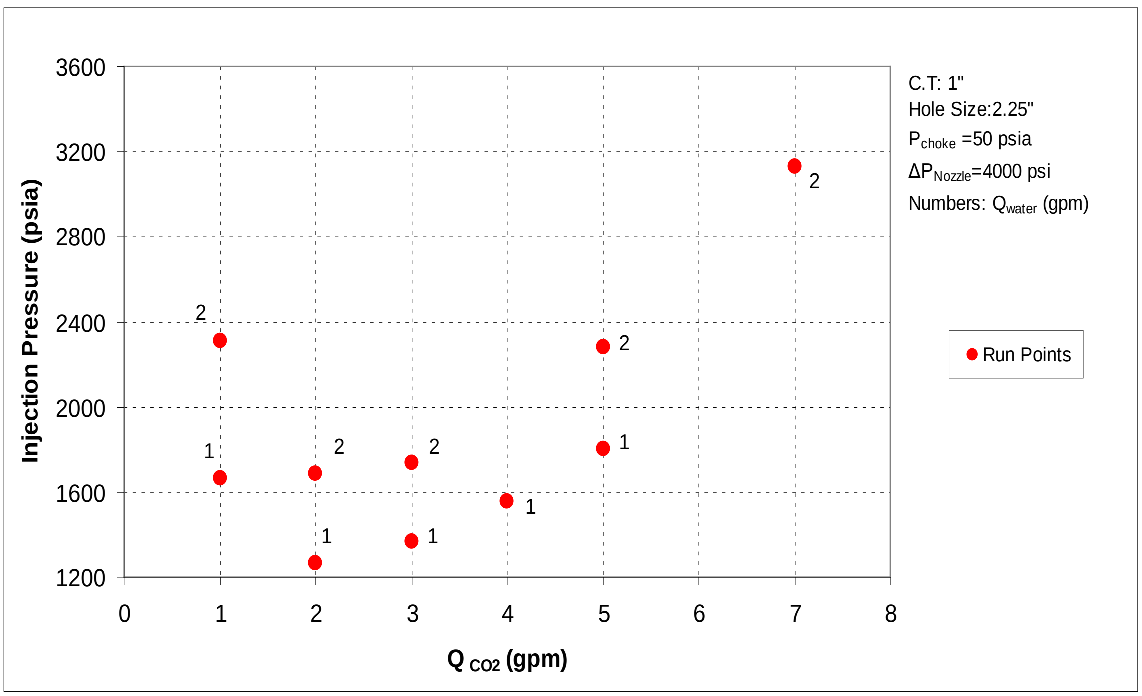


Figure 72: Flow Rate vs. Injection Pressure for CO_2 (CT:1"-HS:2.25", With Water)

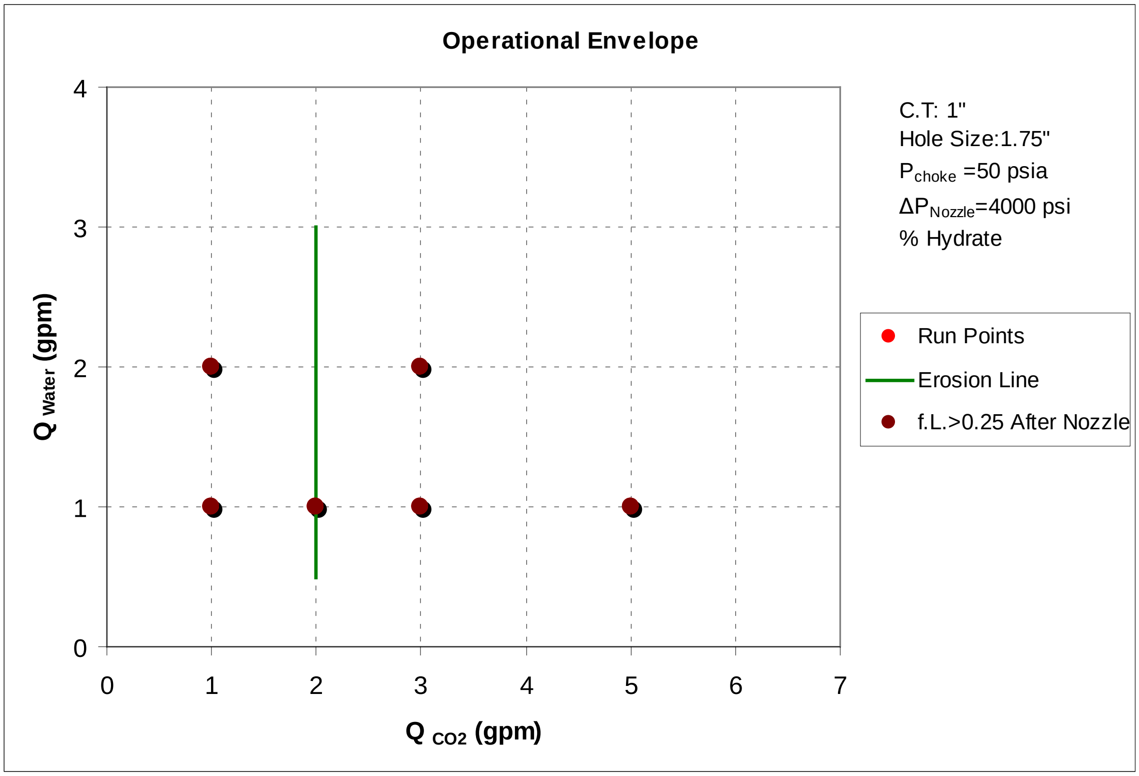


Figure 73: Operational Envelope for CO_2 (CT:1”-HS:1.75”, With Water)

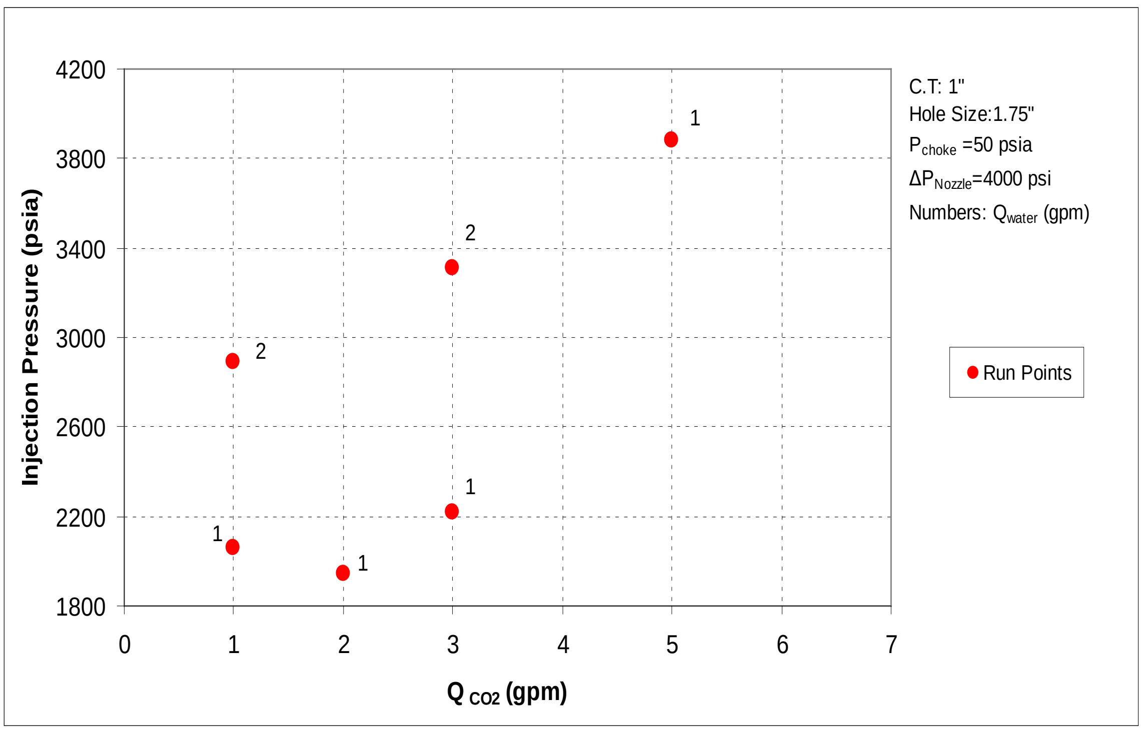


Figure 74: Flow Rate vs. Injection Pressure for CO_2 (CT:1”-HS:1.75”, With Water)

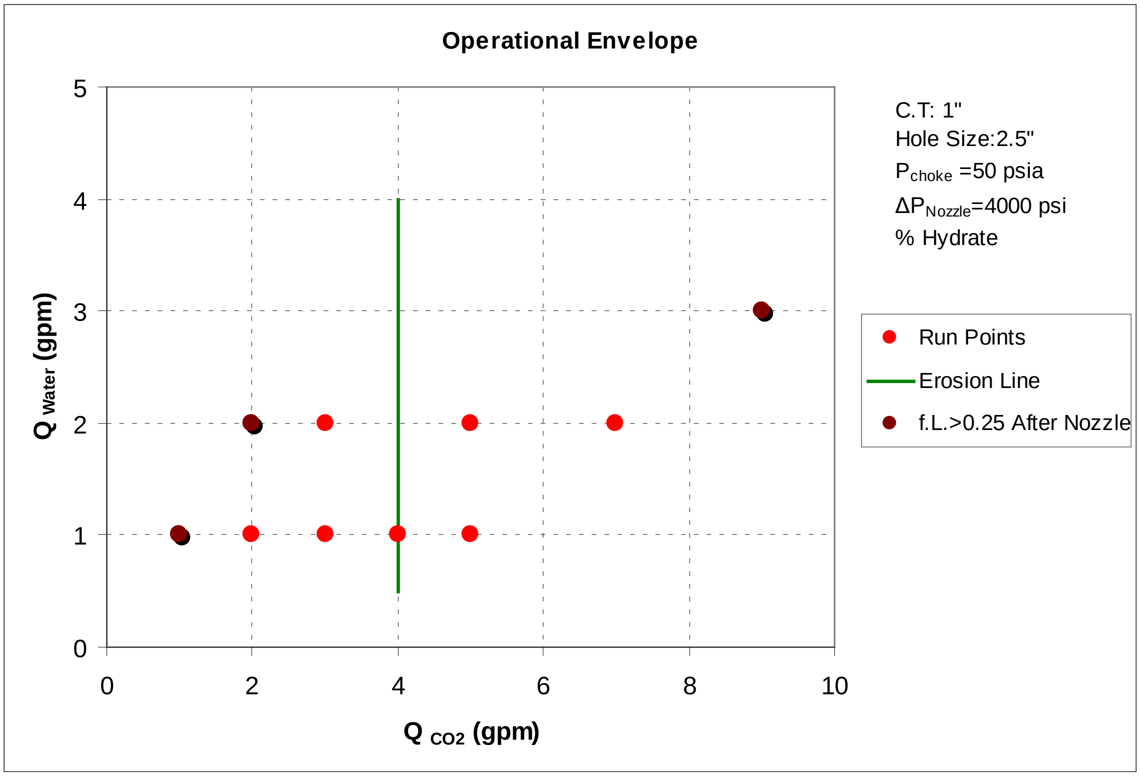


Figure 75: Operational Envelope for CO_2 (CT:1”-HS:2.5”, With Water)

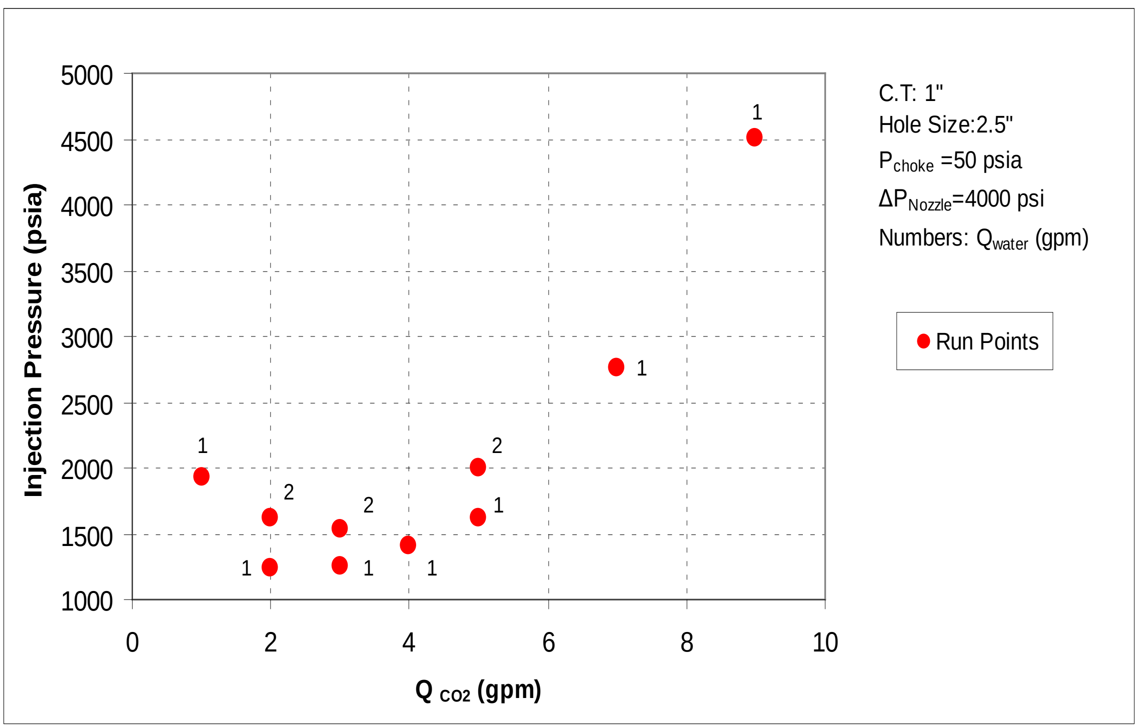


Figure 76: Flow Rate vs. Injection Pressure for CO_2 (CT:1”-HS:2.5”, With Water)

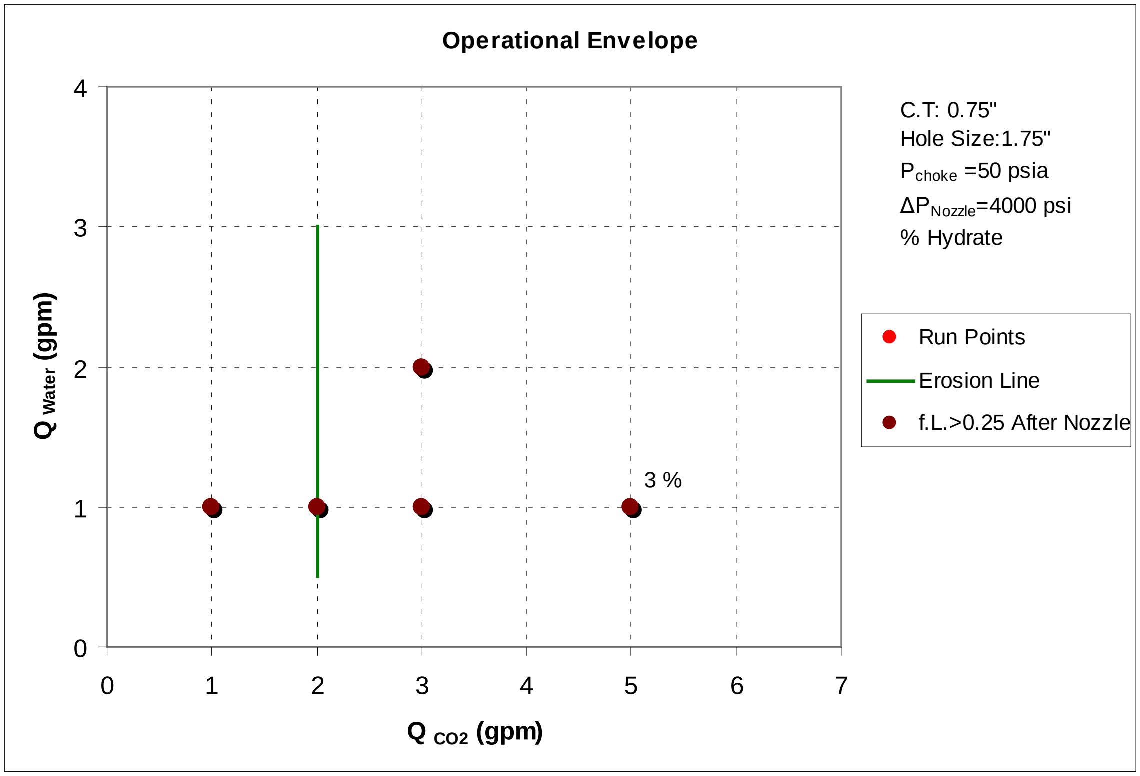


Figure 77: Operational Envelope for CO_2 (CT:0.75”-HS:1.75”, With Water)

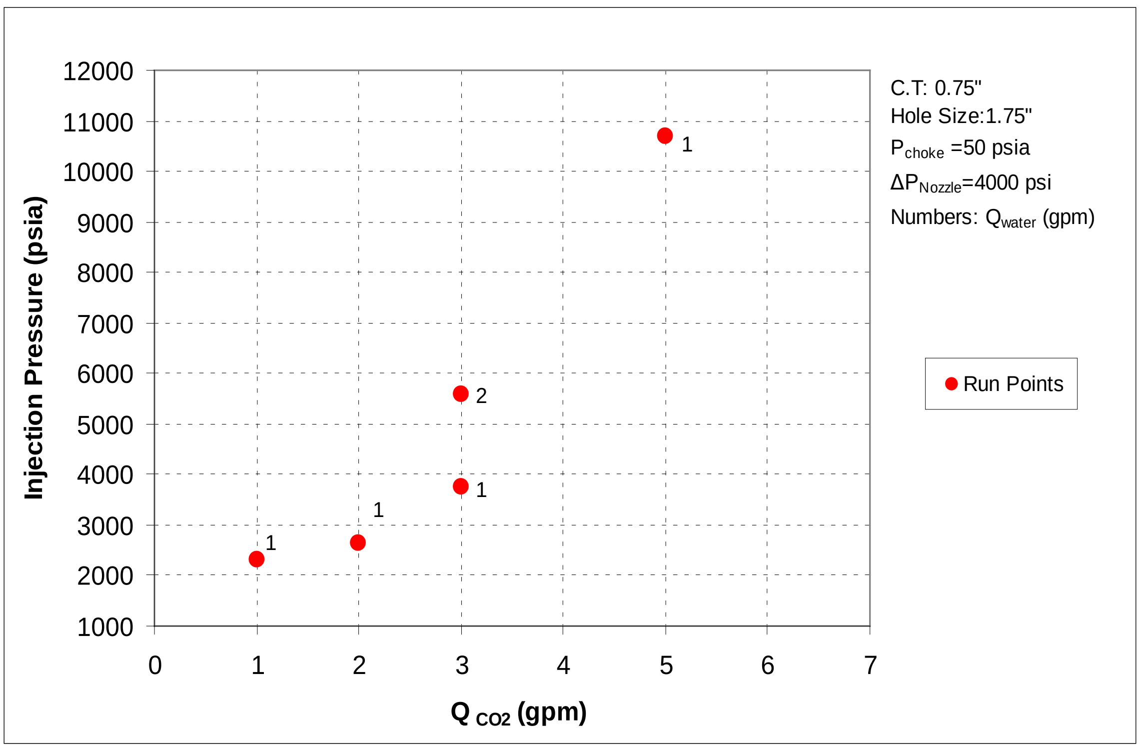


Figure 78: Flow Rate vs. Injection Pressure for CO_2 (CT:0.75”-HS:1.75”, With Water)

3.3 CO_2 with Water Influx Cases

In these simulations, CO_2 was injected with water and also 5 gpm water influx was allowed from the bottom of the well at 10,000 ft in the annulus. Runs were started with 1.25" coiled tubing and 2.25" bore hole size and performed also for other size combinations previously shown in Table 1.

5 gpm water influxes caused high pressure and significant amount of liquid fraction after the nozzle. In most of the cases liquid fraction after the nozzle were higher than 0.25.

3.3.1 CO_2 with Water Influx (CT: 1.25" –H.S: 2.25")

Figure 79 gives the operational envelope for CO_2 injecting with water and 5 gpm water influxes was allowed from bottom of the well. As seen from the graph, brown run points show the points which have more than 0.25 liquid fraction just after the nozzle. For this size combination, 5 gpm water influxes created high liquid fraction after the nozzle in the annulus for all run points.

Figure 80 gives the injection pressure profile of CO_2 with 5 gpm water influx at 10,000 ft. Numbers near the run points are amounts of water injected with CO_2.

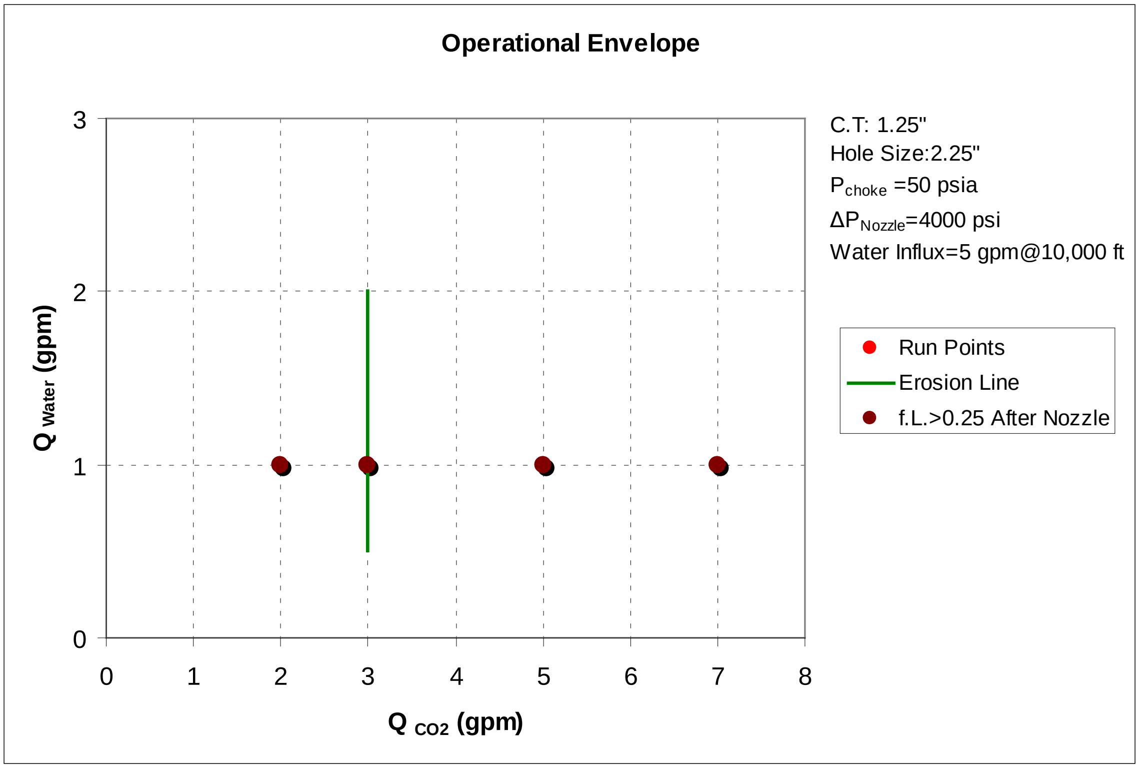


Figure 79: Operational Envelope for CO_2 (CT:1.25”-HS:2.25”, With Water Influx)

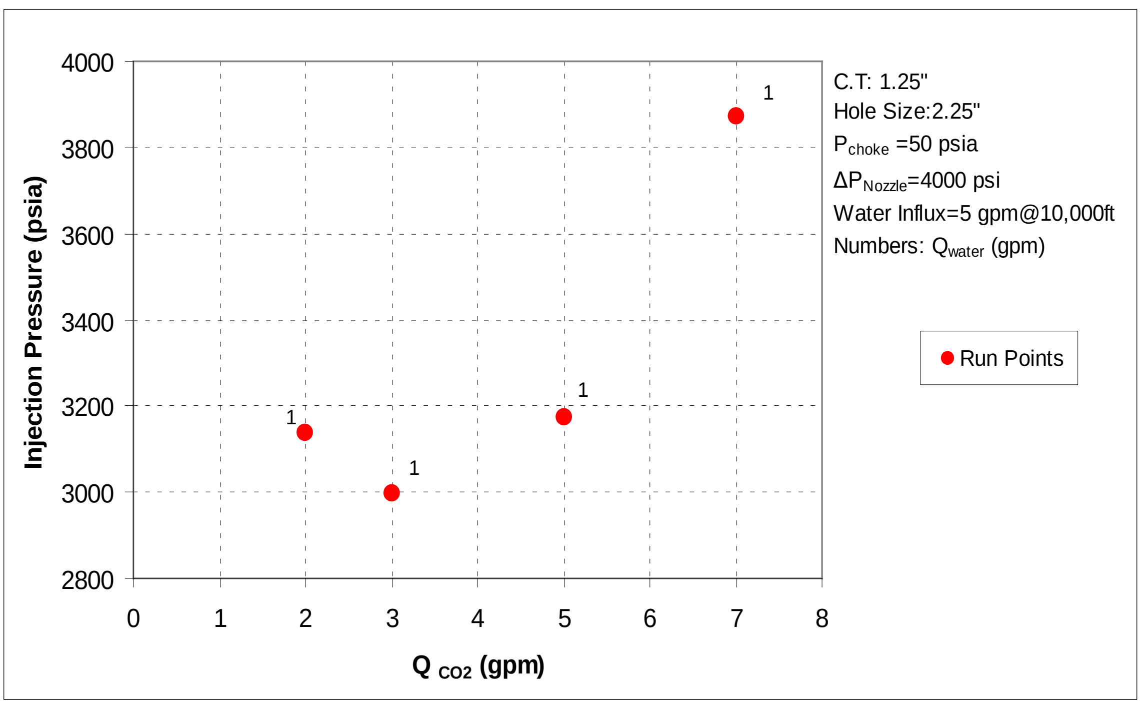


Figure 80: Flow Rate vs. Inj. Pressure for CO_2 (CT:1.25”-HS:2.25”, With Water Influx)

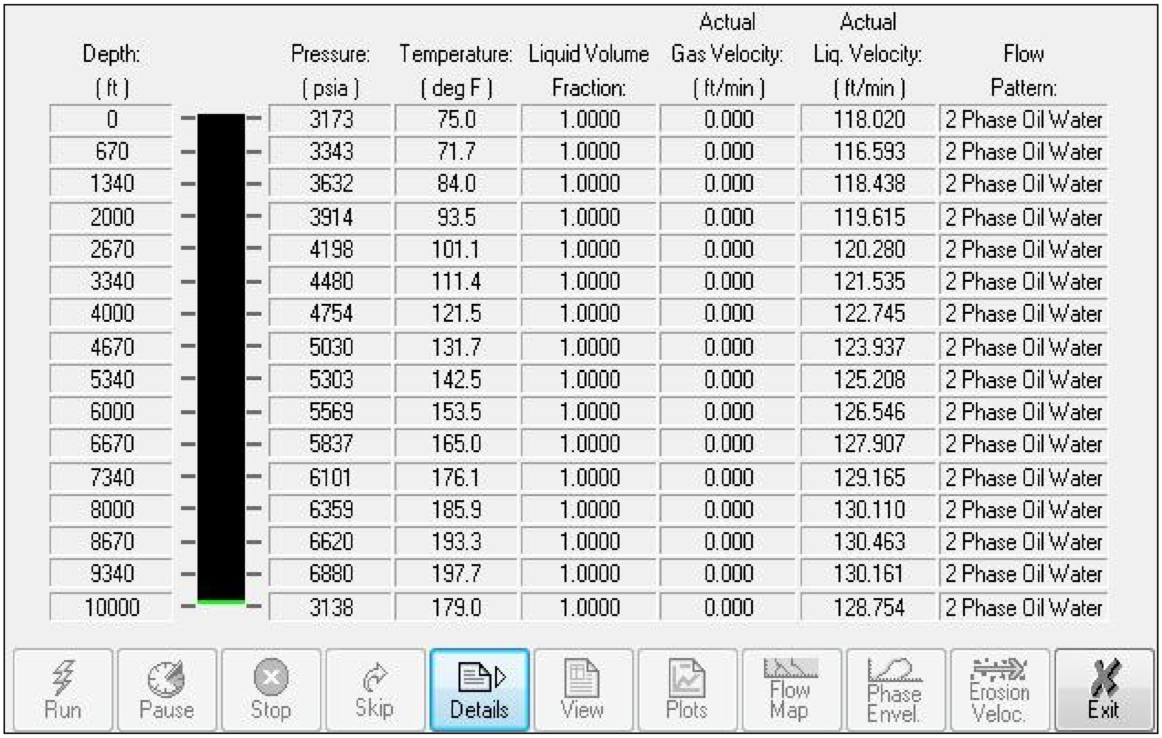
Run monitors for the CO_2 flow rate of 5 gpm, water flow rate of 1 gpm and water influx rate of 5 gpm are given for tubing and annulus sides in Figures 81 and 82, respectively.

An example pressure and temperature profile graphs for same condition are given in Figure 83 and 84, respectively. As can be seen in Figure 83, the pressure drop of 4000 psi occurs at the nozzle. Also due to the surface coiled tubing facility, 124 psi total pressure drop occurred at the surface. Pressure outputs are given in Table 8.

Table 8: Output Pressure Values
(CO_2, With Water Influx, Q_{CO2}=5 gpm, Q_w= 1gpm, Q_{wi}=5 gpm)

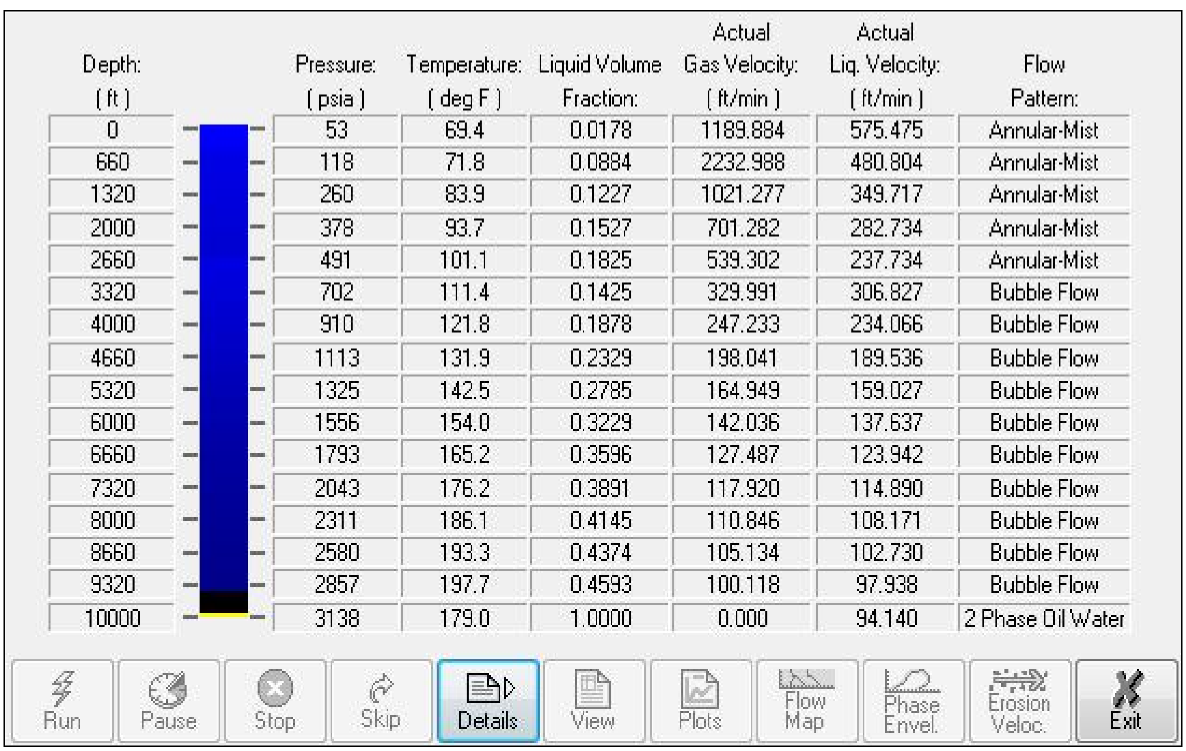
Injection Pressure (psia)	3173
BHP Upstream Nozzle (psia)	7138
BHP Downstream Nozzle (psia)	3138

Figure 84 is the temperature profile of the fluid inside the tubing and annulus (red line) with the formation temperature profile (blue line). Selected output results for all flow rates are given in Appendix A.



Depth: (ft)	Pressure: (psia)	Temperature: (deg F)	Liquid Volume Fraction:	Actual Gas Velocity: (ft/min)	Actual Liq. Velocity: (ft/min)	Flow Pattern:
0	3173	75.0	1.0000	0.000	118.020	2 Phase Oil Water
670	3343	71.7	1.0000	0.000	116.593	2 Phase Oil Water
1340	3632	84.0	1.0000	0.000	118.438	2 Phase Oil Water
2000	3914	93.5	1.0000	0.000	119.615	2 Phase Oil Water
2670	4198	101.1	1.0000	0.000	120.280	2 Phase Oil Water
3340	4480	111.4	1.0000	0.000	121.535	2 Phase Oil Water
4000	4754	121.5	1.0000	0.000	122.745	2 Phase Oil Water
4670	5030	131.7	1.0000	0.000	123.937	2 Phase Oil Water
5340	5303	142.5	1.0000	0.000	125.208	2 Phase Oil Water
6000	5569	153.5	1.0000	0.000	126.546	2 Phase Oil Water
6670	5837	165.0	1.0000	0.000	127.907	2 Phase Oil Water
7340	6101	176.1	1.0000	0.000	129.165	2 Phase Oil Water
8000	6359	185.9	1.0000	0.000	130.110	2 Phase Oil Water
8670	6620	193.3	1.0000	0.000	130.463	2 Phase Oil Water
9340	6880	197.7	1.0000	0.000	130.161	2 Phase Oil Water
10000	3138	179.0	1.0000	0.000	128.754	2 Phase Oil Water

Figure 81: Tubing Monitor (CO_2, CT:1.25”,H.S:2.25”, Q_{CO2}=5, Q_w= 1,Q_{wi}= 5 gpm)



Depth: (ft)	Pressure: (psia)	Temperature: (deg F)	Liquid Volume Fraction:	Actual Gas Velocity: (ft/min)	Actual Liq. Velocity: (ft/min)	Flow Pattern:
0	53	69.4	0.0178	1189.884	575.475	Annular-Mist
660	118	71.8	0.0884	2232.988	480.804	Annular-Mist
1320	260	83.9	0.1227	1021.277	349.717	Annular-Mist
2000	378	93.7	0.1527	701.282	282.734	Annular-Mist
2660	491	101.1	0.1825	539.302	237.734	Annular-Mist
3320	702	111.4	0.1425	329.991	306.827	Bubble Flow
4000	910	121.8	0.1878	247.233	234.066	Bubble Flow
4660	1113	131.9	0.2329	198.041	189.536	Bubble Flow
5320	1325	142.5	0.2785	164.949	159.027	Bubble Flow
6000	1556	154.0	0.3229	142.036	137.637	Bubble Flow
6660	1793	165.2	0.3596	127.487	123.942	Bubble Flow
7320	2043	176.2	0.3891	117.920	114.890	Bubble Flow
8000	2311	186.1	0.4145	110.846	108.171	Bubble Flow
8660	2580	193.3	0.4374	105.134	102.730	Bubble Flow
9320	2857	197.7	0.4593	100.118	97.938	Bubble Flow
10000	3138	179.0	1.0000	0.000	94.140	2 Phase Oil Water

Figure 82: Annulus Monitor (CO_2, CT:1.25”, H.S:2.25”,Q_{CO2}=5, Q_w= 1,Q_{wi}=5 gpm)

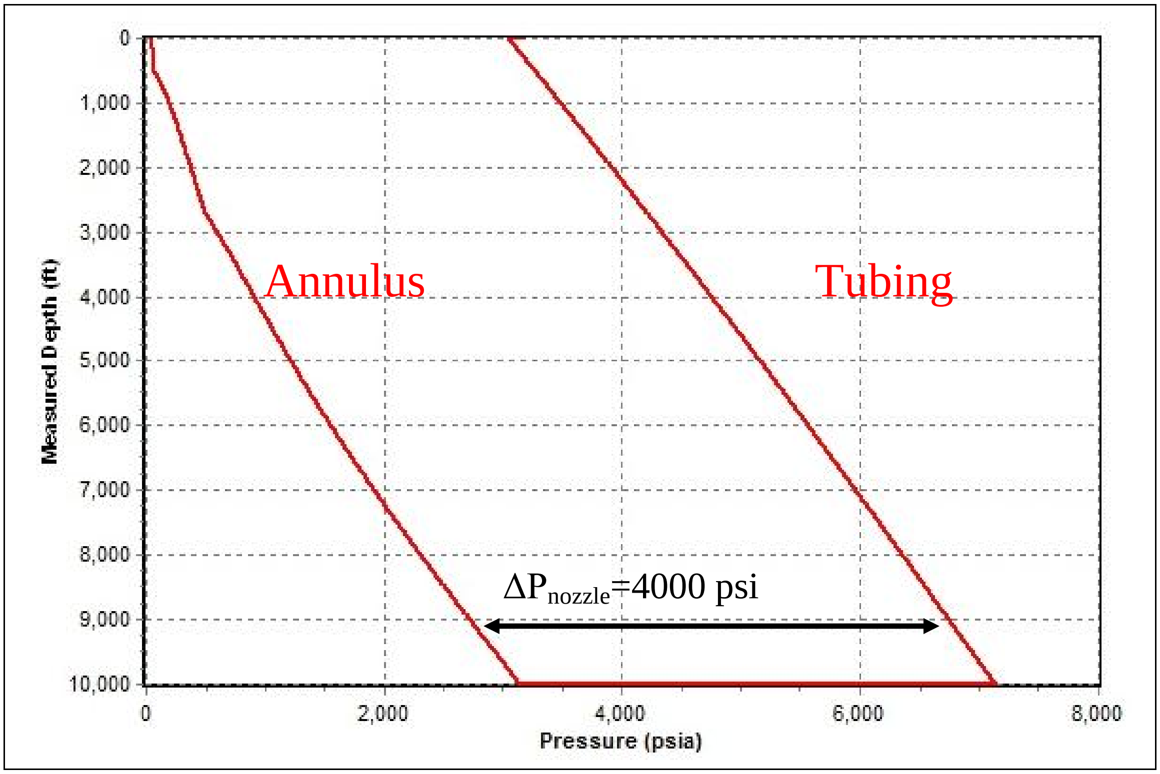


Figure 83: Pressure vs Depth (CO_2, With Water Influx , CT:1.25”, H.S:2.25”)

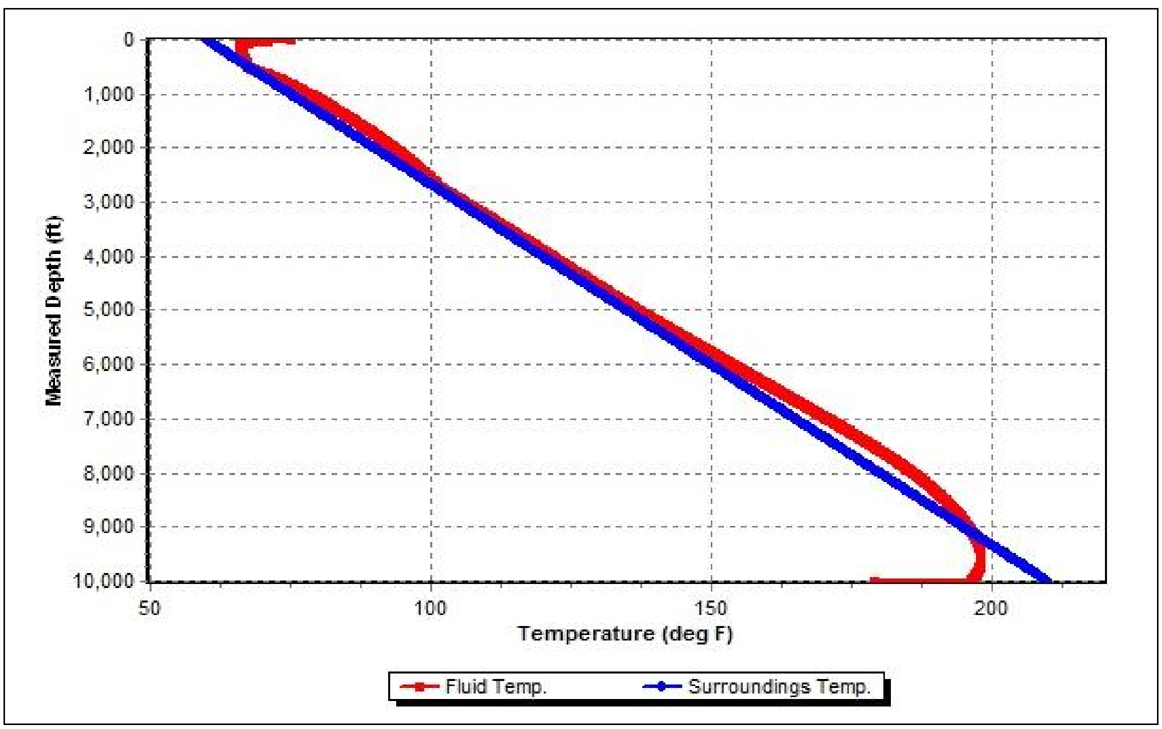


Figure 84: Temperature vs Depth (CO_2, With Water Influx, CT:1.25”, H.S:2.25”)

3.3.2 CO_2 with Water Influx Cases for Different Coiled Tubing and Bore Hole Sizes

In this section, operational envelopes and injection pressure profiles are given for different coiled tubing and borehole size combinations for CO_2 with water influx cases. CO_2 was injected to the tubing with water for all the conditions.

As seen on the operational envelope graphs, due to the 5 gpm water influx from the bottom of the well, liquid fraction after the nozzle are high for almost all different coiled tubing sizes.

Hydrate formation was not a problem for also different size combinations. Most of the cases hydrate did not occur in the system.

For injection pressure versus CO_2 graphs, water flow rates were written near the each run points on the graph. Injection pressures in the system increased with increasing injection flow rates.

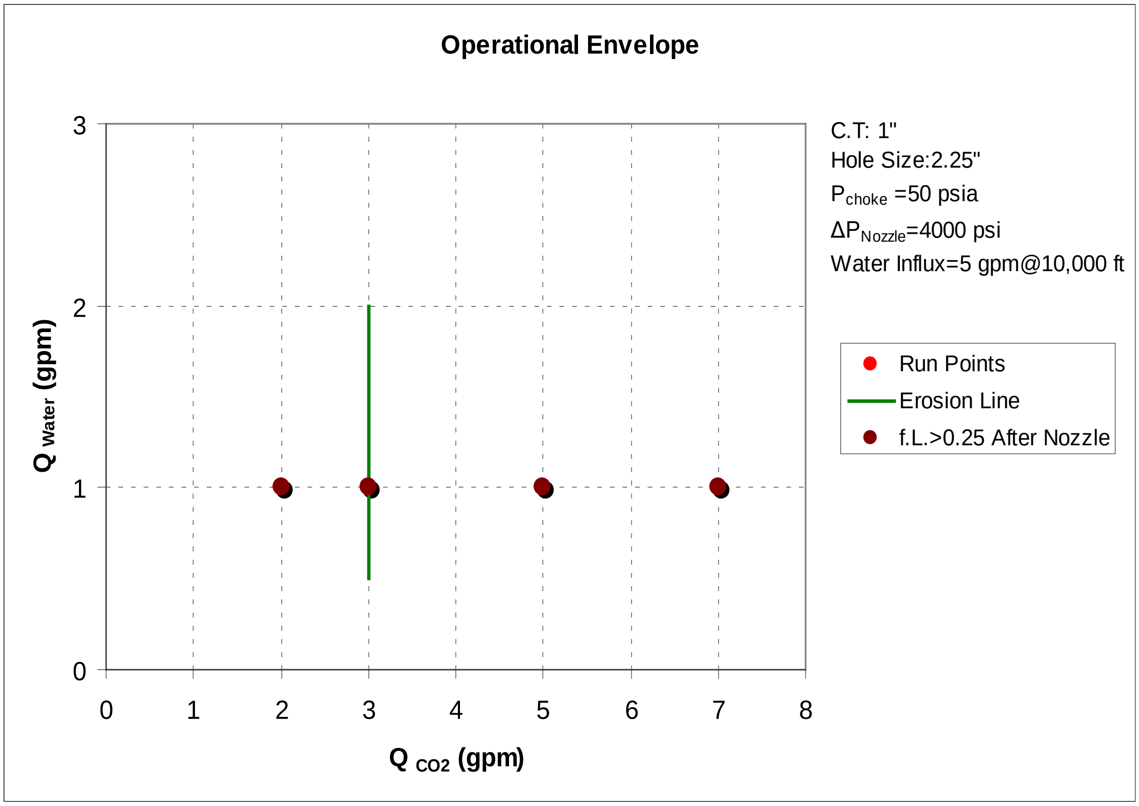


Figure 85: Operational Envelope for CO_2 (CT:1”-HS:2.25”, With Water Influx)

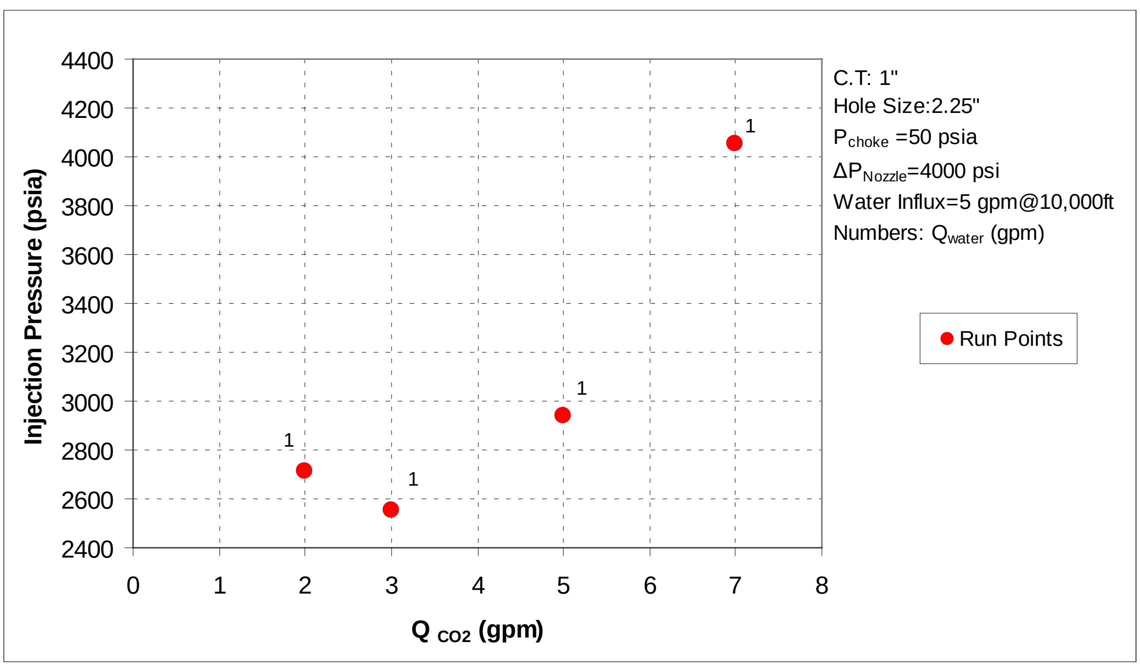


Figure 86: Flow Rate vs. Inj. Pressure for CO_2 (CT:1”-HS:2.25”,With Water Influx)

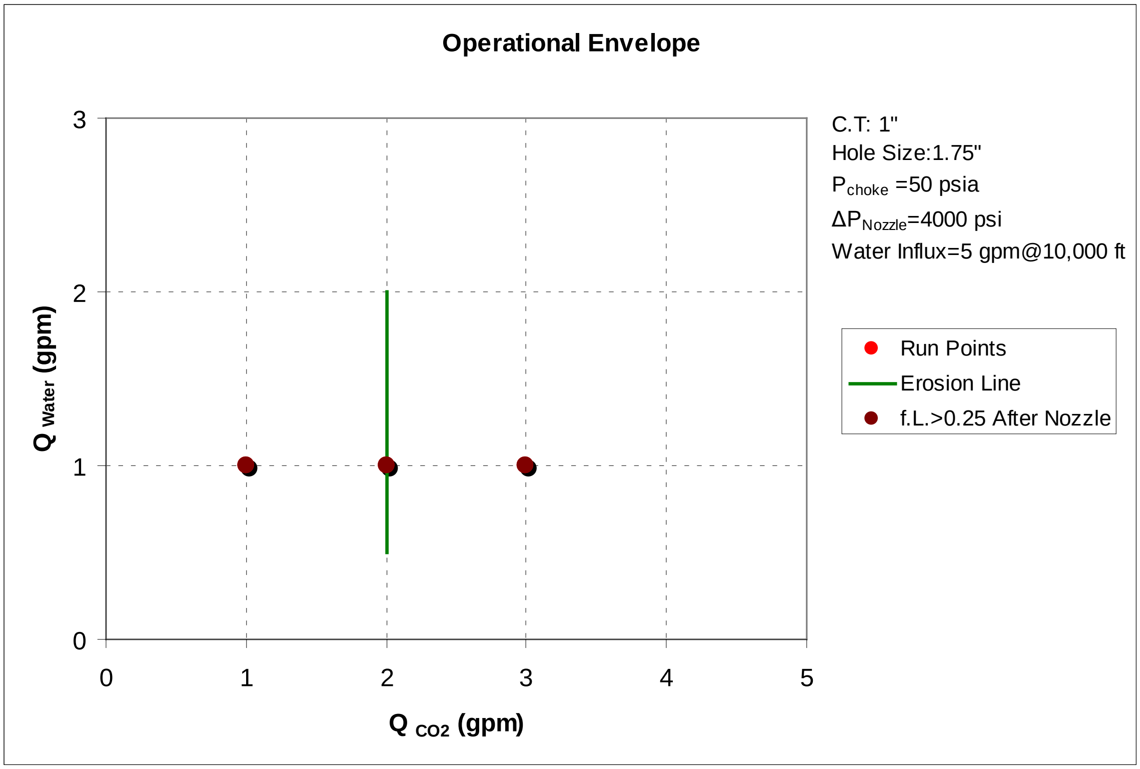


Figure 87: Operational Envelope for CO_2 (CT:1"-HS:1.75", With Water Influx)

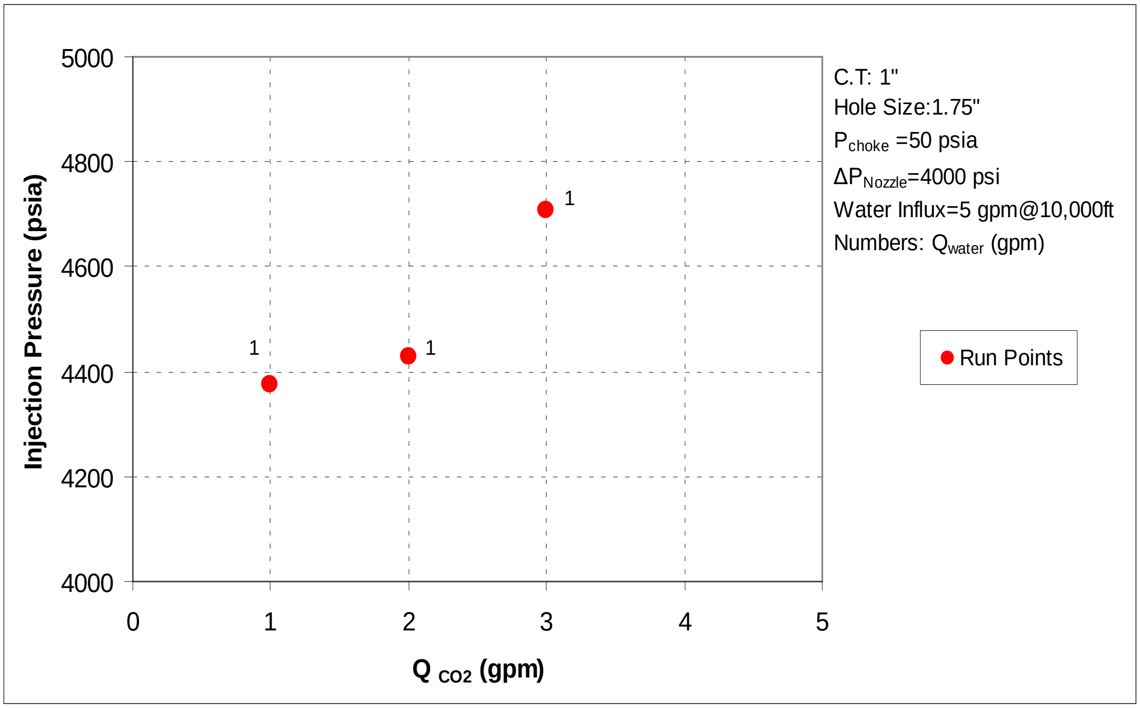


Figure 88: Flow Rate vs. Inj. Pressure for CO_2 (CT:1"-HS:1.75", With Water Influx)

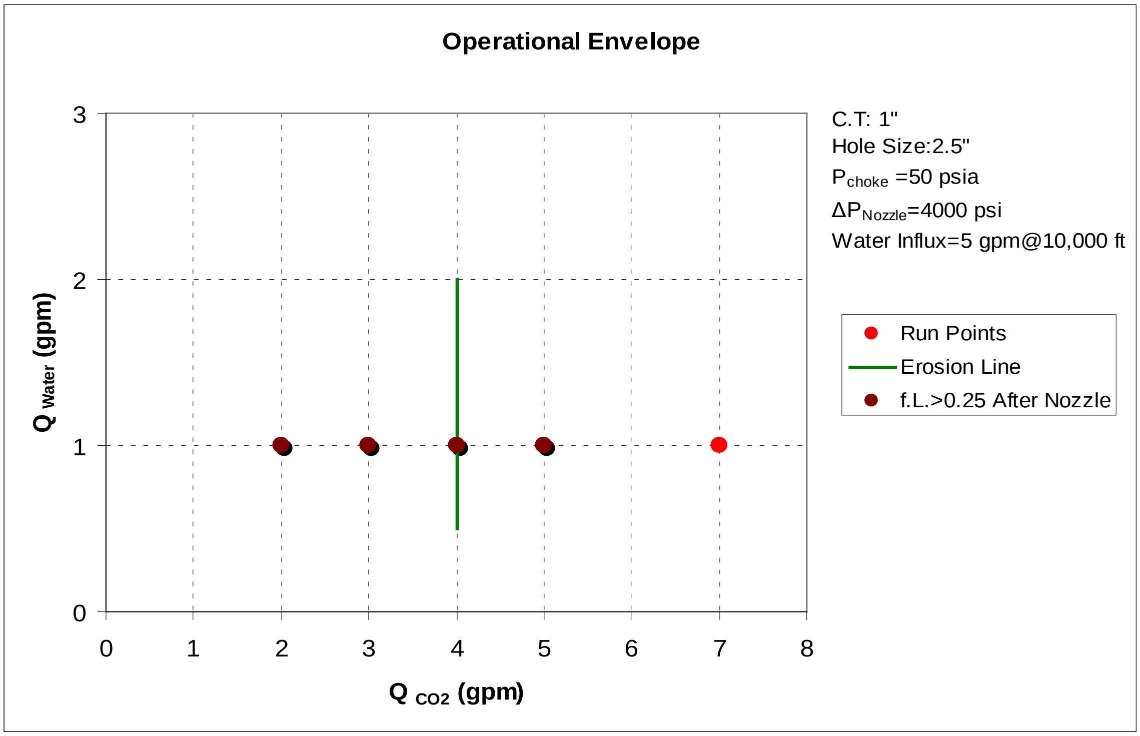


Figure 89: Operational Envelope for CO_2 (CT:1"-HS:2.5", With Water Influx)

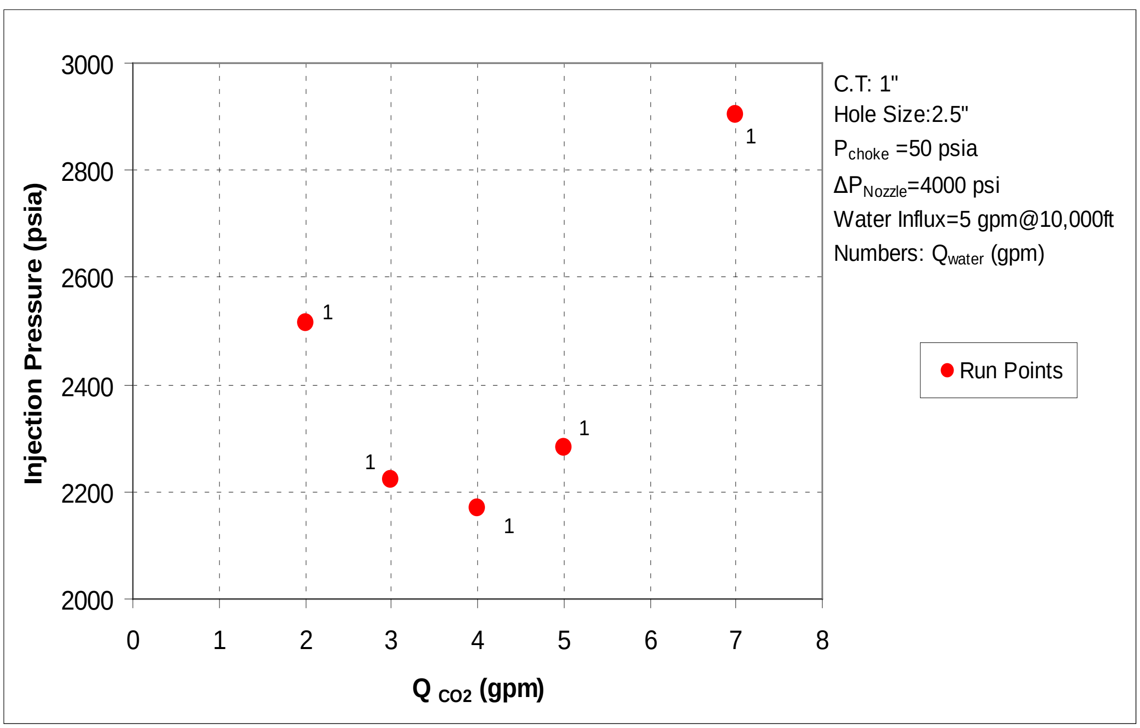


Figure 90: Flow Rate vs. Inj. Pressure for CO_2 (CT:1"-HS:2.5", With Water Influx)

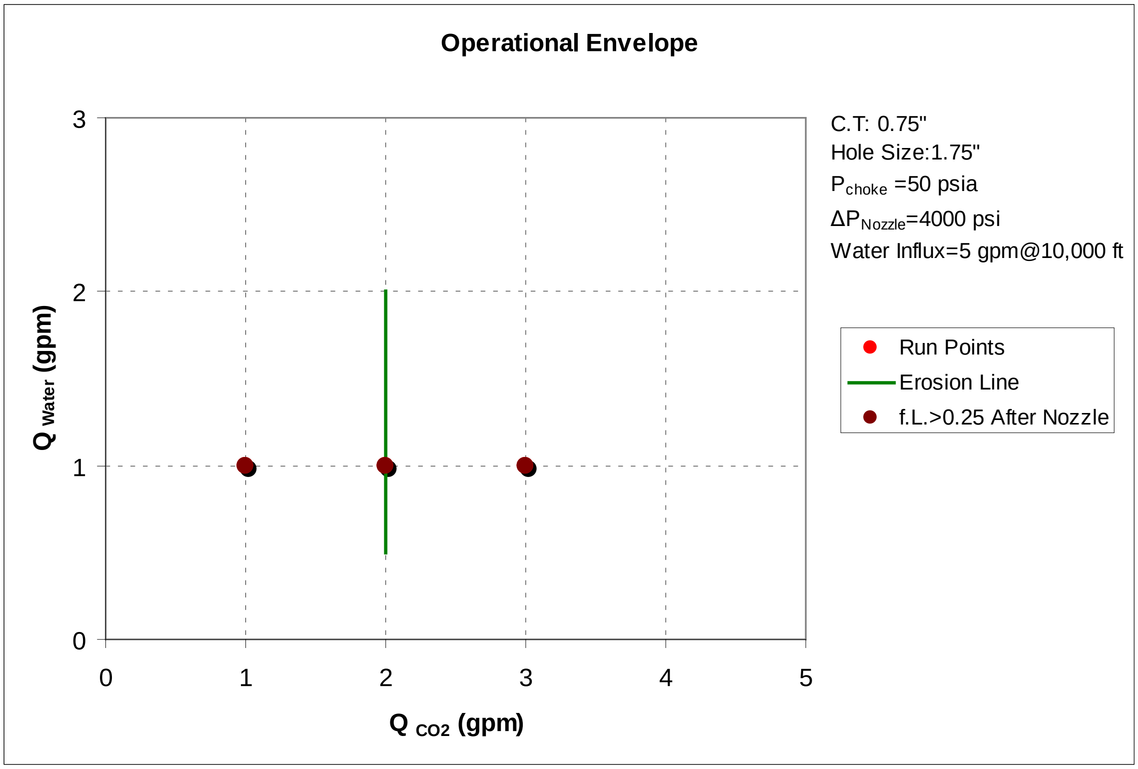


Figure 91: Operational Envelope for CO_2 (CT:0.75”-HS:1.75”, With Water Influx)

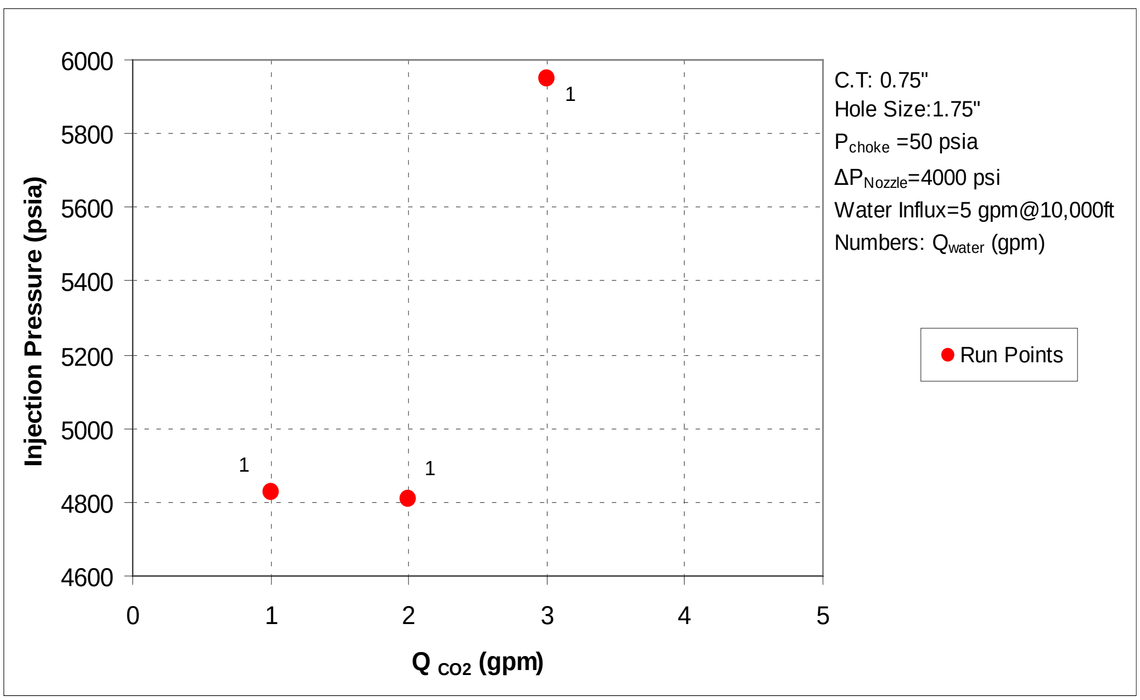


Figure 92: Flow Rate vs Inj. Pressure for CO_2 (CT:0.75-HS:1.75”,With Water Influx)

4. Cutting Transport Analysis

In this part, runs were made in order to analyze cutting transport efficiency in the annulus. In these simulations, first 10,000 ft of the well has different size of casings and then next 100 ft drilled with 1.25'' coiled tubing and 2.25'' hole size combination which becomes totally 10,100 vertical depth.

Table 9 gives different input values for casing size, cutting size and surface return choke pressure.

Table 9: Cutting Transport Analysis Variables

Cutting Size (micron)	Casing Size (in)	Surface Return Pressure (psia)
25	3	15
50	4	30
75	5	50
100	7	

4.1 Cutting Transport Analysis for Nitrogen

In these cases, nitrogen was injected to the system with 3, 5 and 7 gpm injection rates with two different surface return choke pressures which were 15 and 50 psia.

4.1.1. Cutting Transport Analysis for Nitrogen (Pc=15 psia)

In this part, simulations were made with 15 psia surface return choke pressure. Figure 93 through 95 shows cutting transport ratio changes for different casing and cutting sizes. As can be seen from the graphs, increasing casing and cutting size in the system decreases cutting transport ratio. WellFlo notes for drilling applications proposed that a fluid can be considered to provide adequate hole cleaning if the minimum value of the CTR is found to be:

- Greater than 0.55 for vertical sections
- Greater than 0.9 for horizontal sections

It needs to be noted that, for gas drilling application further attention needs to be concerned for cutting transport ratio analysis.

In Figure 93, nitrogen injection rate is 3 gpm. As can be seen from the graph, increasing casing size to 7'' and cutting size to 100 micron made cutting transport ratio around 0.55. As expected increasing nitrogen injection rates increased cutting transport ratio which are shown in Figure 94 and 95.

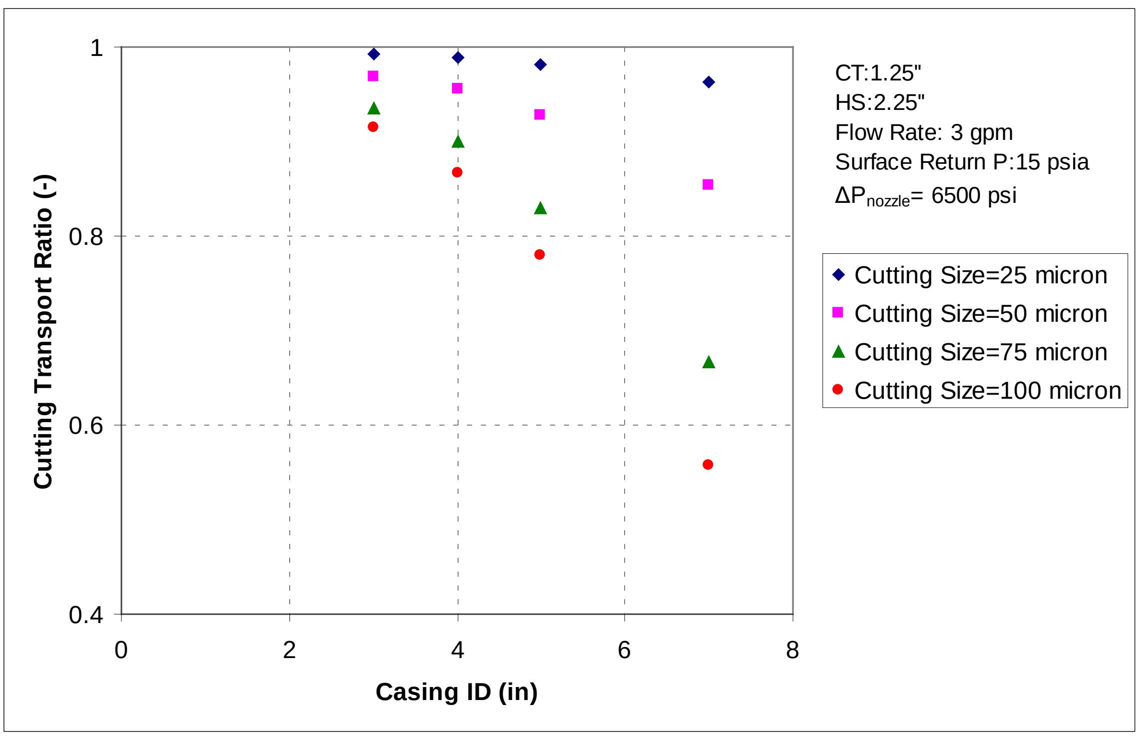


Figure 93: CTR vs Casing ID (Nitrogen Only, Q_{N2}= 3gpm, Pc=15 psia)

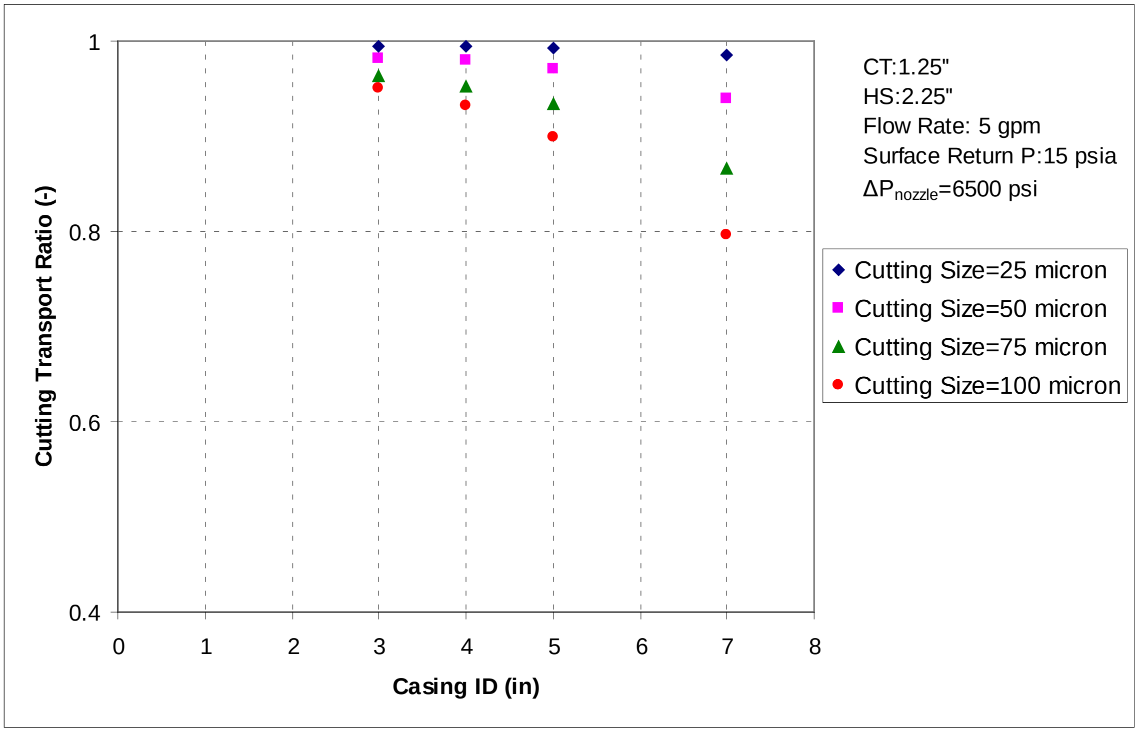


Figure 94: CTR vs Casing ID (Nitrogen Only, Q_{N2}= 5 gpm, Pc=15 psia)

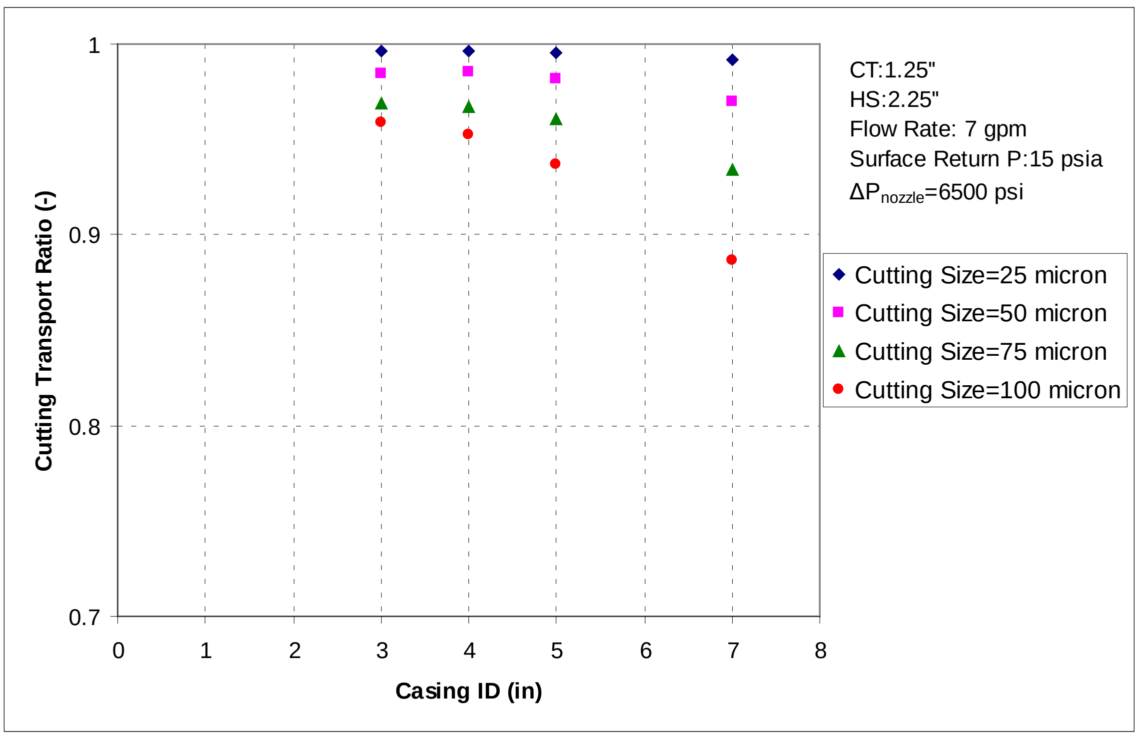


Figure 95: CTR vs Casing ID (Nitrogen Only, Q_{N2}= 7 gpm, Pc=15 psia)

4.1.2 Cutting Transport Analysis for Nitrogen (Pc=50 psia)

In these simulations, return choke pressure was increased to 50 psia. Similar to 15 psia choke pressure, increasing casing and cutting size decreased cutting transport ratio. Moreover, increasing choke pressure also affected cutting transport ratio negatively. Figure 96 through 98 gives cutting transport ratio graphs for 3, 5 and 7 gpm nitrogen injection rates.

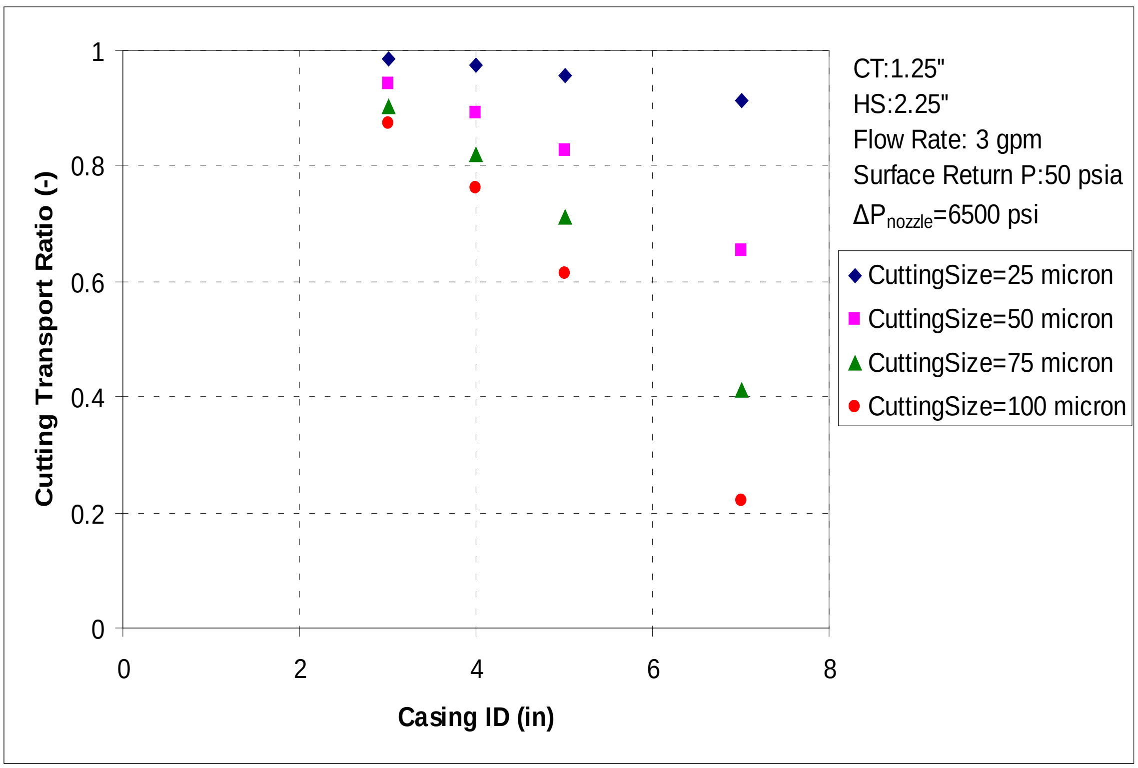


Figure 96: CTR vs Casing ID (Nitrogen Only, Q_{N2}= 3gpm, Pc=50 psia)

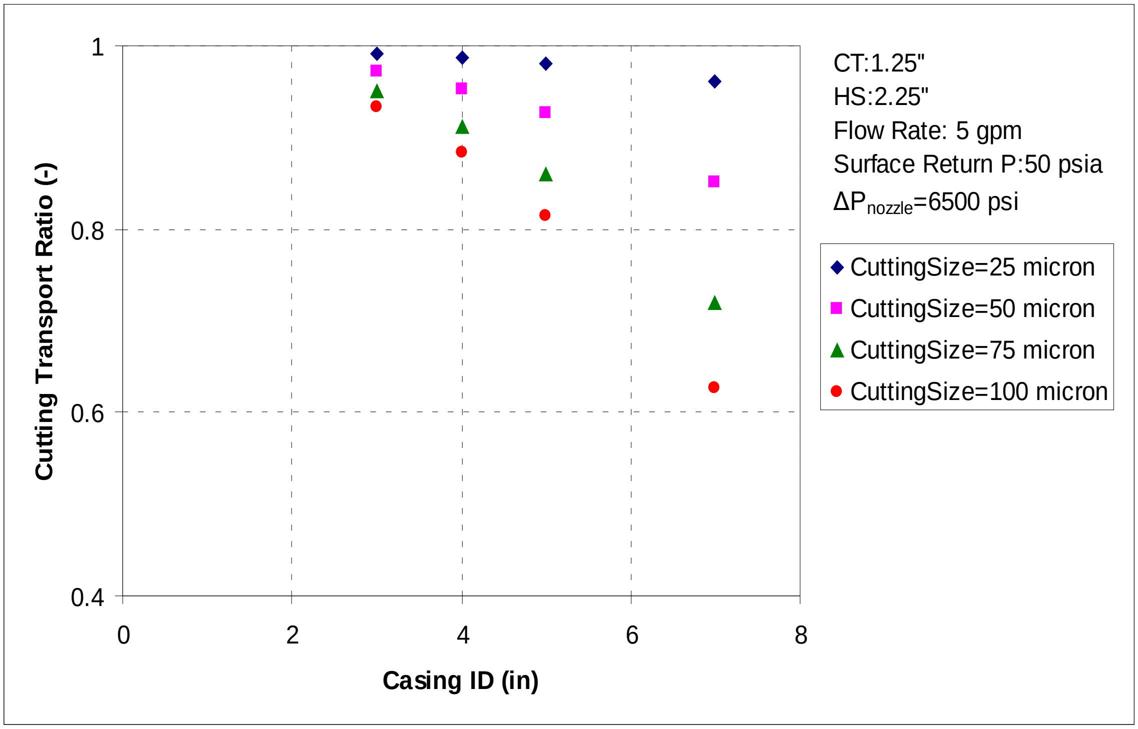


Figure 97: CTR vs Casing ID (Nitrogen Only, Q_{N2}= 5 gpm, Pc=50 psia)

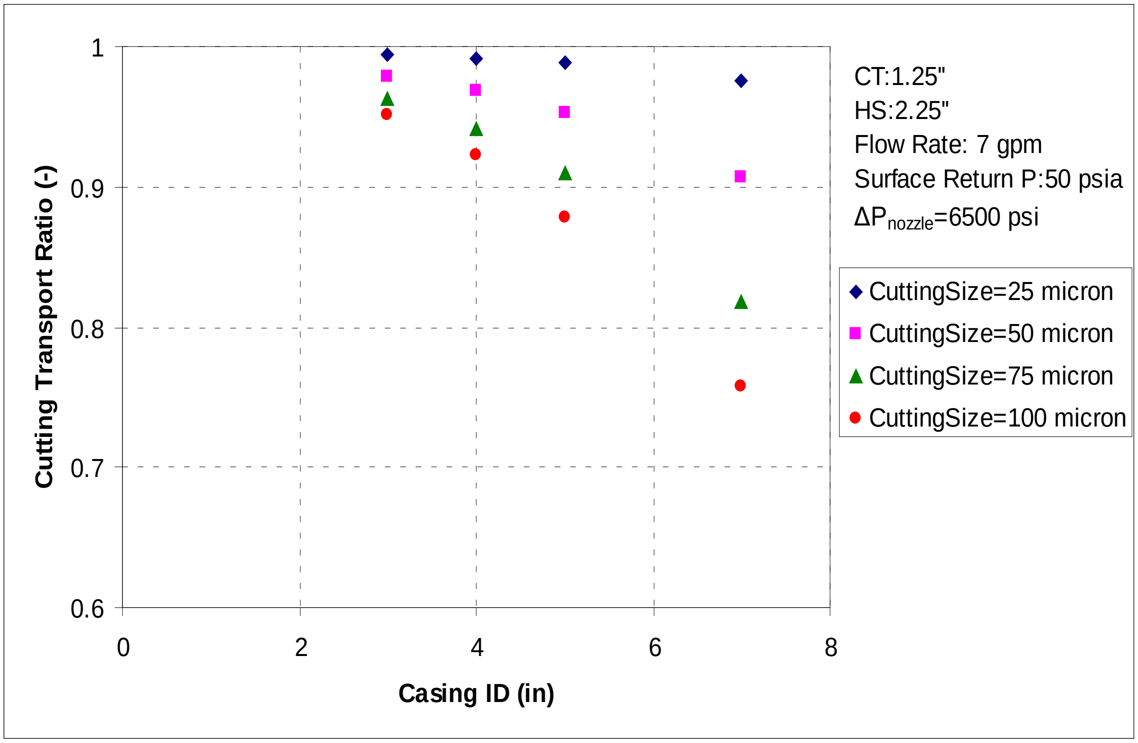


Figure 98: CTR vs Casing ID (Nitrogen Only, Q_{N2}= 7 gpm, Pc=50 psia)

4.2 Cutting Transport Analysis for CO_2

In these part, only carbon dioxide was injected to the system and similar to nitrogen cutting transport analysis, different casing and cutting sizes were used. Also, two different surface return choke pressures were used for simulations which were 30 and 50 psia. Injection flow rates used for simulations are 5 and 7 gpm. For 3 gpm carbon dioxide injection rate, simulation did not converge and software did not give result.

4.2.1. Cutting Transport Analysis for CO_2 (Pc=30 psia)

In this part, simulations were made with 30 psia surface return choke pressure. Figure 99 and 100 shows cutting transport ratio changes for different casing and cutting sizes. As can be seen from the graphs, increasing casing and cutting size in the system decreases cutting transport ratio.

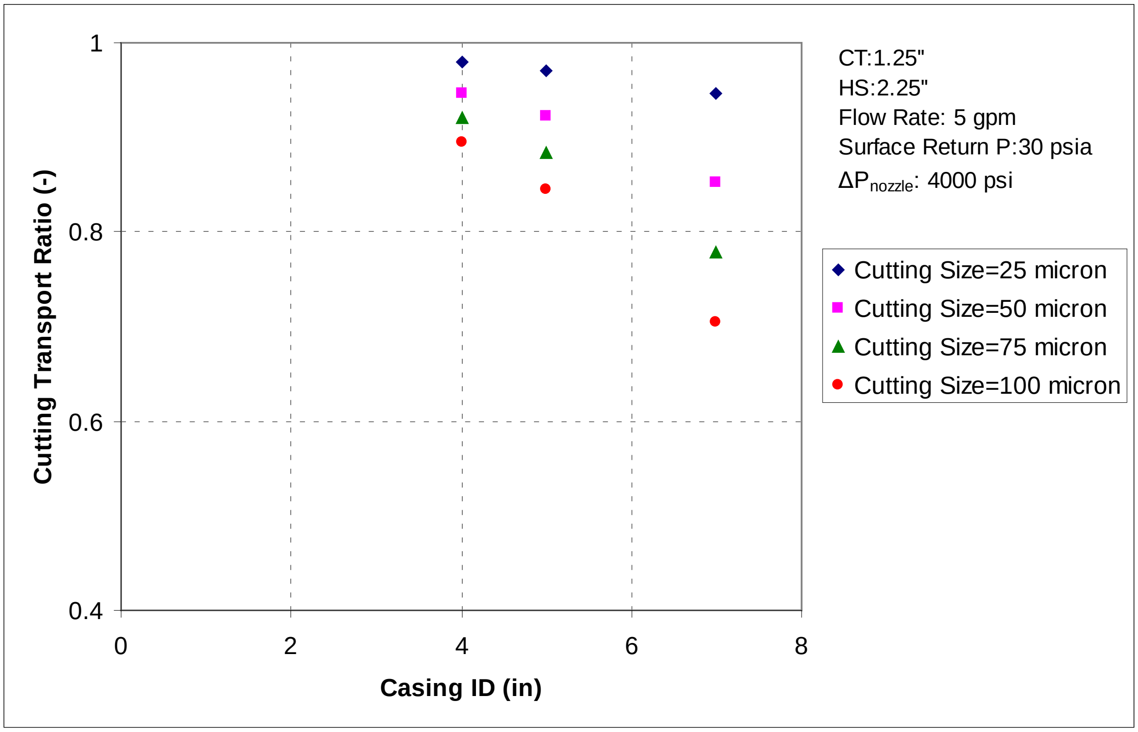


Figure 99: CTR vs Casing ID (CO_2 Only, Q_{CO2}= 5 gpm, Pc=30 psia)

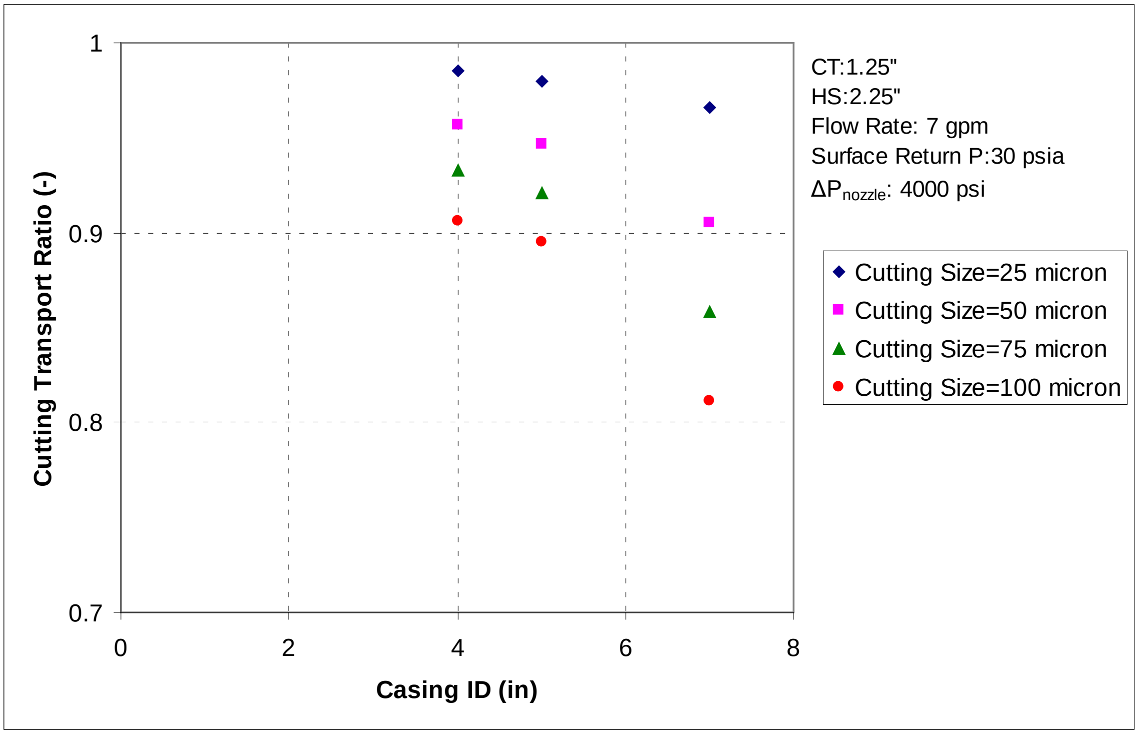


Figure 100: CTR vs Casing ID (CO_2 Only, Q_{CO2}= 7 gpm, Pc=30 psia)

4.2.2 Cutting Transport Analysis for CO_2 (Pc=50 psia)

In these simulations, return choke pressure was increased to 50 psia. Similar to 30 psia choke pressure, increasing casing and cutting size decreased cutting transport ratio. Moreover, increasing choke pressure also affected cutting transport ratio negatively. Figure 101 and 102 gives cutting transport ratio graphs for 5 and 7 gpm CO_2 injection rates.

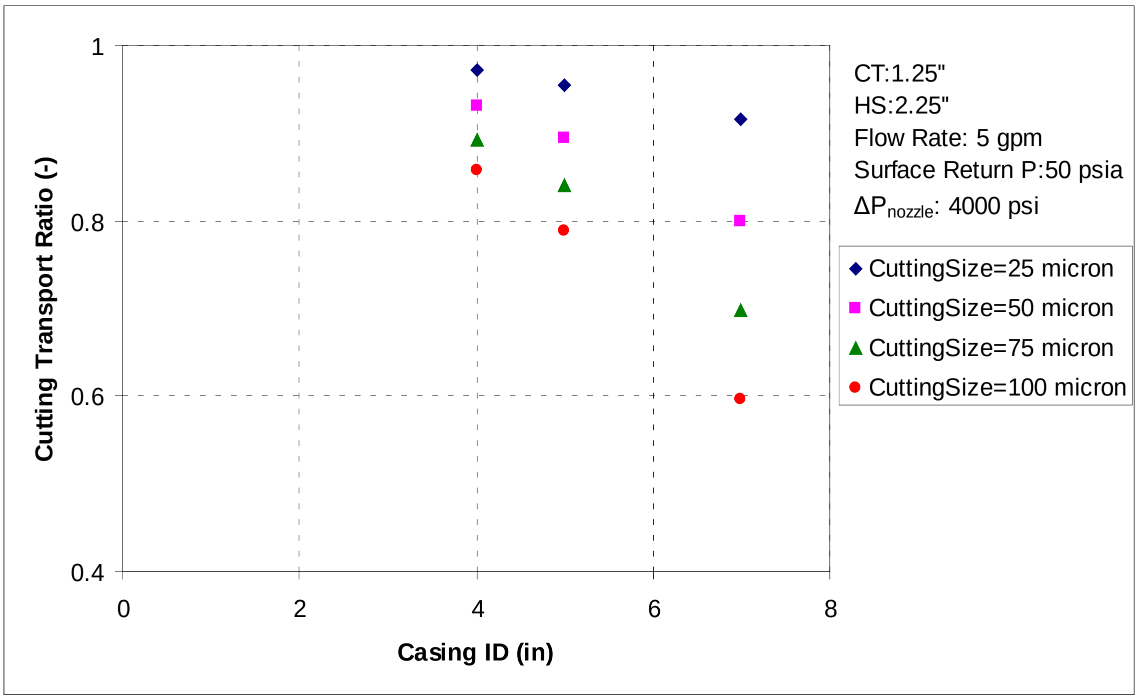


Figure 101: CTR vs Casing ID (CO_2 Only, Q_{CO2}= 5 gpm, Pc=50 psia)

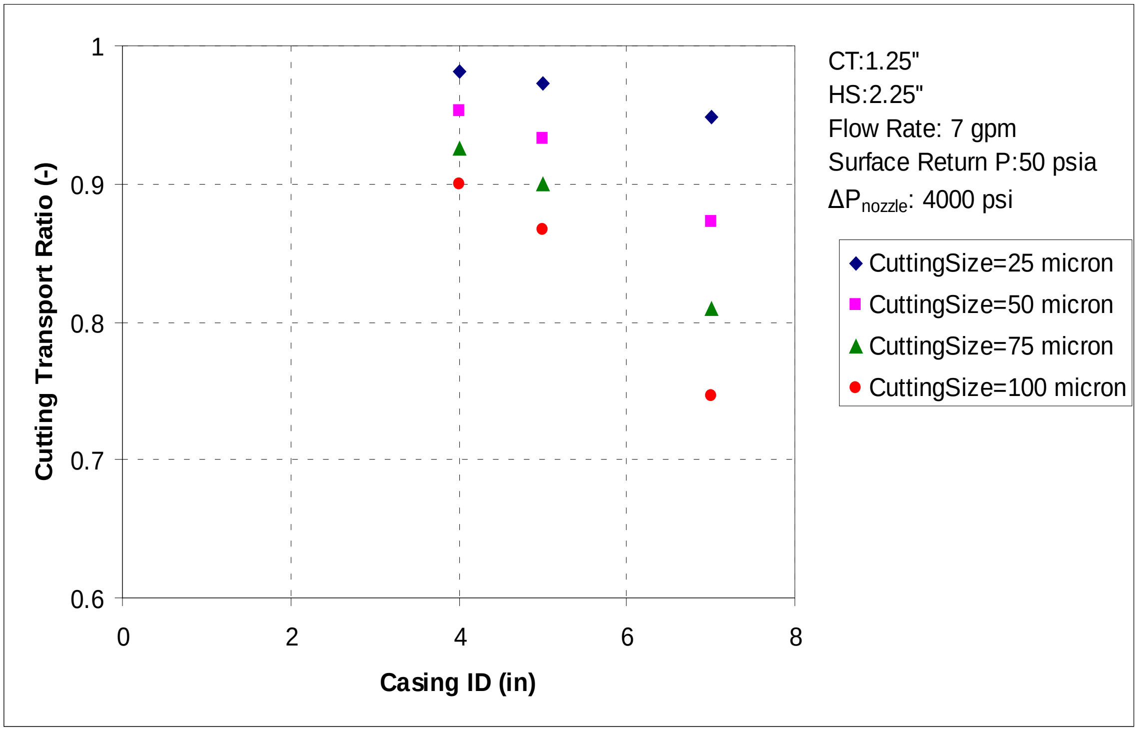


Figure 102: CTR vs Casing ID (CO_2 Only, Q_{CO2}= 7 gpm, Pc=50 psia)

5. CONCLUSIONS

Simulations of drilling operation with supercritical fluids; N_2 and CO_2 have been carried out utilizing WellFlo Version 8.0.13 for 10,000 ft. wells. The following specific outcomes have been accomplished in this report for each of the three topics studied. Important output results for the software runs are given in Appendix A and B.

Nitrogen Cases

Nitrogen runs were performed for three different cases: 1) Nitrogen without Water, 2) Nitrogen with Water Addition, and 3) Nitrogen with Water Influx.

1. Nitrogen without Water Addition Cases:
    - Only Nitrogen was injected into the system with 75 ºF initial temperature and 6000 psi pressure drop set as an input to keep the nitrogen in supercritical liquid state in the tubing.
    - Nitrogen phase in the tubing was liquid in the tubing and all the liquid phase changed to gas phase in the annulus.
    - Operational envelope, temperature and pressure profiles were created for five different coiled tubing and bore hole size combinations.
    - Operational envelopes were created based on erosion velocity which is set at 1800 ft/min maximum mixture velocity (anywhere).
    - For the same coiled tubing size increasing holes size decreased the maximum mixture velocity in annulus and decreased the injection pressure.

- Needed injection pressure increased with increasing flow rate.
- Temperature drop at the bottom of the well did not cause hydrate problems due to higher temperature at 10,000 ft.
- 4'' surface pipe for the first 500 ft in the well decreased the mixture velocity in the annulus while the fluid reaching surface.

2. Nitrogen with Water Addition Cases:
   - Different amounts of water were injected with nitrogen and resulted in decrease of temperature drop across the nozzle.
   - Operational envelope, temperature and pressure profiles were created for five different coiled tubing and bore hole size combinations.
   - Increasing injection flow rates increased the injection pressures.
   - Temperature drop across the nozzle decreased significantly to that of nitrogen only conditions. Also for water addition conditions, hydrate formation did not occur in the system.

3. Nitrogen with Water Influx Cases
   - 5 gpm water influxes were allowed at the bottom of the well in the annulus.
   - Nitrogen was injected to the well with water.
   - Operational envelope, temperature and pressure profiles were created for five different coiled tubing and bore hole size combinations.

- Water influx created significant amounts of liquid fraction after the nozzle in annulus. Increasing nitrogen flow rates decreased the liquid fraction amount for larger annulus coiled tubing-hole size combinations.

CO_2 Cases

Carbon dioxide runs were performed for three different cases: 1) Carbon dioxide without Water, 2) Carbon dioxide with Water Addition, and 3) Carbon dioxide with Water Influx.

1. CO_2 without Water Addition Cases:

   - Only CO_2 was injected to the system with 75 ^oF initial temperature and 4000 psi pressure drop occurred at the nozzle.
   - Operational envelope, temperature and pressure profiles were created for five different coiled tubing and bore hole size combinations.
   - For the same coiled tubing size increasing holes size decreased the maximum mixture velocity in annulus and the needed injection pressure decreased.
   - Needed injection pressure increased with increasing flow rate.
   - Significant temperature drop occurred across the nozzle and possible hydrate formation percentage amounts were reported on the graphs as if CO_2 was saturated with water.
   - Due to the pressure-temperature combination bottom of the well, liquid phase CO_2 after the nozzle was found significantly high for all cases.

2. CO_2 with Water Addition Cases:

   - Different amounts of water were injected with CO_2 and resulted in decrease of temperature drop across the nozzle.
   - Operational envelope, temperature and pressure profiles were created for five different coiled tubing and bore hole size combinations.
   - Increasing injection flow rates increased the injection pressures.
   - For the same CO_2 flow rate, increasing water flow rate increased injection pressure due to the frictional pressure losses.
   - Temperature drop across the nozzle decreased significantly to that of CO_2 only conditions and possible hydrate formation amount became less than 1%.

3. CO_2 with Water Influx Cases

   - 5 gpm water influxes were allowed at the bottom of the well in the annulus.
   - CO_2 was injected to the well with of water.
   - Operational envelope, temperature and pressure profiles were created for five different coiled tubing and bore hole size combinations.
   - Water influx created significant amounts of liquid fraction after the nozzle in annulus. Almost all runs showed that, for given conditions, liquid fraction equals to one. In addition to water influx which can be prior reason for high liquid fraction, also the pressure and temperature values at the bottom caused by the influx helped high liquid fraction result due to

the liquid phase CO_2. Water influx caused high hydrostatic head in the annulus.

Cutting Transport Ratio Analysis

1. Nitrogen Cases

- In these simulations, first 10,000 ft of well has different size of casings and then next 100 ft with 1.25’’ coiled tubing and 2.25’’ hole size combination which becomes totally 10,100 vertical depth.
- Graphs are plotted with different casing and cutting sizes.
- Increasing casing and cutting sizes decreased the cutting transport ratio
- Increasing surface return choke pressure has negative affect on cutting transport ratio.

2. CO_2 Cases

- In these simulations, CO_2 was used as a drilling fluid for cutting transport analysis
- Similar to N_2, increasing casing and cutting size decreased the cutting transport ratio.
- For CO_2 runs, there were two injection rates used for simulations which were 5 and 7 gpm. At 3 gpm injection rate simulation did not converge and software did not give result.

Nomenclature

BHP	= Bottom Hole Pressure (psi)
CO_2	= Carbon dioxide
C.T	= Coiled Tubing
CTR	= Cutting Transport Ratio (CTR)
D. Stream	= Downstream
f.L.	= Liquid fraction (-)
N_2	= Nitrogen
I.D.	= Inner Diameter (inch)
Inj.	= Injection
P_c	= Surface Return Choke Pressure (psia)
ROP	= Rate of Penetration (ft/hour)
Q	= Flow Rate, gpm
Q_w	= Water flow Rate (gpm)
Q_{wi}	= Water Influx Flow Rate (gpm)
O.D.	= Outer Diameter (inch)
T	= Temperature (^oF)

APPENDIX A

Table A-1: Output for N_2 Drilling without Water Addition Cases

Coiled Tubing O.D: 1.25 inch –Bore Hole Size: 2.25 inch							
Q N_2 (gpm)	**Q Water (gpm**	**Maximum Mixture Velocity Annulus (ft/m)**	**Mixture Velocity Annulus (ft/m) 10,000 ft**	**Liquid Fraction After Nozzle (10,000 ft)**	**Liquid Velocity Tubing (ft/m)**	**Total Hydrate (%)**	**Solid Phase (%)**
1	-	534	44.75	0	21.58	-	-
2	-	1066	177.05	0	42.04	-	-
3	-	1634	287	0	63	-	-
4	-	2224	351	0	83.6	-	-
5	-	2877	390.4	0	104.22	-	-
7	-	4053	433	0	145.74	-	-
10	-	5340	469	0	210	-	-
Q N2 (gpm)	**Q Water (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D. Stream Nozzle (psi)**	**T Upstream Nozzle (ºF)**	**T D.Stream Nozzle (ºF)**	**CTR (%)**
1	-	5329	6837	837	188	157	0.901
2	-	4950	6378	378	177	134	0.973
3	-	4932	6344	344	171	127	0.983
4	-	4969	6373	373	167	122	0.986
5	-	5023	6417	417	164	120	0.987
7	-	5155	6524	524	160	118	0.989
10	-	5419	6718	718	157	118	0.99
Coiled Tubing O.D: 1 inch –Bore Hole Size: 2.25 inch							
Q N_2 (gpm)	**Q Water (gpm**	**Maximum Mixture Velocity Annulus (ft/m)**	**Mixture Velocity Annulus (ft/m) 10,000 ft**	**Liquid Fraction After Nozzle (10,000 ft)**	**Liquid Velocity Tubing (ft/m)**	**Total Hydrate (%)**	**Solid Phase (%)**
2	-	919	171	0	81.9	-	-
3	-	1409	300	0	109	-	-
4	-	1875	379	0	145	-	-
5	-	2251	426	0	180	-	-
7	-	3427	488	0	255	-	-
10	-	4952	529	0	368	-	-
Q N_2 (gpm)	**Q Water (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D.Stream Nozzle (psi)**	**T Upstream Nozzle (ºF)**	**T D.stream Nozzle (ºF)**	**CTR (%)**
2	-	4939	6335	335	175	130	0.972
3	-	4934	6281	281	168	121	0.983
4	-	4997	6293	293	163	116	0.987
5	-	5091	6324	324	160	11	0.988
7	-	5358	6406	406	153	106	0.99
10	-	5934	6560	560	147	103	0.99

Table A-1: Continuation

Coiled Tubing O.D: 1 inch –Bore Hole Size: 1.75 inch							
Q N_2 (gpm)	**Q Water (gpm**	**Maximum Mixture Velocity Annulus (ft/m)**	**Mixture Velocity Annulus (ft/m) 10,000 ft**	**Liquid Fraction After Nozzle (10,000 ft)**	**Liquid Velocity Tubing (ft/m)**	**Total Hydrate (%)**	**Solid Phase (%)**
1	-	898	119	0	35	-	-
2	-	2001	268	0	71	-	-
3	-	2743	325	0	106	-	-
5	-	4509	379	0	176	-	-
Q N2 (gpm)	**Q Water (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D. Stream Nozzle (psi)**	**T Upstream Nozzle (ºF)**	**T D.Stream Nozzle (ºF)**	**CTR (%)**
1	-	5039	6483	483	184	145	0.961
2	-	5013	6423	423	176	134	0.98
3	-	5133	6521	521	172	131	0.985
5	-	5474	6776	776	168	133	0.988
Coiled Tubing O.D: 1 inch –Bore Hole Size: 2.5 inch							
Q N_2 (gpm)	**Q Water (gpm**	**Maximum Mixture Velocity Annulus (ft/m)**	**Mixture Velocity Annulus (ft/m) 10,000 ft**	**Liquid Fraction After Nozzle (10,000 ft)**	**Liquid Velocity Tubing (ft/m)**	**Total Hydrate (%)**	**Solid Phase (%)**
2	-	697	110	0	72	-	-
3	-	1081	237	0	109	-	-
5	-	1773	408	0	181	-	-
6	-	2182	460	0	216	-	-
7	-	2629	500	0	259	-	-
10	-	3992	563	0	376	-	-
Q N_2 (gpm)	**Q Water (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D.Stream Nozzle (psi)**	**T Upstream Nozzle (ºF)**	**T D.stream Nozzle (ºF)**	**CTR (%)**
2	-	4996	6405	405	176	134	0.957
3	-	4928	6275	275	168	121	0.979
5	-	5039	6261	261	159	109	0.987
6	-	5133	6276	276	155	105	0.989
7	-	5276	6304	304	151	101	0.99
10	-	5813	6400	400	143	94	0.991

Table A-1: Continuation

Coiled Tubing O.D: 0.75 inch –Bore Hole Size: 1.75 inch							
Q N_2 (gpm)	Q Water (gpm	Maximum Mixture Velocity Annulus (ft/m)	Mixture Velocity Annulus (ft/m) 10,000 ft	Liquid Fraction After Nozzle (10,000 ft)	Liquid Velocity Tubing (ft/m)	Total Hydrate (%)	Solid Phase (%)
1	-	736	112	0	73	-	-
2	-	1472	291	0	147	-	-
3	-	2711	388	0	232	-	-
5	-	4049	446	0	376	-	-
Q N2 (gpm)	Q Water (gpm)	Injection Pressure (psi)	BHP Upstream Nozzle (psi)	BHP D. Stream Nozzle (psi)	T Upstream Nozzle (ºF)	T D.Stream Nozzle (ºF)	CTR (%)
1	-	5034	6422	422	181	140	0.955
2	-	5101	6317	317	171	126	0.977
3	-	5459	6377	377	165	120	0.987
5	-	6503	6562	562	159	116	0.989

Table A-2: Output for N_2 Drilling with Water Addition Cases

Coiled Tubing O.D: 1.25 inch –Bore Hole Size: 2.25 inch							
Q N_2 (gpm)	**Q Water (gpm**	**Maximum Mixture Velocity Annulus (ft/m)**	**Mixture Velocity Annulus (ft/m) 10,000 ft**	**Liquid Fraction After Nozzle (10,000 ft)**	**Liquid Velocity Tubing (ft/m)**	**Total Hydrate (%)**	**Solid Phase (%)**
2	1	789	55	0.14	69	-	-
2	3	620	50	0.45	108	-	-
3	1	1135	93	0.1	90	-	-
4	1	1546	135	0.08	111	-	-
4	2	1480	111.5	0.14	135	-	-
5	1	1862	173	0.07	132	-	-
5	2	1920	144	0.11	156	-	-
6	1	2304	215	0.16	153	-	-
7	1	2607	250	0.14	173	-	-
7	2	2539	212	0.22	197	-	-
7	3	2585	189	0.12	219	-	-
10	1	4298	331	0.1	237	-	-
10	2	4142	304	0.15	262	-	-
Q N2 (gpm)	**Q Water (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D. Stream Nozzle (psi)**	**T Upstream Nozzle (°F)**	**T D.Stream Nozzle (°F)**	**CTR (%)**
2	1	3813	5309	1309	218	221	0.973
2	3	3326	6302	2302	238	246	0.988
3	1	3608	5010	1010	209	209	0.981
4	1	3526	4892	892	200	197	0.985
4	2	3577	5230	1230	220	223	0.986
5	1	3501	4843	843	192	188	0.988
5	2	3536	5138	1138	215	217	0.988
6	1	3483	4790	790	183	177	0.994
7	1	3512	4780	780	176	169	0.994
7	2	3549	5021	1021	205	204	0.995
7	3	3624	5250	1250	219	221	0.991
10	1	3719	4843	843	163	152	0.995
10	2	3770	5014	1014	191	188	0.995

Table A-2: Continuation

Coiled Tubing O.D: 1 inch –Bore Hole Size: 2.25 inch							
Q N_2 (gpm)	**Q Water (gpm**	**Maximum Mixture Velocity Annulus (ft/m)**	**Mixture Velocity Annulus (ft/m) 10,000 ft**	**Liquid Fraction After Nozzle (10,000 ft)**	**Liquid Velocity Tubing (ft/m)**	**Total Hydrate (%)**	**Solid Phase (%)**
2	1	632	52	0.15	118	-	-
3	1	932	96	0.11	155	-	-
3	2	975	80	0.16	196	-	-
5	1	1674	196	0.07	228	-	-
5	2	1620	160	0.1	270	-	-
6	1	2000	235	0.12	262	-	-
8	1	3103	337	0.09	361	-	-
8	2	3358	314	0.13	409	-	-
10	1	4475	396	0.08	449	-	-
Q N2 (gpm)	**Q Water (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D. Stream Nozzle (psi)**	**T Upstream Nozzle (ºF)**	**T D.Stream Nozzle (ºF)**	**CTR (%)**
2	1	3608	5174	1174	217	220	0.973
3	1	3371	4826	826	205	204	0.983
3	2	3431	5151	1151	225	229	0.983
5	1	3465	4621	621	182	176	0.989
5	2	3588	4851	851	209	210	0.989
6	1	3585	4604	604	172	164	0.993
8	1	4010	4610	610	152	141	0.995
8	2	4303	4750	750	183	179	0.995
10	1	4517	4679	679	142	128	0.995
Coiled Tubing O.D: 1 inch –Bore Hole Size: 1.75 inch							
Q N_2 (gpm)	**Q Water (gpm**	**Maximum Mixture Velocity Annulus (ft/m)**	**Mixture Velocity Annulus (ft/m) 10,000 ft**	**Liquid Fraction After Nozzle (10,000 ft)**	**Liquid Velocity Tubing (ft/m)**	**Total Hydrate (%)**	**Solid Phase (%)**
2	1	1425	93	0.14	120	-	-
2	2	1358	86	0.3	155	-	-
3	1	2119	138	0.09	157	-	-
5	1	3535	236	0.19	230	-	-
5	2	3900	201	0.13	271	-	-
7	1	5525	295	0.14	306	-	-
Q N_2 (gpm)	**Q Water (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D.Stream Nozzle (psi)**	**T Upstream Nozzle (ºF)**	**T D.stream Nozzle (ºF)**	**CTR (%)**
2	1	3870	5442	1442	219	222	0.984
2	2	4001	5985	1985	233	240	0.99
3	1	3894	5348	1348	211	212	0.987
5	1	4041	5232	1232	197	194	0.993
5	2	4537	5793	1793	220	223	0.992
7	1	4568	5459	1459	190	186	0.995

Table A-2: Continuation

Coiled Tubing O.D: 1 inch –Bore Hole Size: 2.5 inch							
Q N_2 (gpm)	**Q Water (gpm**	**Maximum Mixture Velocity Annulus (ft/m)**	**Mixture Velocity Annulus (ft/m) 10,000 ft**	**Liquid Fraction After Nozzle (10,000 ft)**	**Liquid Velocity Tubing (ft/m)**	**Total Hydrate (%)**	**Solid Phase (%)**
2	1	464	34	0.18	114	-	-
3	1	778	70	0.14	154	-	-
3	2	750	60	0.18	195	-	-
5	1	1324	167	0.09	231	-	-
5	2	1268	136	0.12	511	-	-
7	1	1891	268	0.07	311	-	-
8	1	2117	306	0.06	345	-	-
8	2	2400	302	0.07	419	-	-
10	1	3501	403	0.07	461	-	-
10	2	3171	387	0.09	508	-	-
Q N2 (gpm)	**Q Water (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D. Stream Nozzle (psi)**	**T Upstream Nozzle (ºF)**	**T D.Stream Nozzle (ºF)**	**CTR (%)**
2	1	3847	5440	1440	220	223	0.964
3	1	3417	4875	875	206	205	0.98
3	2	3462	5184	1184	225	229	0.979
5	1	3414	4556	556	178	171	0.989
5	2	3518	4761	761	207	207	0.988
7	1	3672	4479	479	155	145	0.992
8	1	3806	4470	470	148	136	0.993
8	2	4193	4585	585	175	170	0.993
10	1	4400	4498	498	127	111	0.995
10	2	4784	4594	594	160	152	0.995

Table A-2: Continuation

Coiled Tubing O.D: 0.75 inch –Bore Hole Size: 1.75 inch							
Q N_2 (gpm)	Q Water (gpm	Maximum Mixture Velocity Annulus (ft/m)	Mixture Velocity Annulus (ft/m) 10,000 ft	Liquid Fraction After Nozzle (10,000 ft)	Liquid Velocity Tubing (ft/m)	Total Hydrate (%)	Solid Phase (%)
2	1	1213	99	0.11	250	-	-
2	2	1391	103	0.2	345	-	-
3	1	1923	168	0.08	337	-	-
4	1	3169	266	0.15	444	-	-
4	2	3485	259	0.2	534	-	-
5	1	4540	336	0.12	551	-	-
7	1	7269	398	0.1	713	-	-
Q N2 (gpm)	Q Water (gpm)	Injection Pressure (psi)	BHP Upstream Nozzle (psi)	BHP D. Stream Nozzle (psi)	T Upstream Nozzle (ºF)	T D.Stream Nozzle (ºF)	CTR (%)
2	1	4032	5056	1056	215	217	0.983
2	2	5217	5430	1430	230	235	0.988
3	1	4624	4940	940	203	201	0.988
4	1	5536	4860	860	184	179	0.993
4	2	7368	5138	1138	209	210	0.995
5	1	6956	4959	959	173	166	0.995
7	1	10301	5305	1305	166	157	0.995

Table A-3: Nitrogen with Water Influx Cases

Coiled Tubing O.D: 1.25 inch –Bore Hole Size: 2.25 inch							
Q N_2 (gpm)	**Q Water (gpm**	**Maximum Mixture Velocity Annulus (ft/m)**	**Mixture Velocity Annulus (ft/m) 10,000 ft**	**Liquid Fraction After Nozzle (10,000 ft)**	**Liquid Velocity Tubing (ft/m)**	**Total Hydrate (%)**	**Solid Phase (%)**
3	1	1427	90	0.48	88	-	-
4	1	2013	110	0.4	110	-	-
5	1	2417	129	0.34	132	-	-
7	1	3534	165	0.27	174	-	-
9	1	4338	202	0.22	220	-	-
Q N2 (gpm)	**Q Water (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D. Stream Nozzle (psi)**	**T Upstream Nozzle (ºF)**	**T D.Stream Nozzle (ºF)**	**CTR (%)**
3	1	4875	6463	2463	210	215	0.994
4	1	4778	6286	2286	210	212	0.994
5	1	4755	6213	2213	210	211	0.994
7	1	4796	6180	2180	209	208	0.995
9	1	4936	6233	2233	208	205	0.995
Coiled Tubing O.D: 1 inch –Bore Hole Size: 2.25 inch							
Q N_2 (gpm)	**Q Water (gpm**	**Maximum Mixture Velocity Annulus (ft/m)**	**Mixture Velocity Annulus (ft/m) 10,000 ft**	**Liquid Fraction After Nozzle (10,000 ft)**	**Liquid Velocity Tubing (ft/m)**	**Total Hydrate (%)**	**Solid Phase (%)**
3	1	1155	83	1155	83	-	-
5	1	2116	133	2116	133	-	-
7	1	2904	184	2904	184	-	-
8	1	3426	214	3426	214	-	-
Q N_2 (gpm)	**Q Water (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D.Stream Nozzle (psi)**	**T Upstream Nozzle (ºF)**	**T D.stream Nozzle (ºF)**	**CTR (%)**
3	1	4556	6040	2040	210	213	0.994
5	1	4444	5628	1628	209	207	0.994
7	1	4607	5472	1472	208	203	0.994
8	1	4797	5454	1454	207	200	0.994

Table A-3: Continuation

Coiled Tubing O.D: 1 inch –Bore Hole Size: 1.75 inch							
Q N_2 (gpm)	**Q Water (gpm**	**Maximum Mixture Velocity Annulus (ft/m)**	**Mixture Velocity Annulus (ft/m) 10,000 ft**	**Liquid Fraction After Nozzle (10,000 ft)**	**Liquid Velocity Tubing (ft/m)**	**Total Hydrate (%)**	**Solid Phase (%)**
2	1	1741	114	1	110	-	-
3	1	2888	136	1	146	-	-
5	1	5053	188	1	232	-	-
Q N2 (gpm)	**Q Water (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D. Stream Nozzle (psi)**	**T Upstream Nozzle (ºF)**	**T D.Stream Nozzle (ºF)**	**CTR (%)**
2	1	5890	7755	3755	211	218	0.995
3	1	6048	7745	3745	211	217	0.995
5	1	6524	7894	3894	211	215	0.995
Coiled Tubing O.D: 1 inch –Bore Hole Size: 2.5 inch							
Q N_2 (gpm)	**Q Water (gpm**	**Maximum Mixture Velocity Annulus (ft/m)**	**Mixture Velocity Annulus (ft/m) 10,000 ft**	**Liquid Fraction After Nozzle (10,000 ft)**	**Liquid Velocity Tubing (ft/m)**	**Total Hydrate (%)**	**Solid Phase (%)**
3	1	871	68	0.43	155	-	-
5	1	1525	112	0.26	231	-	-
6	1	1971	138	0.21	270	-	-
9	1	3128	228	0.14	391	-	-
Q N_2 (gpm)	**Q Water (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D.Stream Nozzle (psi)**	**T Upstream Nozzle (ºF)**	**T D.stream Nozzle (ºF)**	**CTR (%)**
3	1	4404	5863	1863	210	213	0.992
5	1	4215	5379	1379	209	206	0.992
6	1	4257	5259	1259	208	203	0.992
9	1	4636	5071	1071	205	194	0.993

Table A-3: Continuation

Coiled Tubing O.D: 0.75 inch –Bore Hole Size: 1.75 inch							
Q N_2 (gpm)	**Q Water (gpm**	**Maximum Mixture Velocity Annulus (ft/m)**	**Mixture Velocity Annulus (ft/m) 10,000 ft**	**Liquid Fraction After Nozzle (10,000 ft)**	**Liquid Velocity Tubing (ft/m)**	**Total Hydrate (%)**	**Solid Phase (%)**
2	1	1414	101	0.6	234	-	-
3	1	2340	126	0.48	310	-	-
5	1	5107	193	0.32	506	-	-
7	1	7085	245	1	645	-	-
Q N2 (gpm)	**Q Water (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D. Stream Nozzle (psi)**	**T Upstream Nozzle (ºF)**	**T D.Stream Nozzle (ºF)**	**CTR (%)**
2	1	5867	7000	3000	211	217	0.995
3	1	6358	6849	2849	211	215	0.996
5	1	8736	6973	2973	210	212	0.996
7	1	11395	7184	3184	210	210	0.994

Table A-4: CO_2 without Water Addition Cases

Coiled Tubing O.D: 1.25 inch –Bore Hole Size: 2.25 inch							
Q CO_2 (gpm)	**Q Water (gpm**	**Maximum Mixture Velocity Annulus (ft/m)**	**Mixture Velocity Annulus (ft/m) 10,000 ft**	**Liquid Fraction After Nozzle (10,000ft)**	**Liquid Velocity Tubing (ft/m)**	**Total Hydrate (%)**	**Solid Phase (%)**
1	-	753	6.2	1	20	0.255	-
2	-	1508	11.5	1	42	0.76	-
3	-	2335	17.6	1	62	1.225	-
5	-	4036	31.4	1	105	0.125	-
7	-	6125	45	1	147	0.05	-
10	-	7961	68	1	211	0	-
Q CO_2 (gpm)	**Q Water (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D. Stream Nozzle (psi)**	**T Upstream Nozzle (ºF)**	**T D.Stream Nozzle (ºF)**	**CTR (%)**
1	-	1320	4717	717	68	47	0.888
2	-	1197	4520	520	35	25	0.954
3	-	1259	4600	600	39	28	0.966
5	-	1492	4880	880	55	41	0.974
7	-	1789	5186	1186	62	48	0.974
10	-	2338	5656	1656	72	59	0.981
Coiled Tubing O.D: 1 inch –Bore Hole Size: 2.25 inch							
Q CO_2 (gpm)	**Q Water (gpm**	**Maximum Mixture Velocity Annulus (ft/m)**	**Mixture Velocity Annulus (ft/m) 10,000 ft**	**Liquid Fraction After Nozzle (10,000ft)**	**Liquid Velocity Tubing (ft/m)**	**Total Hydrate (%)**	**Solid Phase (%)**
1	-	660	5.2	1	34	0.255	-
2	-	1357	9.5	1	72	0.785	-
3	-	2051	14	1	107	1.25	-
5	-	3368	26	1	179	2.395	-
7	-	5241	39	1	254	0.205	-
Q CO2 (gpm	**Q Water (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D.Stream Nozzle (psi)**	**T Upstream Nozzle (ºF)**	**T D.stream Nozzle (ºF)**	**CTR (%)**
1	-	1290	4650	650	58	41	0.878
2	-	1187	4415	415	19	13	0.953
3	-	1292	4463	463	24	16	0.967
5	-	1692	4669	669	41	30	0.979
7	-	2313	4922	922	52	39	0.979

Table A-4: Continuation

Coiled Tubing O.D: 1 inch –Bore Hole Size: 1.75 inch							
Q CO_2 (gpm)	**Q Water (gpm**	**Maximum Mixture Velocity Annulus (ft/m)**	**Mixture Velocity Annulus (ft/m) 10,000 ft**	**Liquid Fraction After Nozzle (10,000ft)**	**Liquid Velocity Tubing (ft/m)**	**Total Hydrate (%)**	**Solid Phase (%)**
1	-	1264	10	1	35	0.26	-
2	-	2665	21	1	71	0.05	-
3	-	4257	33	1	107	0	-
5	-	7007	60	1	180	0	-
7	-	9922	90	1	253	0	-
Q CO2 (gpm	**Q Water (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D. Stream Nozzle (psi)**	**T Upstream Nozzle (ºF)**	**T D.Stream Nozzle (ºF)**	**CTR (%)**
1	-	1270	4608	608	54	38	0.94
2	-	1438	4794	794	57	42	0.964
3	-	1720	5083	1083	65	49	0.967
5	-	2486	5720	1720	81	65	0.978
7	-	3560	6448	2448	99	85	0.984
Coiled Tubing O.D: 1 inch –Bore Hole Size: 2.5 inch							
Q CO_2 (gpm)	**Q Water (gpm**	**Maximum Mixture Velocity Annulus (ft/m)**	**Mixture Velocity Annulus (ft/m) 10,000 ft**	**Liquid Fraction After Nozzle (10,000ft)**	**Liquid Velocity Tubing (ft/m)**	**Total Hydrate (%)**	**Solid Phase (%)**
2	-	1029	7	1	72	0.76	-
3	-	1621	11	1	108	1.2	-
4	-	2111	15	1	142	1.7	-
5	-	2635	20	1	183	2.38	-
7	-	3802	30	1	259	3.905	-
10	-	5989	47	1	380	0.335	-
Q CO2 (gpm)	**Q Water (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D.Stream Nozzle (psi)**	**T Upstream Nozzle (ºF)**	**T D.stream Nozzle (ºF)**	**CTR (%)**
2	-	1177	4403	403	18	12	0.939
3	-	1241	4382	382	12	7	0.961
4	-	1375	4428	428	18	12	0.969
5	-	1590	4505	505	26	19	0.974
7	-	2159	4680	680	40	30	0.978
10	-	3534	5009	1009	51	39	0.982

Table A-4: Continuation

Coiled Tubing O.D: 0.75 inch –Bore Hole Size: 1.75 inch							
Q CO_2 (gpm)	**Q Water (gpm**	**Maximum Mixture Velocity Annulus (ft/m)**	**Mixture Velocity Annulus (ft/m) 10,000 ft**	**Liquid Fraction After Nozzle (10,000ft)**	**Liquid Velocity Tubing (ft/m)**	**Total Hydrate (%)**	**Solid Phase (%)**
1	-	1152	8	1	73	0.355	-
2	-	2266	17	1	152	0.9	-
3	-	4042	28	1	229	0.16	-
5	-	6524	54	1	394	0	-
Q CO2 (gpm	**Q Water (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D. Stream Nozzle (psi)**	**T Upstream Nozzle (ºF)**	**T D.Stream Nozzle (ºF)**	**CTR (%)**
1	-	1270	4447	447	31	21	0.939
2	-	1729	4563	563	36	26	0.968
3	-	2567	4779	779	51	37	0.974
5	-	5689	5331	1331	64	51	0.977

Table A-5: CO_2 with Water Addition Cases

Coiled Tubing O.D: 1.25 inch –Bore Hole Size: 2.25 inch							
Q CO_2 (gpm)	**Q Water (gpm**	**Maximum Mixture Velocity Annulus (ft/m)**	**Mixture Velocity Annulus (ft/m) 10,000 ft**	**Liquid Fraction After Nozzle (10,000ft)**	**Liquid Velocity Tubing (ft/m)**	**Total Hydrate (%)**	**Solid Phase (%)**
1	1	792	20	0.37	40	-	-
1	2	791	27	0.56	61	-	-
2	1	1437	25	0.29	60	-	-
2	2	1543	39	0.38	81	-	-
3	1	1975	59	0.13	80	-	-
3	2	2342	47	0.32	99	-	-
3	3	2334	54	0.41	122	-	-
5	1	3227	40	1	118	-	-
5	2	3254	51	1	140	-	-
5	4	5351	76	1	180	-	-
7	2	4983	68	1	180	-	-
7	3	7424	82	1	203	3	-
Q CO2 (gpm)	**Q Water (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D. Stream Nozzle (psi)**	**T Upstream Nozzle (°F)**	**T D.Stream Nozzle (°F)**	**CTR (%)**
1	1	1845	5888	1888	168	156	0.973
1	2	2415	6600	2600	206	206	0.987
2	1	1355	5144	1144	115	96	0.98
2	2	1661	5616	1616	144	131	0.987
3	1	1378	5085	1085	126	92	0.985
3	2	1596	5421	1421	132	114	0.988
3	3	1955	5810	1810	145	136	0.991
5	1	1558	5236	1236	83	73	0.977
5	2	1771	5505	1505	100	92	0.99
5	4	2668	6360	2360	156	150	0.994
7	2	2464	6180	2180	119	110	0.991
7	3	3369	7080	3080	158	152	0.993

Table A-5: Continuation

Coiled Tubing O.D: 1 inch –Bore Hole Size: 2.25 inch							
Q CO_2 (gpm)	**Q Water (gpm**	**Maximum Mixture Velocity Annulus (ft/m)**	**Mixture Velocity Annulus (ft/m) 10,000 ft**	**Liquid Fraction After Nozzle (10,000ft)**	**Liquid Velocity Tubing (ft/m)**	**Total Hydrate (%)**	**Solid Phase (%)**
1	1	660	10	0.34	68	-	-
1	2	649	25	0.53	104	-	-
2	1	1211	48	0.14	101	-	-
2	2	1281	35	0.36	137	-	-
3	1	1528	79	0.09	133	-	-
3	2	1689	52	0.25	173	-	-
4	1	2060	108	0.08	170	-	-
5	1	2713	125	0.07	207	-	-
5	2	3087	102	0.13	245	-	-
7	2	4273	56	1	316	-	-
Q CO2 (gpm	**Q Water (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D. Stream Nozzle (psi)**	**T Upstream Nozzle (ºF)**	**T D.Stream Nozzle (ºF)**	**CTR (%)**
1	1	1667	5598	1597	156	140	0.969
1	2	2306	6275	2275	200	198	0.984
2	1	1262	4900	900	112	77	0.981
2	2	1689	5258	1258	122	106	0.985
3	1	1367	4829	829	108	71	0.985
3	2	1737	5091	1091	115	92	0.982
4	1	1552	4829	829	107	71	0.989
5	1	1804	4879	879	107	76	0.991
5	2	2282	5055	1055	120	90	0.991
7	2	3131	5372	1372	85	78	0.987
Coiled Tubing O.D: 1 inch –Bore Hole Size: 1.75 inch							
Q CO_2 (gpm)	**Q Water (gpm**	**Maximum Mixture Velocity Annulus (ft/m)**	**Mixture Velocity Annulus (ft/m) 10,000 ft**	**Liquid Fraction After Nozzle (10,000ft)**	**Liquid Velocity Tubing (ft/m)**	**Total Hydrate (%)**	**Solid Phase (%)**
1	1	1379	33	0.38	68	0	-
1	2	1498	44	0.58	104	0	-
2	1	2808	43	0.29	102	0	-
3	1	4034	52	1	136	0	-
3	2	4424	73	1	171	0	-
5	1	8101	84	1	204	0	-
Q CO2 (gpm)	**Q Water (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D.Stream Nozzle (psi)**	**T Upstream Nozzle (ºF)**	**T D.stream Nozzle (ºF)**	**CTR (%)**
1	1	2058	6058	2058	172	162	0.984
1	2	2893	6888	2888	211	212	0.992
2	1	1941	5733	1733	134	120	0.986
3	1	2217	5910	1910	121	110	0.988
3	2	3309	6920	2920	174	169	0.922
5	1	3879	7359	3359	162	152	0.992

Table A-5: Continuation

Coiled Tubing O.D: 1 inch –Bore Hole Size: 2.5 inch							
Q CO_2 (gpm)	**Q Water (gpm**	**Maximum Mixture Velocity Annulus (ft/m)**	**Mixture Velocity Annulus (ft/m) 10,000 ft**	**Liquid Fraction After Nozzle (10,000ft)**	**Liquid Velocity Tubing (ft/m)**	**Total Hydrate (%)**	**Solid Phase (%)**
1	1	519	14	0.37	68	0	-
2	1	967	40	0.13	101	0	-
2	2	1006	29	0.34	137	0	-
3	1	1495	90	0.09	140	0	-
3	2	1469	64	0.16	173	0	-
4	1	2026	125	0.07	174	0	-
5	1	2573	151	0.06	206	0	-
5	2	2614	126	0.09	247	0	-
7	2	3987	153	0.08	320	0	-
9	3	5038	60	1	428	0	-
Q CO2 (gpm	**Q Water (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D. Stream Nozzle (psi)**	**T Upstream Nozzle (ºF)**	**T D.Stream Nozzle (ºF)**	**CTR (%)**
1	1	1931	5910	1910	168	156	0.96
2	1	1238	4865	865	110	74	0.979
2	2	1618	5173	1173	117	100	0.98
3	1	1260	4644	644	98	52	0.987
3	2	1532	4865	865	104	74	0.986
4	1	1413	4620	620	97	49	0.99
5	1	1616	4637	637	98	52	0.991
5	2	1998	4776	776	99	66	0.991
7	2	2764	4857	857	102	74	0.993
9	3	4505	5393	1393	84	77	0.988
Coiled Tubing O.D: 0.75 inch –Bore Hole Size: 1.75 inch							
Q CO_2 (gpm)	**Q Water (gpm**	**Maximum Mixture Velocity Annulus (ft/m)**	**Mixture Velocity Annulus (ft/m) 10,000 ft**	**Liquid Fraction After Nozzle (10,000ft)**	**Liquid Velocity Tubing (ft/m)**	**Total Hydrate (%)**	**Solid Phase (%)**
1	1	1144	30	0.35	143	0	-
2	1	2264	32	1	216	0	-
3	1	3875	42	1	291	0	-
3	2	4062	66	0.31	365	0	-
5	1	6740	88	1	513	3	-
Q CO2 (gpm)	**Q Water (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D.Stream Nozzle (psi)**	**T Upstream Nozzle (ºF)**	**T D.stream Nozzle (ºF)**	**CTR (%)**
1	1	2316	5469	1469	142	125	0.981
2	1	2649	5209	1209	94	86	0.986
3	1	3743	5284	1284	88	80	0.982
3	2	5594	5723	1723	137	123	0.991
5	1	10702	7167	3167	156	149	0.993

Table A-6: CO_2 with Water Influx Cases

Coiled Tubing O.D: 1.25 inch –Bore Hole Size: 2.25 inch							
Q CO_2 (gpm)	**Q Water (gpm**	**Maximum Mixture Velocity Annulus (ft/m)**	**Mixture Velocity Annulus (ft/m) 10,000 ft**	**Liquid Fraction After Nozzle (10,000ft)**	**Liquid Velocity Tubing (ft/m)**	**Total Hydrate (%)**	**Solid Phase (%)**
2	1	1497	62	1	59	0	-
3	1	2341	75	1	79	0	-
5	1	3830	94	1	118	0	-
7	1	5385	107	1	157	3.1	-
Q CO2 (gpm	**Q Water (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D. Stream Nozzle (psi)**	**T Upstream Nozzle (°F)**	**T D.Stream Nozzle (°F)**	**CTR (%)**
2	1	3137	7256	3256	205	196	0.995
3	1	2998	7045	3046	201	186	0.995
5	1	3173	7138	3138	196	179	0.995
7	1	3871	7819	3819	197	183	0.995
Coiled Tubing O.D: 1 inch –Bore Hole Size: 2.25 inch							
Q CO_2 (gpm)	**Q Water (gpm**	**Maximum Mixture Velocity Annulus (ft/m)**	**Mixture Velocity Annulus (ft/m) 10,000 ft**	**Liquid Fraction After Nozzle (10,000ft)**	**Liquid Velocity Tubing (ft/m)**	**Total Hydrate (%)**	**Solid Phase (%)**
2	1	1340	58	0.67	102	0	-
3	1	2067	74	0.52	135	0	-
5	1	3765	99	0.39	205	0	-
7	1	4735	103	1	273	0	-
Q CO2 (gpm)	**Q Water (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D.Stream Nozzle (psi)**	**T Upstream Nozzle (°F)**	**T D.stream Nozzle (°F)**	**CTR (%)**
2	1	2711	6580	2580	203	186	0.995
3	1	2552	6210	2210	195	168	0.994
5	1	2940	6170	2170	183	152	0.995
7	1	4053	6863	2863	187	165	0.995

Table A-6: Continuation

Coiled Tubing O.D: 1 inch –Bore Hole Size: 1.75 inch							
Q CO_2 (gpm)	**Q Water (gpm**	**Maximum Mixture Velocity Annulus (ft/m)**	**Mixture Velocity Annulus (ft/m) 10,000 ft**	**Liquid Fraction After Nozzle (10,000ft)**	**Liquid Velocity Tubing (ft/m)**	**Total Hydrate (%)**	**Solid Phase (%)**
1	1	1228	86	1	69	0	-
2	1	2638	102	1	102	0	-
3	1	4647	118	1	137	0	-
Q CO2 (gpm	**Q Water (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D. Stream Nozzle (psi)**	**T Upstream Nozzle (ºF)**	**T D.Stream Nozzle (ºF)**	**CTR (%)**
1	1	4376	8498	4498	209	211	0.995
2	1	4427	8507	4507	207	205	0.996
3	1	4708	8654	4654	206	202	0.996
Coiled Tubing O.D: 1 inch –Bore Hole Size: 2.5 inch							
Q CO_2 (gpm)	**Q Water (gpm**	**Maximum Mixture Velocity Annulus (ft/m)**	**Mixture Velocity Annulus (ft/m) 10,000 ft**	**Liquid Fraction After Nozzle (10,000ft)**	**Liquid Velocity Tubing (ft/m)**	**Total Hydrate (%)**	**Solid Phase (%)**
2	1	1038	46	0.65	101	0	-
3	1	1532	66	0.45	136	0	-
4	1	2235	92	0.33	171	0	-
5	1	2686	115	0.26	205	0	-
7	1	3656	133	0.22	278	0	-
Q CO2 (gpm)	**Q Water (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D.Stream Nozzle (psi)**	**T Upstream Nozzle (ºF)**	**T D.stream Nozzle (ºF)**	**CTR (%)**
2	1	2515	6352	2352	201	182	0.993
3	1	2223	5808	1808	191	153	0.993
4	1	2171	5512	1512	178	129	0.993
5	1	2282	5372	1372	165	114	0.993
7	1	2904	5413	1413	147	108	0.994
Coiled Tubing O.D: 0.75 inch –Bore Hole Size: 1.75 inch							
Q CO_2 (gpm)	**Q Water (gpm**	**Maximum Mixture Velocity Annulus (ft/m)**	**Mixture Velocity Annulus (ft/m) 10,000 ft**	**Liquid Fraction After Nozzle (10,000ft)**	**Liquid Velocity Tubing (ft/m)**	**Total Hydrate (%)**	**Solid Phase (%)**
1	1	1086	72	1	143	0	-
2	1	2349	87	1	211	0	-
3	1	3604	102	1	287	0	-
Q CO2 (gpm)	**Q Water (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D.Stream Nozzle (psi)**	**T Upstream Nozzle (ºF)**	**T D.stream Nozzle (ºF)**	**CTR (%)**
1	1	4825	7932	3932	209	208	0.995
2	1	4810	7661	3661	206	200	0.995
3	1	5949	7717	3717	203	194	0.996

Appendix B

Table B-1: Total Pressure Losses at Surface Coiled Tubing Unit (N_2 without Water)

Coiled Tubing O.D: 1.25 inch –Bore Hole Size: 2.25 inch				
Q N2 (gpm)	**Q Water (gpm)**	**Frictioal Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (psi/ft)**
1	-	0.0001067	0.00001	0.00012
2	-	0.0003667	0.00001	0.00038
3	-	0.0007933	0.00001	0.000807
4	-	0.0013733	0.00001	0.001387
5	-	0.0021067	0.00001	0.00212
7	-	0.0039867	0.00001	0.004
10	-	0.0083467	0.00001	0.00838
Coiled Tubing O.D: 1 inch –Bore Hole Size: 2.25 inch				
Q N2 (gpm)	**Q Water (gpm)**	**Frictioal Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (psi/ft)**
2	-	0.00143	0.00001	0.00145
3	-	0.00315	0.00001	0.00316
4	-	0.00547	0.00001	0.00549
5	-	0.00839	0.00001	0.00841
7	-	0.01694	0.00002	0.01696
10	-	0.03583	0.00002	0.03585
Coiled Tubing O.D: 1 inch –Bore Hole Size: 1.75 inch				
Q N2 (gpm)	**Q Water (gpm)**	**Frictioal Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (psi/ft)**
1	-	0.00037	0.00001	0.00039
2	-	0.00141	0.00002	0.00143
3	-	0.00306	0.00001	0.00307
5	-	0.00854	0.00002	0.00856
Coiled Tubing O.D: 1 inch –Bore Hole Size: 2.5 inch				
Q N2 (gpm)	**Q Water (gpm)**	**Frictioal Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (psi/ft)**
2	-	0.00142	0.00001	0.00143
3	-	0.00315	0.00001	0.00316
5	-	0.00845	0.00001	0.00847
6	-	0.01198	0.00001	0.01199
7	-	0.01713	0.00001	0.01715
10	-	0.03637	0.00001	0.03639

Table B-1: Continuation

Coiled Tubing O.D: 0.75 inch –Bore Hole Size: 1.75 inch				
Q N2 (gpm)	**Q Water (gpm)**	**Frictioal Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (psi/ft)**
1	-	0.00236	0.00001	0.00237
2	-	0.00905	0.00001	0.00907
3	-	0.02217	0.00001	0.02218
5	-	0.05915	0.00001	0.05917

Table B-2: Total Pressure Losses at Surface Coiled Tubing Unit(N_2 with Water Addition)

Coiled Tubing O.D: 1.25 inch –Bore Hole Size: 2.25 inch				
Q N2 (gpm)	**Q Water (gpm)**	**Frictioal Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (psi/ft)**
2	1	0.00853	0.03760	0.04613
2	3	0.00875	0.00079	0.00954
3	1	0.00943	0.02424	0.03367
4	1	0.01019	0.01422	0.02441
4	2	0.01550	0.01920	0.03470
5	1	0.01073	0.00787	0.01860
5	2	0.01637	0.01070	0.02707
6	1	0.01109	0.00393	0.01503
7	1	0.01153	0.00208	0.01361
7	2	0.01753	0.00314	0.02067
7	3	0.02327	0.00373	0.02699
10	1	0.01433	0.00033	0.01466
10	2	0.02078	0.00063	0.02141
Coiled Tubing O.D: 1 inch –Bore Hole Size: 2.25 inch				
Q N2 (gpm)	**Q Water (gpm)**	**Frictioal Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (psi/ft)**
2	1	0.01667	0.02072	0.03739
3	1	0.01823	0.00600	0.02423
3	2	0.02994	0.00619	0.03613
5	1	0.02142	0.00059	0.02201
5	2	0.03504	0.00085	0.03589
6	1	0.02425	0.00025	0.02451
8	1	0.03663	0.00003	0.03667
8	2	0.05507	0.00007	0.05514
10	1	0.05271	0.00001	0.05272

Table B-2: Continuation

Coiled Tubing O.D: 1 inch –Bore Hole Size: 1.75 inch				
Q N2 (gpm)	**Q Water (gpm)**	**Frictioal Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (psi/ft)**
2	1	0.01673	0.02107	0.03779
2	2	0.02451	0.01869	0.04320
3	1	0.01940	0.00865	0.02805
5	1	0.02413	0.00113	0.02525
5	2	0.04018	0.00209	0.04225
7	1	0.03345	0.00018	0.03363
Coiled Tubing O.D: 1 inch –Bore Hole Size: 2.5 inch				
Q N2 (gpm)	**Q Water (gpm)**	**Frictioal Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (psi/ft)**
2	1	0.01627	0.02380	0.04007
3	1	0.01831	0.00655	0.02487
3	2	0.02999	0.00660	0.03658
5	1	0.02130	0.00051	0.02181
5	2	0.03485	0.00070	0.03555
7	1	0.02907	0.00007	0.02915
8	1	0.03347	0.00004	0.03351
8	2	0.05549	0.00006	0.05555
10	1	0.05347	0.00002	0.05350
10	2	0.07487	0.00002	0.07487
Coiled Tubing O.D: 0.75 inch –Bore Hole Size: 1.75 inch				
Q N2 (gpm)	**Q Water (gpm)**	**Frictioal Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (psi/ft)**
2	1	0.05129	0.00179	0.05308
2	2	0.10800	0.00160	0.10960
3	1	0.06899	0.00026	0.06925
4	1	0.10094	0.00000	0.10093
4	2	0.18067	0.00000	0.18067
5	1	0.14927	0.00000	0.14927
7	1	0.26271	0.00000	0.26271

Table B-3: Total Pressure Losses at Surface Coiled Tubing Unit (N_2 Water Influx)

Coiled Tubing O.D: 1.25 inch –Bore Hole Size: 2.25 inch				
Q N2 (gpm)	**Q Water (gpm)**	**Frictioal Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (psi/ft)**
3	1	0.00881	0.02348	0.03229
4	1	0.01009	0.01619	0.02627
5	1	0.01133	0.01093	0.02227
7	1	0.01367	0.00460	0.01827
9	1	0.01647	0.00147	0.01793
Coiled Tubing O.D: 1 inch –Bore Hole Size: 2.25 inch				
Q N2 (gpm)	**Q Water (gpm)**	**Frictioal Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (psi/ft)**
3	1	0.01940	0.01213	0.03153
5	1	0.02567	0.00153	0.02720
7	1	0.03340	0.00020	0.03360
8	1	0.04000	0.00004	0.04004
Coiled Tubing O.D: 1 inch –Bore Hole Size: 1.75 inch				
Q N2 (gpm)	**Q Water (gpm)**	**Frictioal Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (psi/ft)**
2	1	0.01473	0.02233	0.03707
3	1	0.01893	0.01300	0.03200
5	1	0.03031	0.00247	0.03277
Coiled Tubing O.D: 1 inch –Bore Hole Size: 2.5 inch				
Q N2 (gpm)	**Q Water (gpm)**	**Frictioal Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (psi/ft)**
3	1	0.01967	0.01100	0.03067
5	1	0.02487	0.00127	0.02613
6	1	0.02820	0.00040	0.02860
9	1	0.04480	0.00007	0.04487
Coiled Tubing O.D: 0.75 inch –Bore Hole Size: 1.75 inch				
Q N2 (gpm)	**Q Water (gpm)**	**Frictioal Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (psi/ft)**
2	1	0.05493	0.00560	0.06053
3	1	0.07420	0.00080	0.07507
5	1	0.15440	0	0.15440
7	1	0.24773	0	0.24773

Table B-4: Total Pressure Losses at Surface Coiled Tubing Unit (CO_2 without Water)

Coiled Tubing O.D: 1.25 inch –Bore Hole Size: 2.25 inch				
Q CO2 (gpm)	**Q Water (gpm)**	**Frictioal Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (psi/ft)**
1	-	0.00022	0.00003	0.00025
2	-	0.00083	0.00003	0.00086
3	-	0.00179	0.00003	0.00182
5	-	0.00508	0.00003	0.00511
7	-	0.01007	0.00004	0.01011
10	-	0.02115	0.00004	0.02119
Coiled Tubing O.D: 1 inch –Bore Hole Size: 2.25 inch				
Q CO2 (gpm)	**Q Water (gpm)**	**Frictioal Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (psi/ft)**
1	-	0.00127	0.00005	0.00132
2	-	0.00493	0.00005	0.00498
3	-	0.01070	0.00005	0.01075
5	-	0.03026	0.00006	0.03032
7	-	0.06180	0.00006	0.06186
Coiled Tubing O.D: 1 inch –Bore Hole Size: 1.75 inch				
Q CO2 (gpm)	**Q Water (gpm)**	**Frictioal Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (psi/ft)**
1	-	0.00085	0.00003	0.00089
2	-	0.00342	0.00003	0.00346
3	-	0.00773	0.00002	0.00775
5	-	0.02212	0.00003	0.02216
7	-	0.04527	0.00003	0.04530
Coiled Tubing O.D: 1 inch –Bore Hole Size: 2.5 inch				
Q CO2 (gpm)	**Q Water (gpm)**	**Frictioal Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (psi/ft)**
2	-	0.00329	0.00003	0.00333
3	-	0.00720	0.00003	0.00723
4	-	0.01240	0.00003	0.01243
5	-	0.02047	0.00003	0.02050
7	-	0.04173	0.00004	0.04177
10		0.09347	0.00004	0.09353

Table B-4: Continuation

Coiled Tubing O.D: 0.75 inch –Bore Hole Size: 1.75 inch				
Q CO2 (gpm)	**Q Water (gpm)**	**Frictioal Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (psi/ft)**
1	-	0.00541	0.00003	0.00545
2	-	0.02293	0.00003	0.02297
3	-	0.05360	0.00004	0.05364
5	-	0.16920	0.00007	0.16927

Table B-5: Total Pressure Losses at Surface Coiled Tubing Unit (CO_2 with Water Addition)

Coiled Tubing O.D: 1.25 inch –Bore Hole Size: 2.25 inch				
Q CO2 (gpm)	**Q Water (gpm)**	**Frictioal Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (psi/ft)**
1	1	0.00185	0.00351	0.00535
1	2	0.00297	0.00058	0.00355
2	1	0.00333	0.00373	0.00707
2	2	0.00533	0.00173	0.00707
3	1	0.00500	0.00213	0.00713
3	2	0.00720	0.00180	0.00900
3	3	0.01187	0.00033	0.01220
5	1	0.00867	0.00040	0.00907
5	2	0.01260	0.00033	0.01293
5	4	0.02253	0.00007	0.02260
7	2	0.01873	0.00007	0.01880
7	3	0.02500	0.00007	0.02507
Coiled Tubing O.D: 1 inch –Bore Hole Size: 2.25 inch				
Q CO2 (gpm)	**Q Water (gpm)**	**Frictioal Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (psi/ft)**
1	1	0.00560	0.00207	0.00767
1	2	0.01147	0.00013	0.01160
2	1	0.01033	0.00227	0.01260
2	2	0.02027	0.00040	0.02067
3	1	0.01600	0.00073	0.01673
3	2	0.02740	0.00027	0.02767
4	1	0.02320	0.00007	0.02327
5	1	0.03187	0.00007	0.03193
5	2	0.04773	0.00000	0.04773
7	2	0.07680	0.00007	0.07687

Table B-5: Continuation

Coiled Tubing O.D: 1 inch –Bore Hole Size: 1.75 inch				
Q CO2 (gpm)	**Q Water (gpm)**	**Frictioal Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (psi/ft)**
1	1	0.00560	0.00100	0.00660
1	2	0.01220	0.00007	0.01227
2	1	0.01033	0.00060	0.01093
3	1	0.01613	0.00007	0.01620
3	2	0.02773	0.00000	0.02773
5	1	0.03147	0.00007	0.03153
Coiled Tubing O.D: 1 inch –Bore Hole Size: 2.5 inch				
Q CO2 (gpm)	**Q Water (gpm)**	**Frictioal Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (psi/ft)**
1	1	0.00560	0.00133	0.00693
2	1	0.01033	0.00240	0.01273
2	2	0.02027	0.00047	0.02073
3	1	0.01727	0.00073	0.01800
3	2	0.02713	0.00047	0.02760
4	1	0.02373	0.00013	0.02387
5	1	0.03127	0.00000	0.03127
5	2	0.04747	0.00007	0.04753
7	2	0.07660	0.00007	0.07667
9	3	0.13433	0.00007	0.13440
Coiled Tubing O.D: 0.75 inch –Bore Hole Size: 1.75 inch				
Q CO2 (gpm)	**Q Water (gpm)**	**Frictioal Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (psi/ft)**
1	1	0.03893	0.00013	0.03907
2	1	0.06173	0.00007	0.06180
3	1	0.10333	0.00007	0.10340
3	2	0.16420	0.00007	0.16427
5	1	0.32120	0.00007	0.32127

Table B-6: Total Pressure Losses at Surface Coiled Tubing Unit
(CO_2 with Water Influx)

Coiled Tubing O.D: 1.25 inch –Bore Hole Size: 2.25 inch				
Q CO2 (gpm)	**Q Water (gpm)**	**Frictioal Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (psi/ft)**
2	1	0.00260	0.00007	0.00267
3	1	0.00407	0.00007	0.00413
5	1	0.00820	0.00007	0.00827
7	1	0.01333	0.00007	0.01340
Coiled Tubing O.D: 1 inch –Bore Hole Size: 2.25 inch				
Q CO2 (gpm)	**Q Water (gpm)**	**Frictioal Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (psi/ft)**
2	1	0.01000	0.00007	0.01007
3	1	0.01580	0.00007	0.01587
5	1	0.03347	0.00007	0.03353
7	1	0.05553	0.00007	0.05560
Coiled Tubing O.D: 1 inch –Bore Hole Size: 1.75 inch				
Q CO2 (gpm)	**Q Water (gpm)**	**Frictioal Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (psi/ft)**
1	1	0.00767	0.00020	0.00787
2	1	0.00913	0.00007	0.00920
3	1	0.01553	0.00007	0.01560
Coiled Tubing O.D: 1 inch –Bore Hole Size: 2.5 inch				
Q CO2 (gpm)	**Q Water (gpm)**	**Frictioal Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (psi/ft)**
2	1	0.01013	0.00007	0.01020
3	1	0.01613	0.00007	0.01620
4	1	0.02360	0.00007	0.02367
5	1	0.03260	0.00007	0.03267
7	1	0.05827	0.00007	0.05833
Coiled Tubing O.D: 0.75 inch –Bore Hole Size: 1.75 inch				
Q CO2 (gpm)	**Q Water (gpm)**	**Frictioal Pres. Loss (psi/ft)**	**Hydrostatic Pres. Loss (psi/ft)**	**Total Pres. Loss (psi/ft)**
1	1	0.05260	0.00007	0.05267
2	1	0.05727	0.00007	0.05733
3	1	0.10187	0.00007	0.10193

APPENDIX C

Additional Runs to Fill the Gaps

In this part, WellFlo simulation results are given for drilling 10,000 ft wells with injecting nitrogen with water addition. Three different coiled tubing-hole size combinations are used for simulations. These combinations are: CT: 1''-HS: 2.25'', CT: 1.25''-HS: 3'' and CT: 0.75''-HS: 1.75''. Simulations were made two different cutting size which are 50 and 100 micron.

Table C-1 gives input conditions for the runs.

Table C-1: Input Parameters (10,000 ft)

	N_2 & Water
Depth (ft)	10,000
Formation	Sandstone
Geothermal Gradient (ºF/ft)	0.015
Surface Temperature (ºF)	60
Injected Fluid Temperature (ºF)	75
Return Choke Pressure (psia)	50
Nozzle Pressure Drop (psi)	4000
Cutting Size (micron)	25-100
ROP (ft/hour)	400

Figure C-1 is the operational envelope for CT: 0.5’’-HS:3’’ combination. In the graph, the vertical erosion line shows the maximum injection flow rates for the erosion velocity limit (1800 ft/min). Run points, left of the erosion line are for the conditions where the maximum mixture velocity of fluid in the annulus does not exceed erosion velocity limit.

Figure C-2 is injection pressure profile for the runs. Increasing injection flow rates increased the injection pressure in the system.

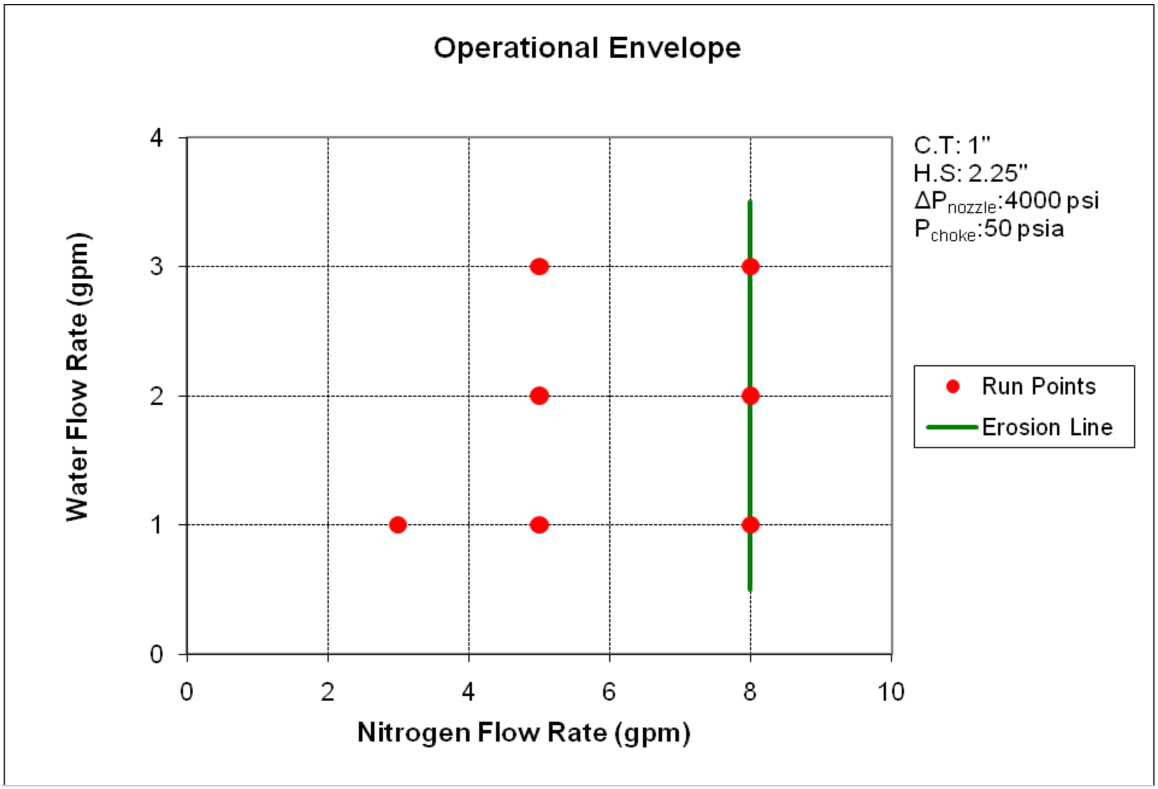


Figure C-1: Operational Envelope for N_2 with Water (CT: 1”-HS:2.25”, 10,000 ft)

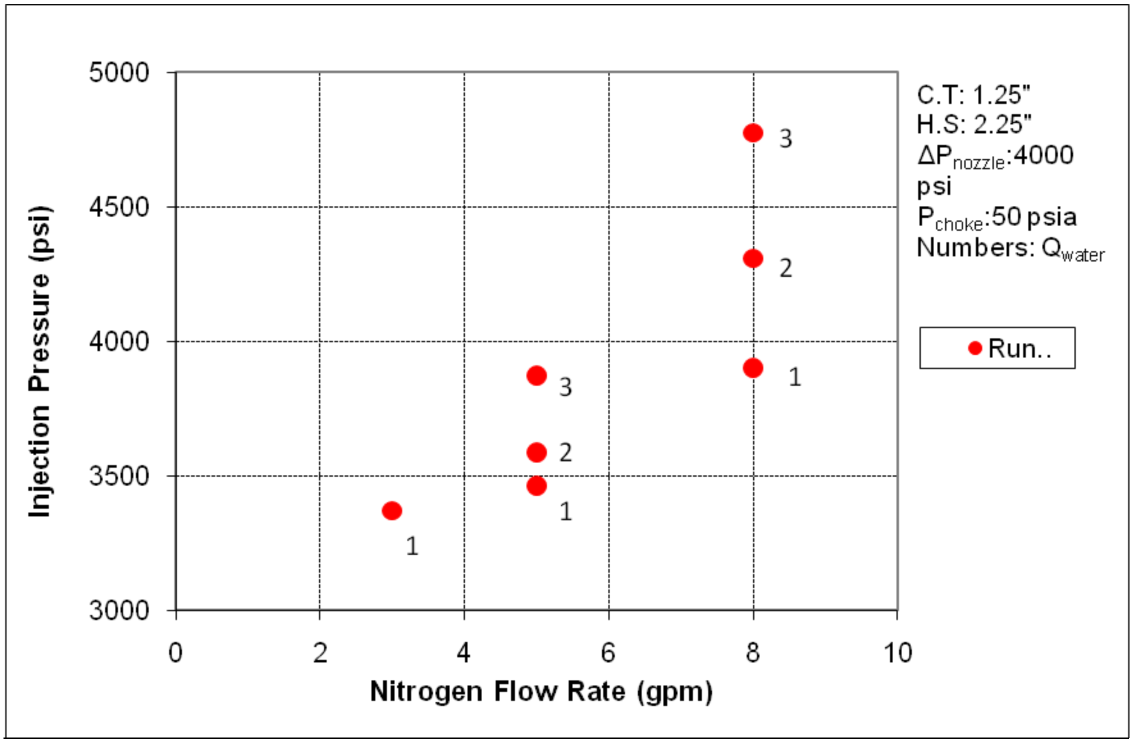


Figure C-2: Flow Rate vs. Inj. Pressure for N_2 with Water (CT: 1”-HS:2.25”, 10,000 ft)

Example pressure and temperature profile graph for nitrogen with water addition case is given for 5 gpm nitrogen and 1 gpm water flow rate in Figures C-3 and C-4, respectively. As seen in Figure C-3, the pressure drop of 4,000 psi occurs at the nozzle. Pressure outputs are given in Table C-2.

Table C-2: Output Press. Values (Nitrogen with Water, Q_{N2}=5 gpm,Q_w=1 gpm,10,000 ft)

Injection Pressure (psia)	3465
BHP Upstream Nozzle (psia)	4621
BHP Downstream Nozzle (psi)	621

Figure C-4 is the temperature profile of the fluid inside the coiled tubing and annulus with the formation temperature profile. The red line shows the temperature profile for fluid in the pipe and annulus and blue line shows the surrounding temperature profile. Selected output results for all other flow rate data are given after conclusions.

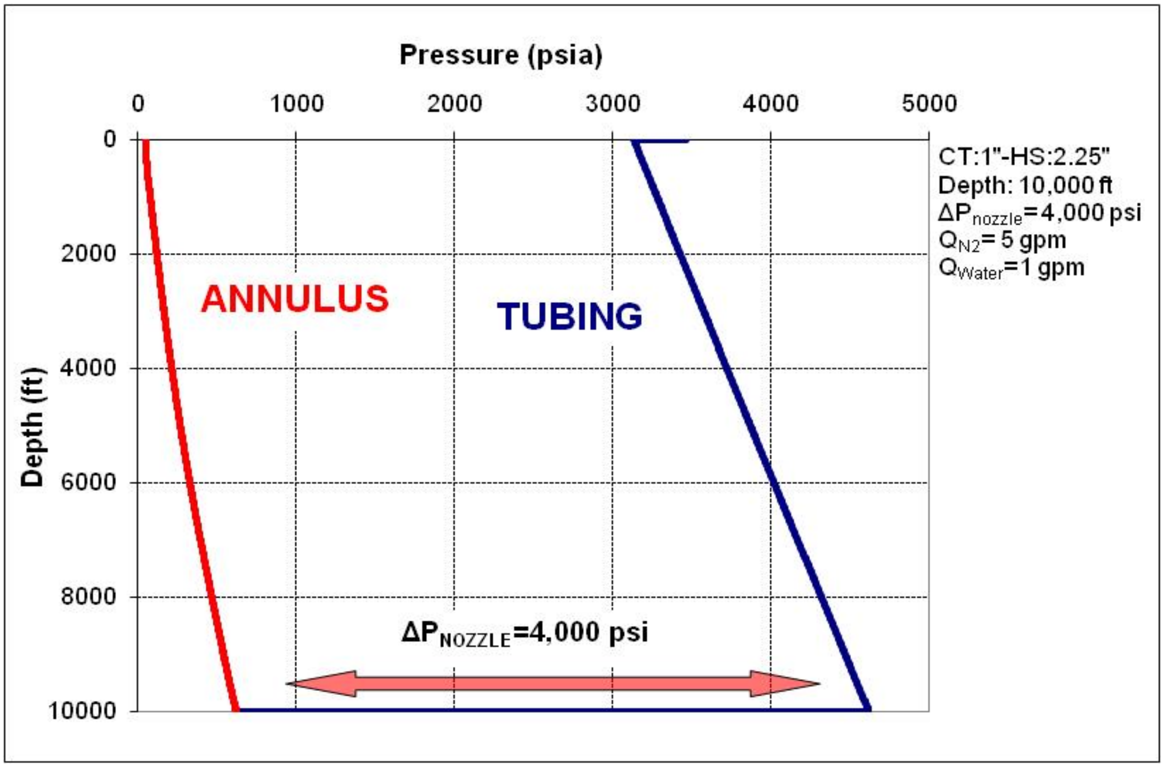


Figure C-3: Pressure vs Depth (CT:1”, H.S:2.25”, Q_{N2}: 5 gpm Q_w: 1 gpm, 10,000 ft)

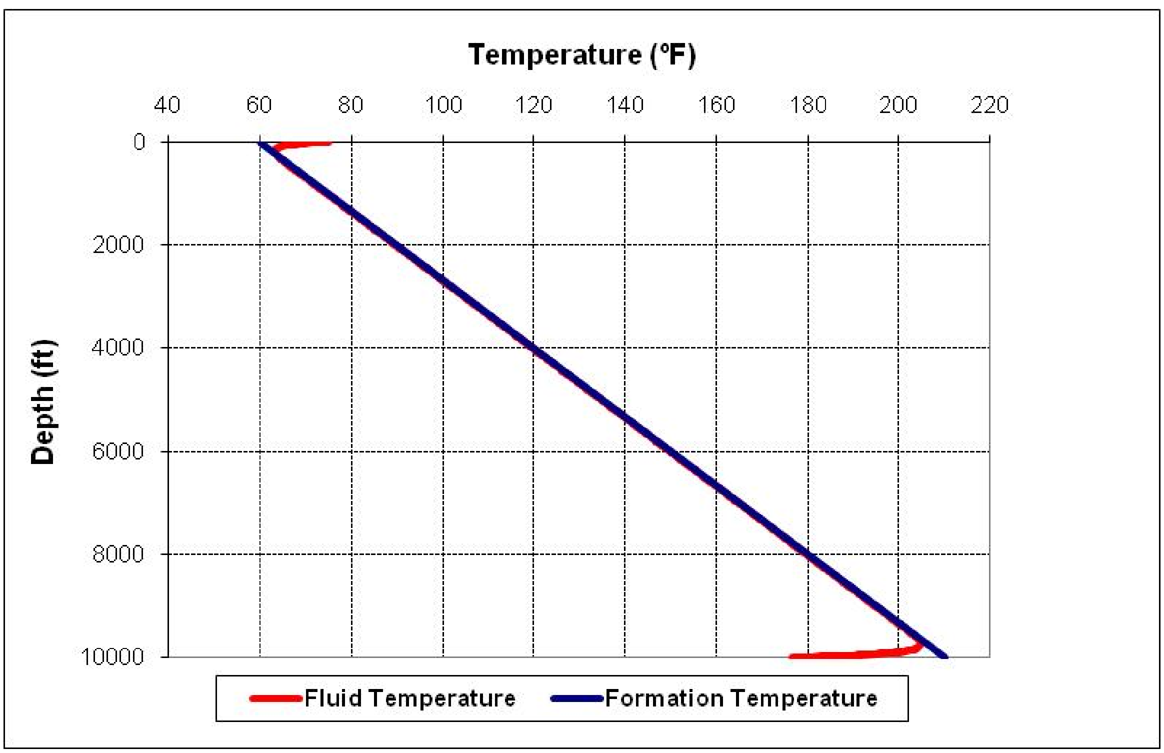


Figure C-4: Temperature vs Depth (CT:1”, H.S:2.25”, Q_{N2}: 5 gpm, Q_w: 1 gpm, 10,000 ft)

Figures C-5 through C-8 are operational envelopes and injection pressure profiles for CT: 1.25"-HS:2.25" and CT:0.75"-HS:1.75" combinations. As can be seen from the injection pressure profile graphs, due to the higher frictional pressure loss in smaller size coiled tubing, injection pressures are higher for 0.75" coiled tubing size.

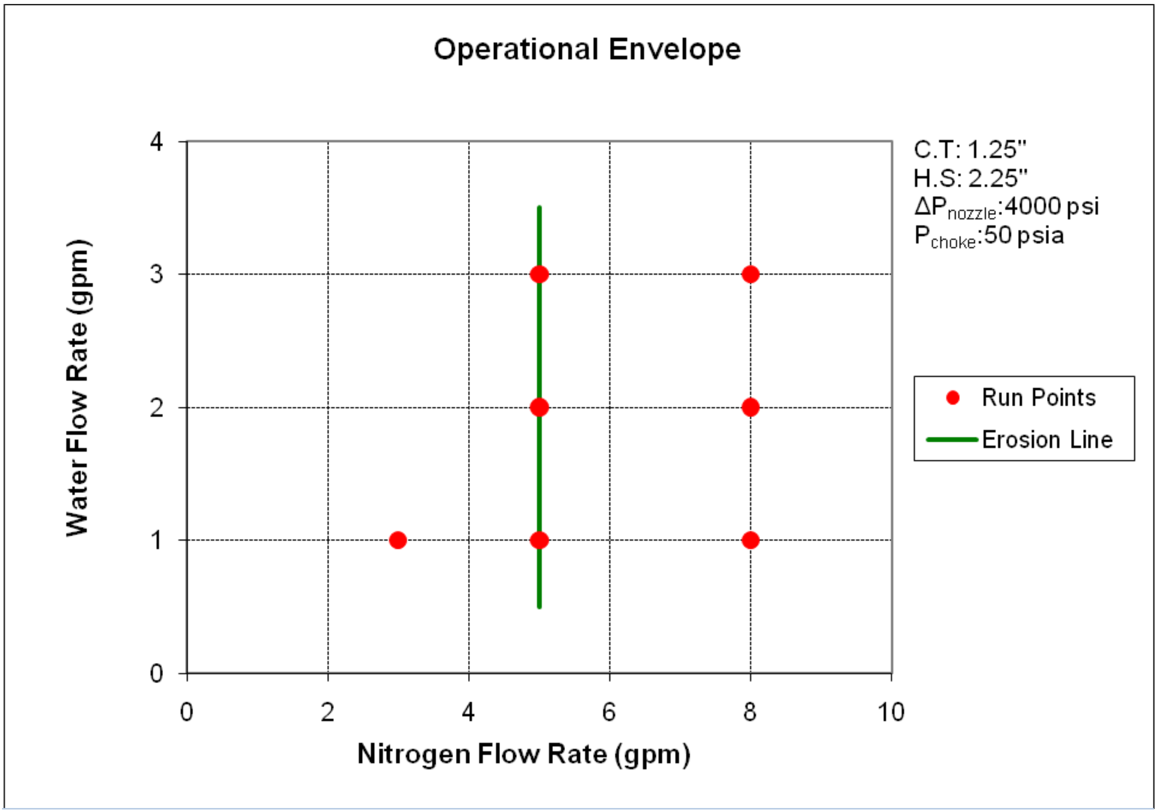


Figure C-5: Operational Envelope for N_2 with Water (CT: 1.25”-HS:2.25”, 10,000 ft)

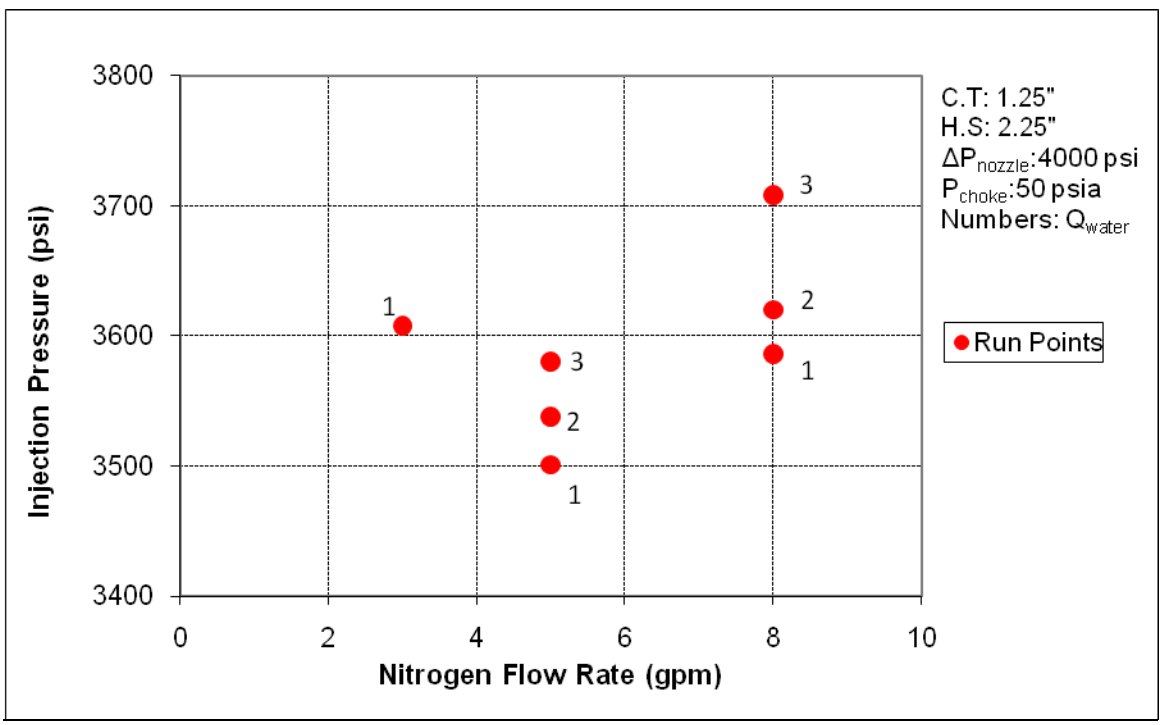


Figure C-6: Flow Rate vs. Inj. Pressure for N_2 with Water (CT: 1.25”-HS:2.25”,10,000 ft)

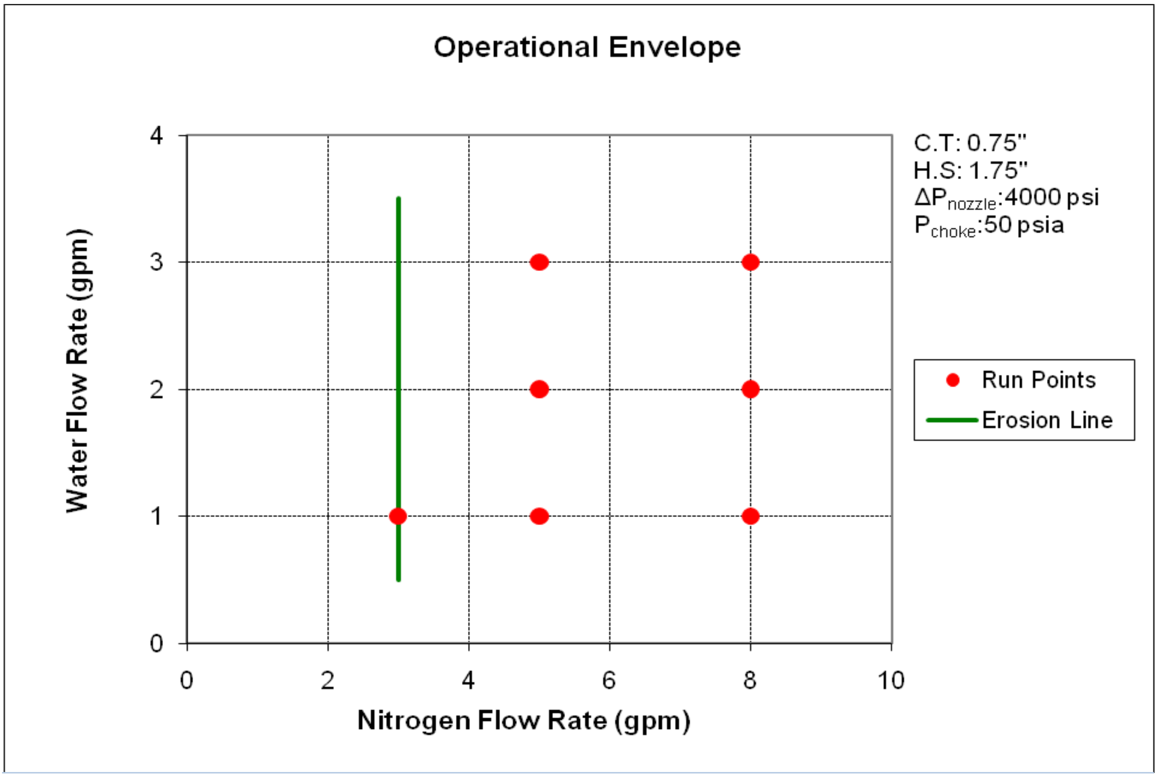


Figure C-7: Operational Envelope for N_2 with Water (CT: 0.75”-HS:1.75”, 10,000 ft)

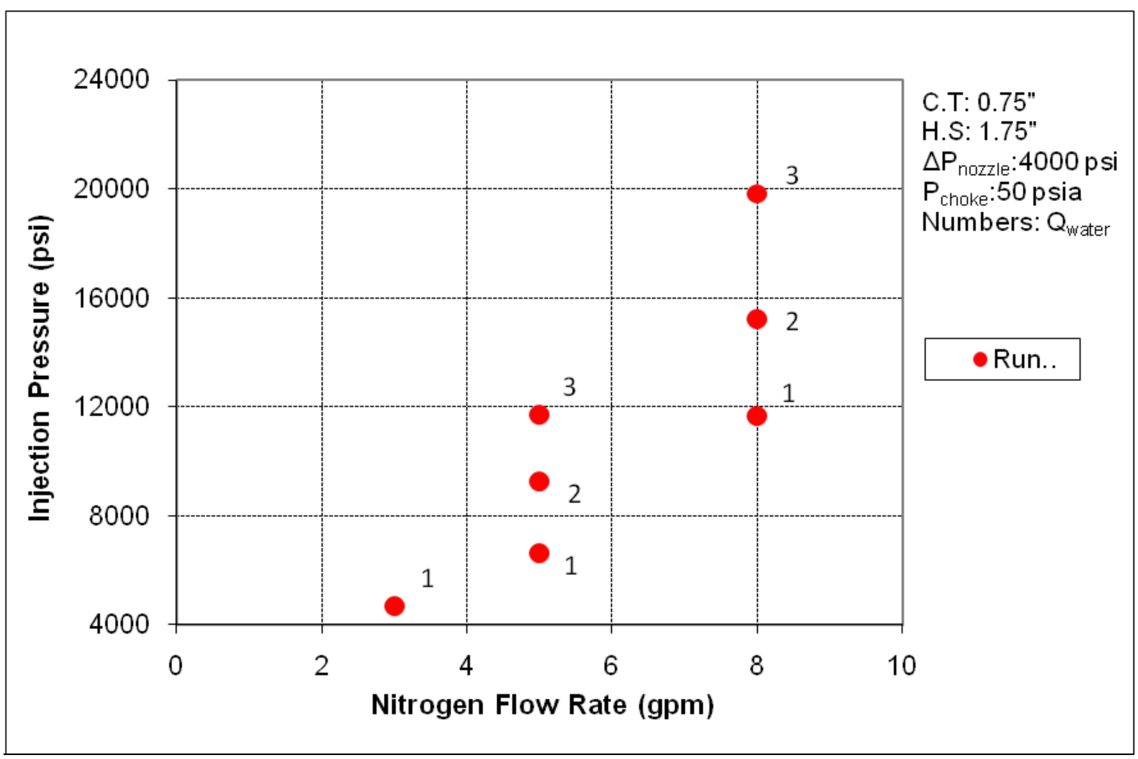


Figure C-8: Flow Rate vs. Inj. Pressure for N_2 with Water (CT: 0.75”-HS:1.75”,10,000 ft)

CONCLUSIONS

Nitrogen with water addition:

- ✓ Nitrogen is injected with different amount of water into the system.
- ✓ Three different coiled tubing-hole size combinations were used for the simulations.
- ✓ Nitrogen is in liquid phase after the nozzle at the bottom of the well for few runs.
- ✓ Cutting transport ratio is higher than 0.8 for all the runs.
- ✓ Increasing flow rates increased the injection pressures.

Table C-3: Output for Nitrogen with water addition (10,000 ft)

Coiled Tubing O.D: 1 inch –Bore Hole Size: 2.25 inch							
Q N_2 (gpm)	**Q Water (gpm**	**Maximum Mixture Velocity Annulus (ft/m)**	**Liquid Fraction After Nozzle (10,000 ft)**	**Liquid Velocity Tubing (ft/m)**	**CTR (50 Micron)**	**CTR (100 Micron)**	
3	1	925	0.11	156	0.941	0.882	
5	1	1669	0.01	229	0.966	0.931	
8	1	2543	0.1	338	0.982	0.964	
5	2	1611	0.1	270	0.963	0.927	
5	3	1650	0.14	313	0.964	0.929	
8	2	3080	0.13	409	0.983	0.967	
8	3	3141	0.16	462	0.984	0.969	
Q N2 (gpm)	**Q Water (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D. Stream Nozzle (psi)**	**T Upstream Nozzle (°F)**	**T D.Stream Nozzle (°F)**	
3	1	3371	4826	826	205	204	
5	1	3465	4621	621	182	176	
8	1	3902	4606	605	157	147	
5	2	3588	4853	853	210	210	
5	3	3874	5069	1069	223	226	
8	2	4310	4754	754	185	181	
8	3	4775	4896	896	200	199	
Coiled Tubing O.D: 1.25 inch –Bore Hole Size: 2.25 inch							
Q N_2 (gpm)	**Q Water (gpm**	**Maximum Mixture Velocity Annulus (ft/m)**	**Liquid Fraction After Nozzle (10,000 ft)**	**Liquid Velocity Tubing (ft/m)**	**CTR (50 Micron)**	**CTR (100 Micron)**	
3	1	1118	0.1	90	0.938	0.875	
5	1	1842	0.07	132	0.961	0.922	
8	1	2861	0.12	200	0.982	0.964	
5	2	1874	0.11	156	0.961	0.922	
5	3	1802	0.17	179	0.966	0.931	
8	2	2871	0.18	224	0.983	0.966	
8	3	2850	0.1	246	0.975	0.95	
Q N2 (gpm)	**Q Water (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D. Stream Nozzle (psi)**	**T Upstream Nozzle (°F)**	**T D.Stream Nozzle (°F)**	
3	1	3608	5013	1013	209	209	
5	1	3501	4844	844	192	188	
8	1	3586	4795	795	170	162	
5	2	3538	5142	1142	215	217	
5	3	3580	5380	1380	226	231	
8	2	3620	4994	994	198	196	
8	3	3708	5208	1208	214	216	

Table C-3: Continuation

Coiled Tubing O.D: 0.75 inch –Bore Hole Size: 1.75 inch							
Q N_2 (gpm)	**Q Water (gpm**	**Maximum Mixture Velocity Annulus (ft/m)**	**Liquid Fraction After Nozzle (10,000 ft)**	**Liquid Velocity Tubing (ft/m)**	**CTR (50 Micron)**	**CTR (100 Micron)**	
3	1	2029	0.23	346	0.978	0.956	
5	1	4759	0.12	529	0.984	0.969	
8	1	7827	0.09	761	0.987	0.975	
5	2	4619	0.16	633	0.986	0.972	
5	3	4592	0.11	688	0.982	0.964	
8	2	9636	0.07	819	0.984	0.968	
8	3	9434	0.1	892	0.985	0.969	
Q N2 (gpm)	**Q Water (gpm)**	**Injection Pressure (psi)**	**BHP Upstream Nozzle (psi)**	**BHP D. Stream Nozzle (psi)**	**T Upstream Nozzle (ºF)**	**T D.Stream Nozzle (ºF)**	
3	1	4682	4926	926	202	200	
5	1	6621	4925	925	175	168	
8	1	11657	5441	1441	166	157	
5	2	9257	5245	1245	201	199	
5	3	11695	5592	1592	218	220	
8	2	15230	6187	2187	204	203	
8	3	19827	7015	3015	224	227	

APPENDIX D

Combined Plots

In this part, relevant part 2.2 graphs (Nitrogen with water addition) are updated with additional runs from Appendix C. Figure D-1 through D-6 give operational envelopes and injection pressure profiles for given coiled tubing and hole size combination.

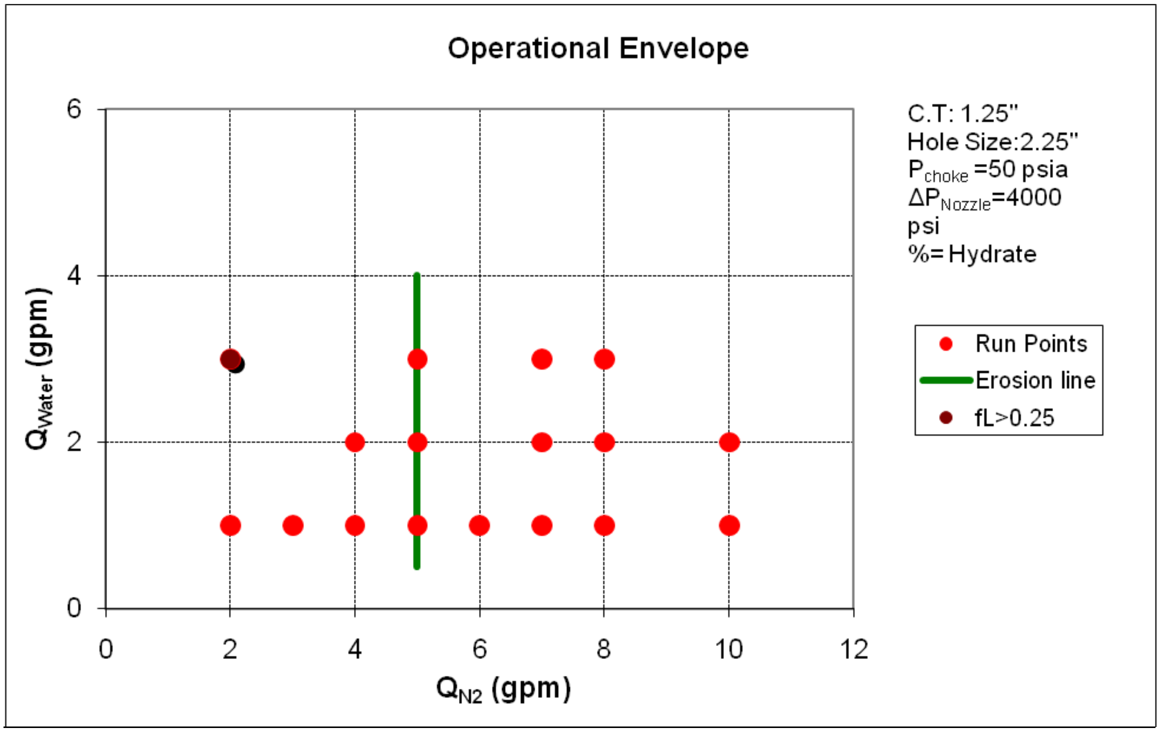


Figure D-1: Operational Envelope for updated N_2 with Water (CT: 1.25"-HS:2.25")

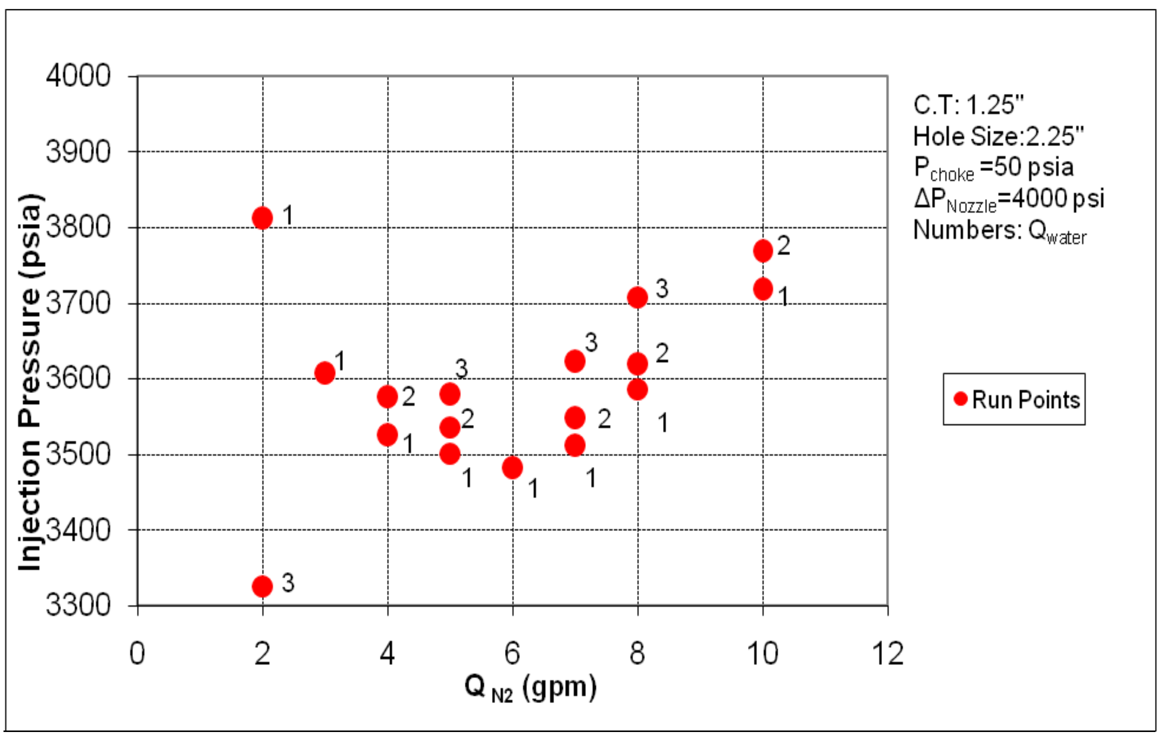


Figure D-2: Flow Rate vs. Inj. Pressure for updated N_2 with Water (CT: 1.25"-HS:2.25")

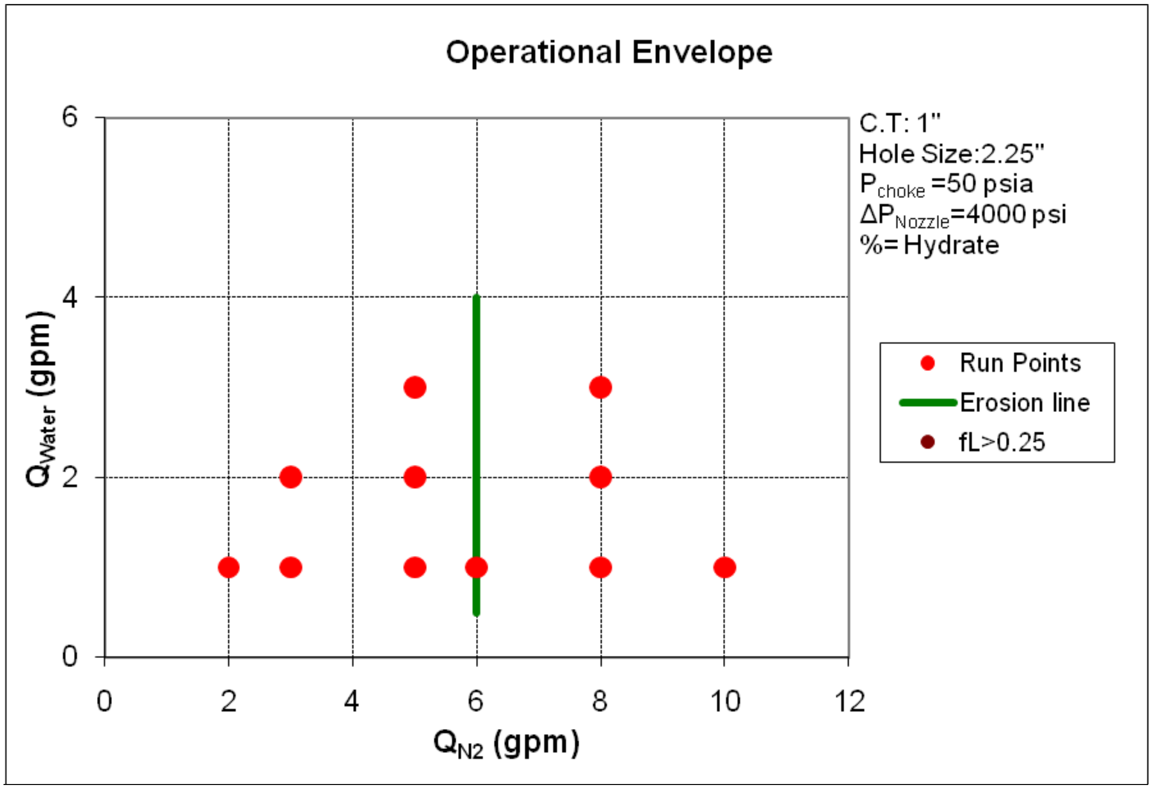


Figure D-3: Operational Envelope for updated N_2 with Water (CT: 1”-HS:2.25”)

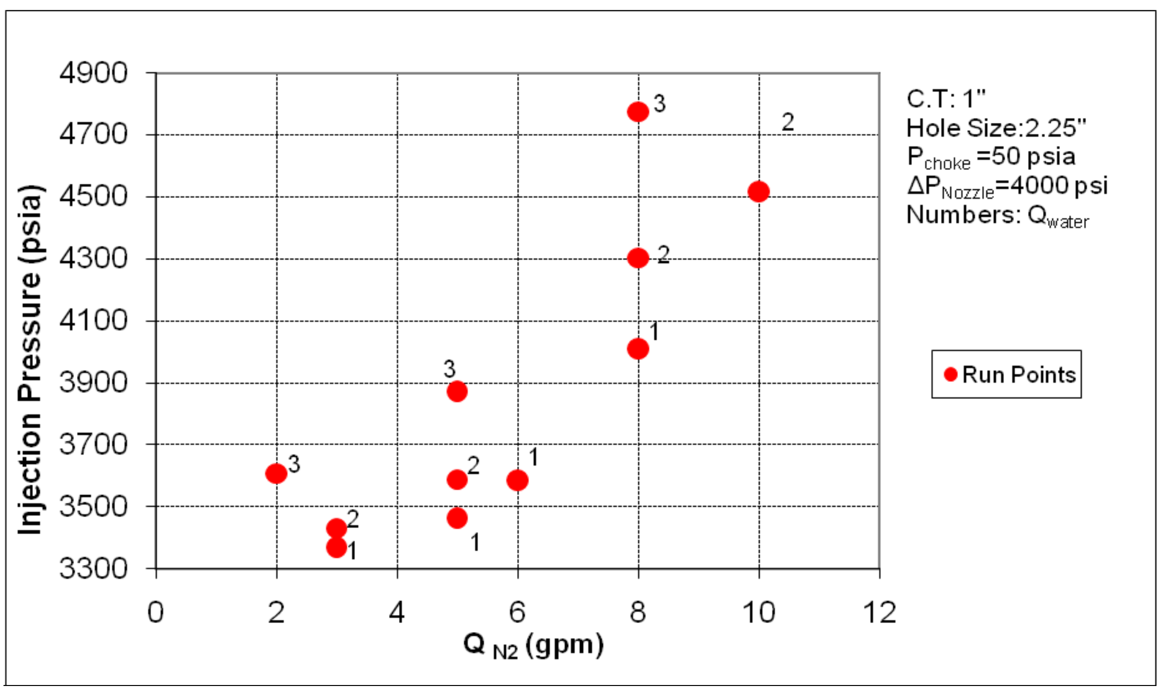


Figure D-4: Flow Rate vs. Inj. Pressure for updated N_2 with Water (CT: 1”-HS:2.25”)

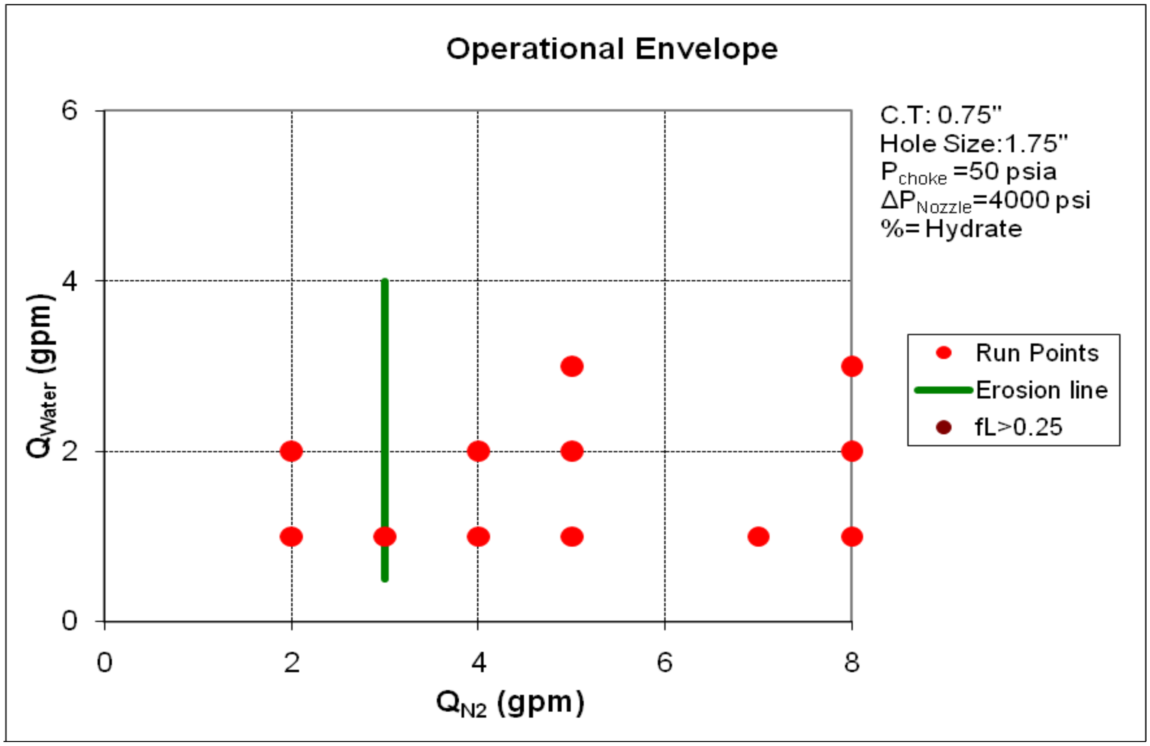


Figure D-5: Operational Envelope for updated N_2 with Water (CT: 0.75”-HS:1.75”)

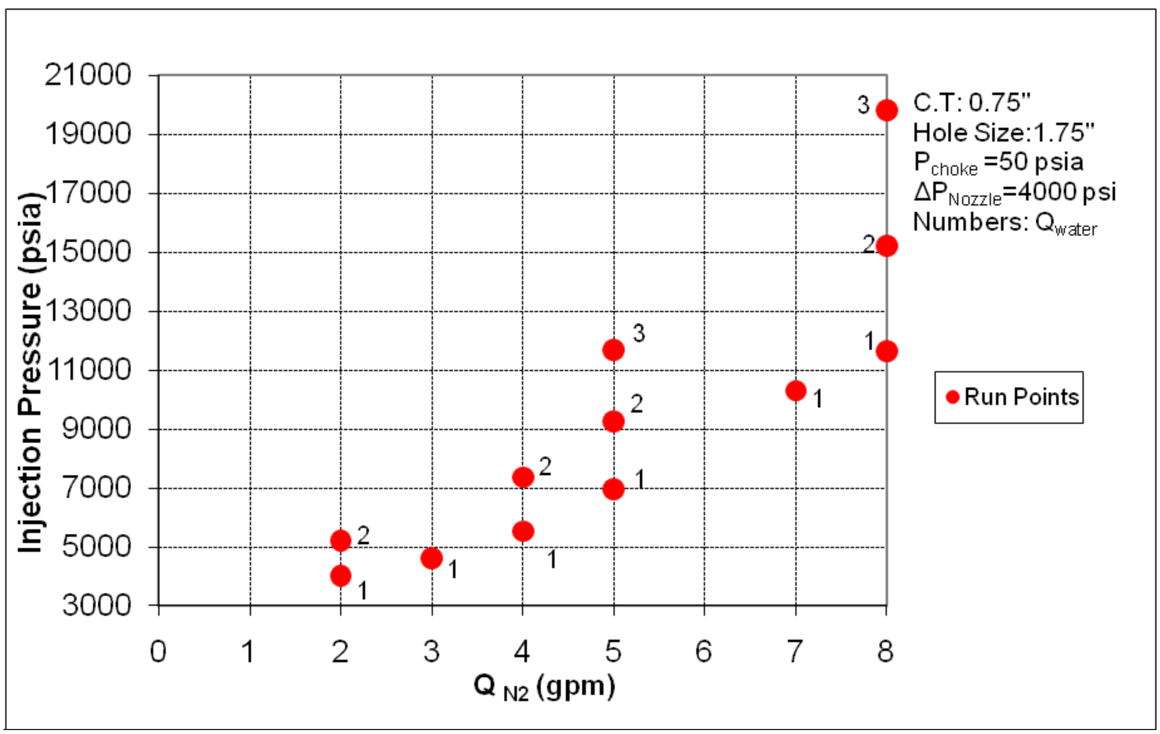


Figure D-6: Flow Rate vs. Inj. Pressure for updated N_2 with Water (CT: 0.75”-HS:1.75”)