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In-Line Multiphase Flow Measurement – Permian Basin, Texas Field Trial

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1 Introduction

Pietro Fiorentini's Multiphase Flow Meter (MPFM) Mobile Unit successfully measured oil, water and gas flow rates simultaneously from vertical wells producing to a Chevron central tank battery near Midland – Odessa, Texas. This field trial, conducted over 10 days in November 2013, focused on wells producing from the Wolfberry zones; the Wolfberry will be the subject of significant future drilling in the Permian Basin. The flow conditions in this area are particularly challenging: high gas void fractions (GVF) (>95%), low pressures (50 - 100 psi), variable water-cut (40% - 80%), tight emulsions, severe slug flow, large flow velocity turndowns (5 - 30 m/s), and highly varying flow temperatures (39 – 102 °F; 4 - 34 °C).

A new dedicated Multiphase Flow meter was designed and built to be suitable for this flow condition and to fulfill the requirements for this area. The MPFM configuration included a flow velocity module, impedance section, fast-gamma densitometer, Venturi mass flow meter, and a near-infrared water-cut meter. Flow conditions, fluid properties and and piping configurations determined that the flow velocity module and impedance section were not required to obtain the most accurate results. The MPFM is an in-line meter without the environmental risks of separators. (See picture on page 5)

MPFM metering flow rates agreed with results from a test separator equipped with both Coriolis and turbine meters on all flow legs three legs from the separator. The agreed upon target for MPFM measurements was +/- 10% of Coriolis flow rates on each phase.

Ten of the eleven subject wells were near or within the +/- 10% measurement target; the cause of the outlying measurement is not known and requires further investigation. The MPFM produced excellent water-cut measurements in comparison water-cut results from fluid samples; superior to the water-cuts yielded from the Coriolis and turbine meters, a significant advantage for the MPFM.

The MPFM provided real time data showing the slugging and variations in water liquid ratios and liquid gas ratios common, which seemed common for this set of wells. This information has been useful in reservoir assessment and management.

In conclusion, the MPFM was shown to provide results in agreement with, and in some cases superior to, conventional well tests with tests separators. Further work to identify ways to improve reservoir management and optimize production based on MPFM results are expected to add value to development in the Permian Basin. Future work will also focus on MPFM measurements of horizontal hydraulically fractured wells.

2 Observations and Results (a detailed report of data is listed in the Discussion section)

A 1.3 inch bore multiphase flow meter equipped with a gamma densitometer, near infrared (NIR) water-cut meter, and the Venturi were able to provide accurate MPFM measurements, without the need of neither the impedance section nor the flow velocity module that were also included on the meter. (This meter was equipped with all the measurement components available so we could determine optimal performance).

- The NIR water-cut meter was accurate within +/-5% when compared to water-cut measurements from samples despite a very stable emulsion flowing through the meter.

- MPFM results clearly showed the real time slugging and water-cut changes in real time that are not observable with when using the well test separator.

- The NIR water-cut meter, Venturi and gamma densitometer provided all of the information necessary to obtain accurate real-time flow measurements.

  - The flow velocity module was not applicable given the absence of a "wet gas" flow regime. Effectiveness of the impedance section, measuring conductivity or capacitance, was limited by flow characteristics such as piping configurations, flow conditions and fluid properties. Although their inclusion with the other components may provide benefits in most flow conditions in the future, it remains to be seen if these conditions exist with the Wolfberry production zones, which are the primary focus of this work.

- Total liquid rates for all three measurement devices were in general agreement.

  - Eight of eleven wells varied less than +-8% from the Coriolis meter.
  - Two wells, Well 9 and Well 11, varied from the Coriolis results by about 14%.
  - One well, 10, where the MPFM report a total liquid flow rate 21% lower than the Coriolis meter. The cause of this large variation is not understood at this time.

- Because the total liquid rates were in general agreement, variations in water and oil rates are largely the result of variations in water-cut measurements.

- By comparing the results of all three meters with water-cuts measured on samples showed:
  - The NIR water-cut meter on the MPFM yielded the best match with results on actual sample (water-cut measurements on samples were the result of centrifugation assisted by heat and a drop of demulsifier).
  - Water-cuts calculated from Coriolis results were uniformly lower than the sample measurements.
  - The turbine meter yielded a high level of variation from the sample measurements in three wells, with the largest deviation being about 61%.

- Gas measurements by MPFM and Coriolis matched very well for all wells tested, with less than 10% deviation. The deviation between turbine and Coriolis showed a greater range with 5 of 11 wells showing greater than 10% difference. The Turbine meter yielded gas rates higher that the MPFM and Coriolis in a number of wells.

- Deviations between MPFM and Coriolis showed no significant bias except for the water-cut and water production rates, where the Coriolis was consistently lower than the results from the MPFM.

- Differences between the MPFM and Coriolis results were not correlated with the GVF even though the GVF often extended above the 97% level.

- Examples of continuous multiphase flow rates indicate some wells exhibit highly irregular flow with slugging. In some cases, the flow patterns indicated potential production issues that could warrant further investigation to improve the efficiency of well inflow and surface flow.

3 Data and Discussion

The discussion is organized in three sections as follows:

1. MPFM Equipment Deployed
2. Stability of Produced Emulsion and Impact on Measurement
3. Data Plots
4. Production Flow Profiles
5. Data Tables

3.1 MPFM Equipment

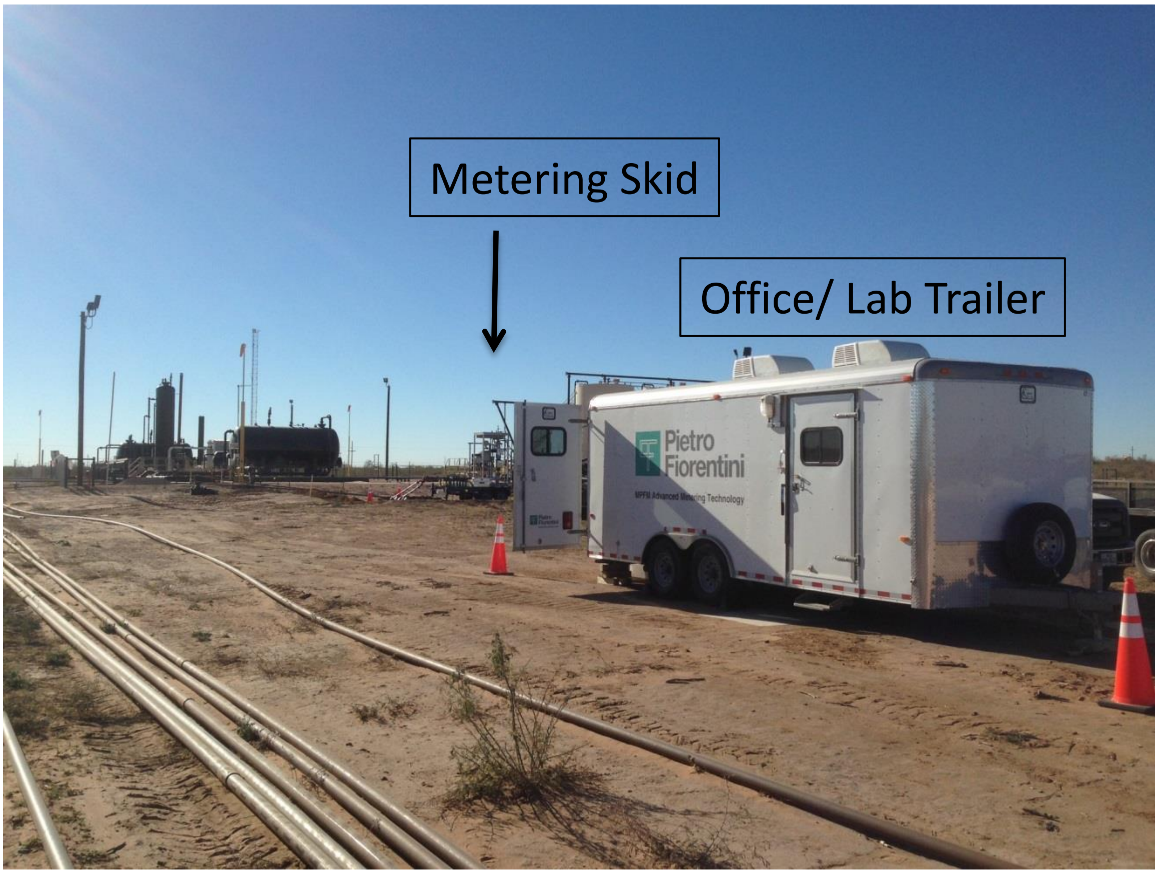


Figure 1: Office / Lab Trailer with Metering Skid connected to flow manifold.

The metering equipment includes a metering skid for mounting the MPFM, hydro-test equipment, and the choke manifold. The meter is connected to the production header with conventional pipes and fittings. A generator contained in the office/lab trailer powers the meter. The data link between the meter and the office/lab is established through the redundant systems of Wi-Fi and Ethernet cable. The Office/Lab trailer is located in a safe area away from sources of hydrocarbon and H_2S gases. The metering skid and its components, located near natural gas sources, is either intrinsically safe or explosion proof.

Following is a picture of the metering skid showing the connection to the production header. Because wells were producing at low pressure (50 – 100 psig), the manifold was configured to bypass the chokes.

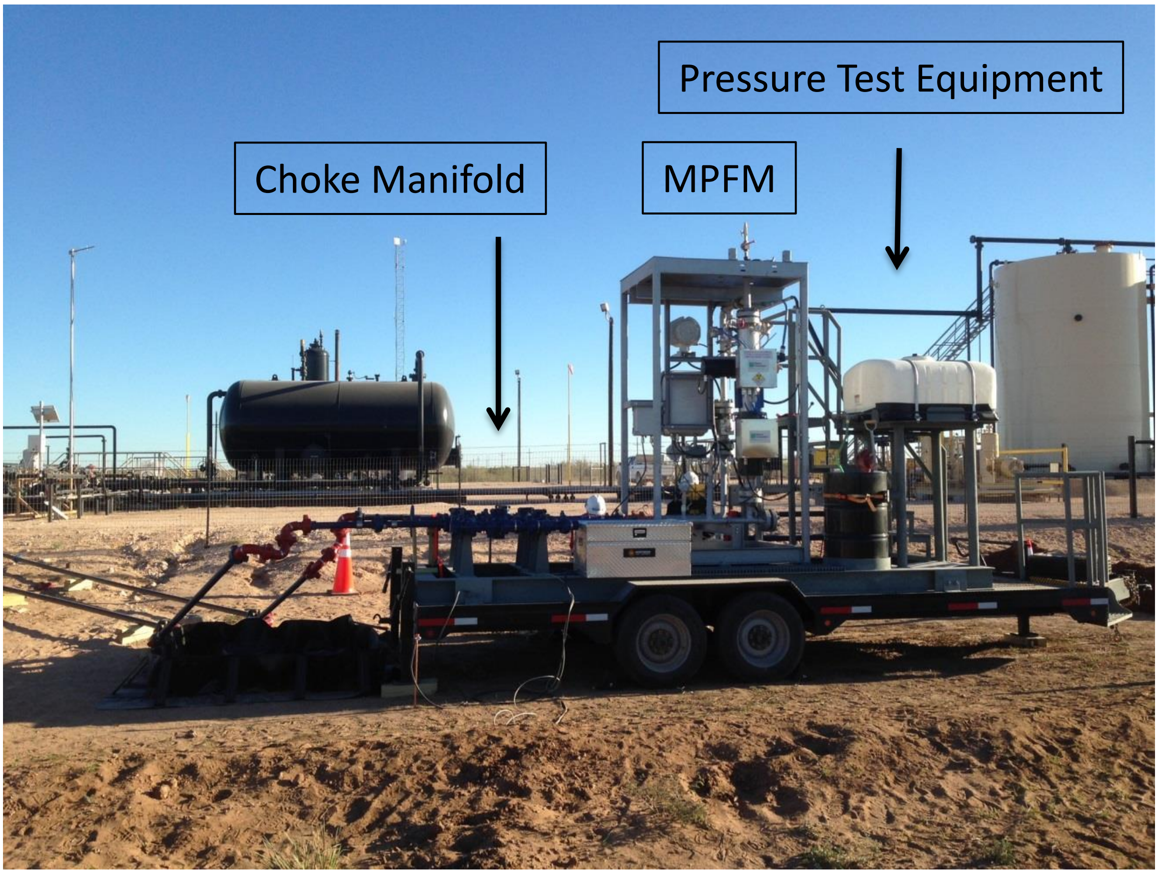


Figure 2: Intrinsically safe metering skid connected to flow manifold.

Below, the meter used in the field trial is detailed with labels identifying the components:

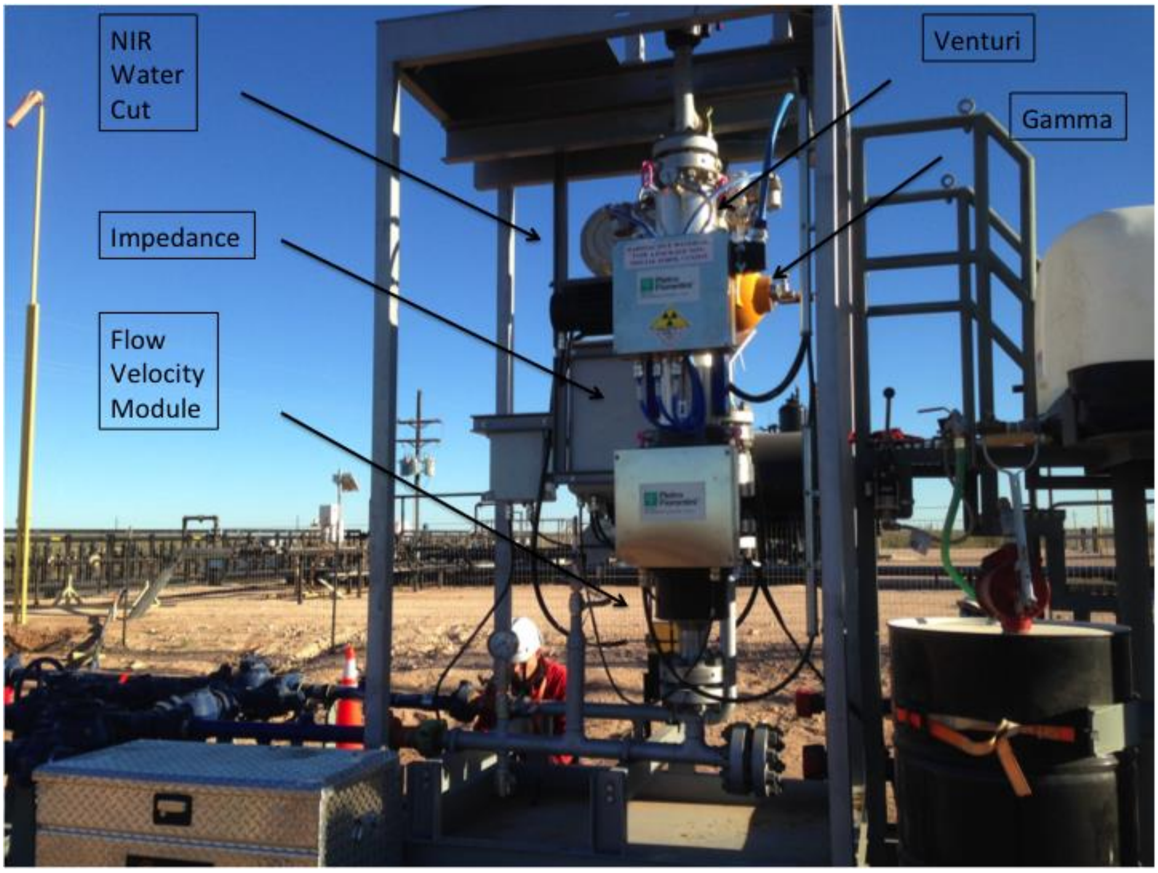


Figure 3: Metering elements.

Following is the well test separator with Coriolis meters and turbine meters on all three legs of the separator.

Figure 4: Well test separator instrumented with Coriolis Meters and Turbine Meters.

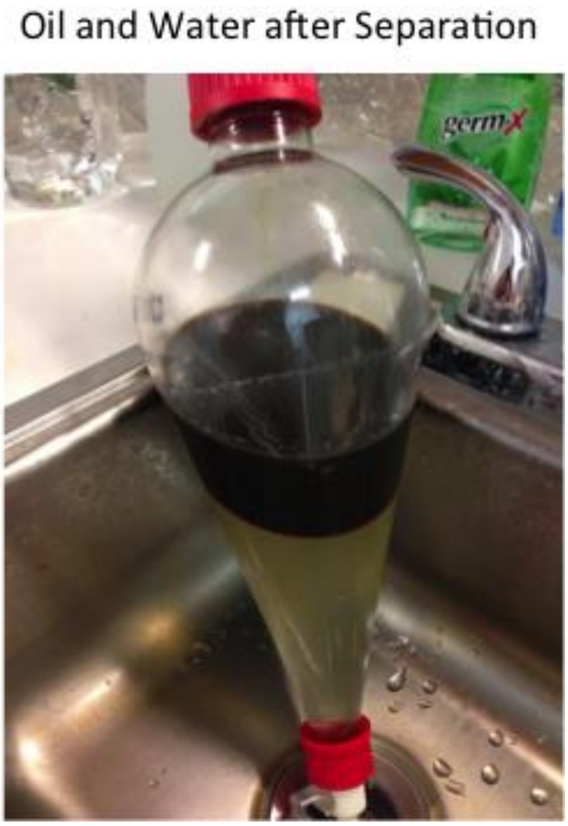
3.2 Stability of emulsion and impact on measurements

All wells produced very stable emulsions that required heat, demulsifier and centrifugation in order to break adequately for water-cut measurement. The flowing temperature of the production fluids was low and even near freezing for a number of days perhaps adding to emulsion stability. In addition, small wax particles as observed on the sides of glass containers of oil and water may have stabilized the emulsion further.

We observed that the impedance section was ineffective in measuring flow properties during certain periods of time. It is possible that the unusually stable emulsion flowing through a small sensor diameter combined with low flow temperature impacted performance of the impedance section. We observed that the impedance section yielded good results at times in cases where the emulsion was not as stable as others. We also verified the impedance sensor worked normally after the tests, when the meter was filled with lease water and also checked with empty pipe flow calibration.

However, the NIR yielded excellent water-cut results by measuring the emulsified oil and water in-line.

Following are pictures of the emulsion as it is produced and oil and water after separation.



Figures 5: Produced Emulsion **Figure 6: Broken Emulsion**

3.3 Data Plots – All Flow Rates Stated at Standard Conditions

3.3.1 Total Liquid Flow Rates

Figure 7: Comparison of liquid flow rate from MPFM compared with Coriolis - Outlying well is Well 10.

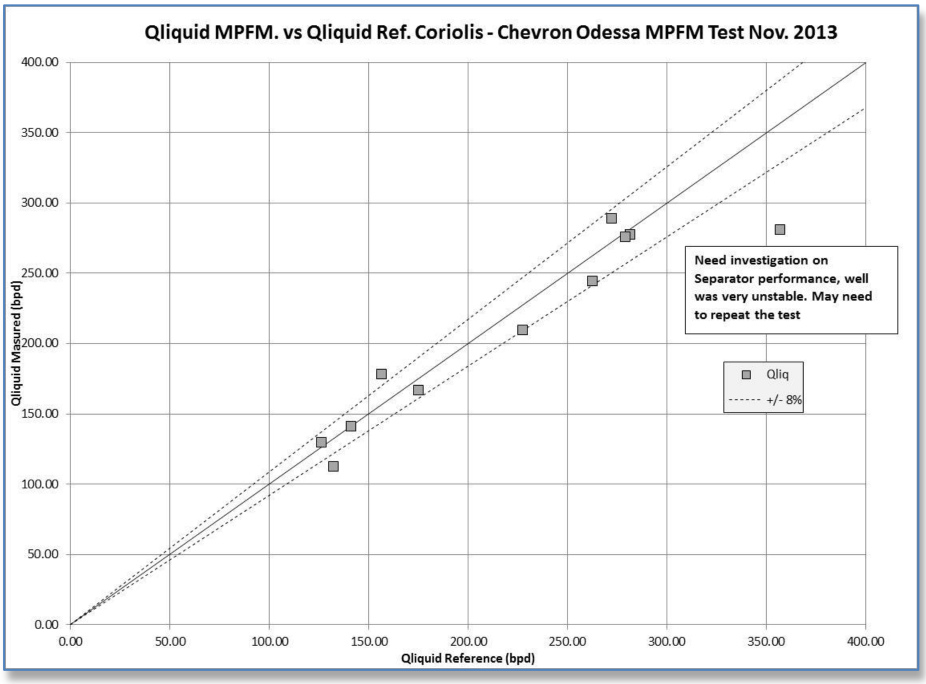


Figure 8: The following plot displays the total liquid production for each well as measured by MPFM, Coriolis, and Turbine

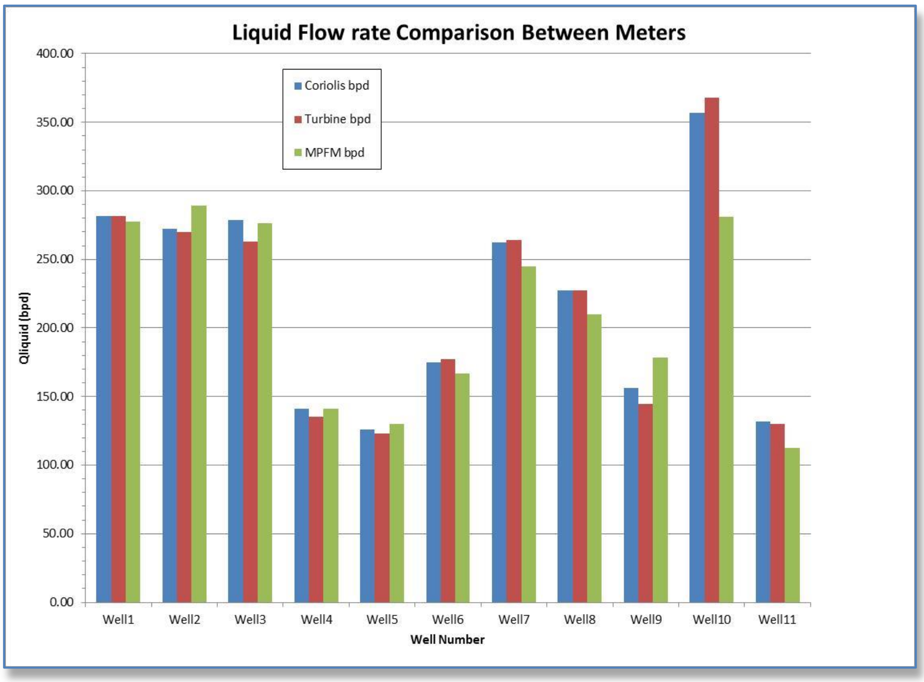
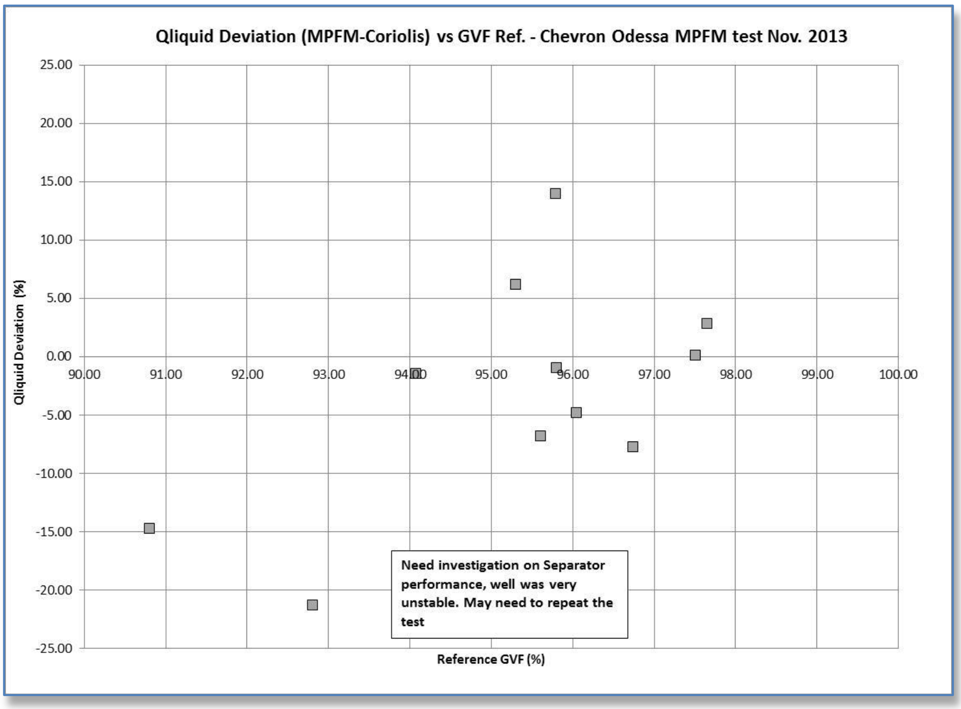


Figure 9: The plot below shows that the deviation between MPFM and Coriolis Meter is not correlated with %GVF (existence of a correlation would suggest GVF% as a possible source of error)



3.3.2 Water-cut Measurements

Figure 10: The Water Liquid Ratio (WLR) measured with the MPFM matches within +-5% of WLR measured on physical samples via separation of oil and water by heated centrifugation.

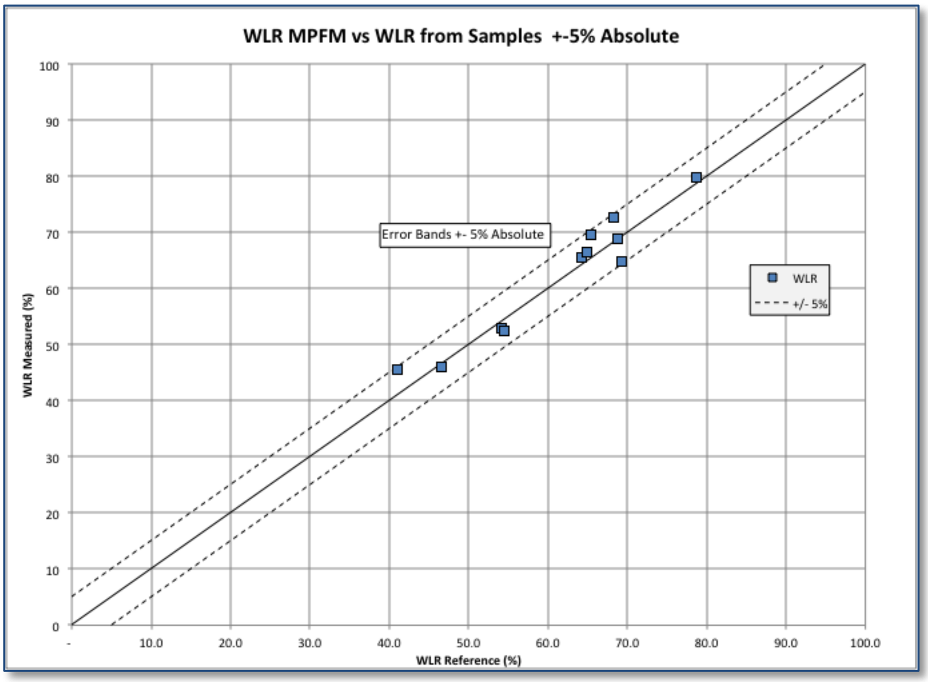
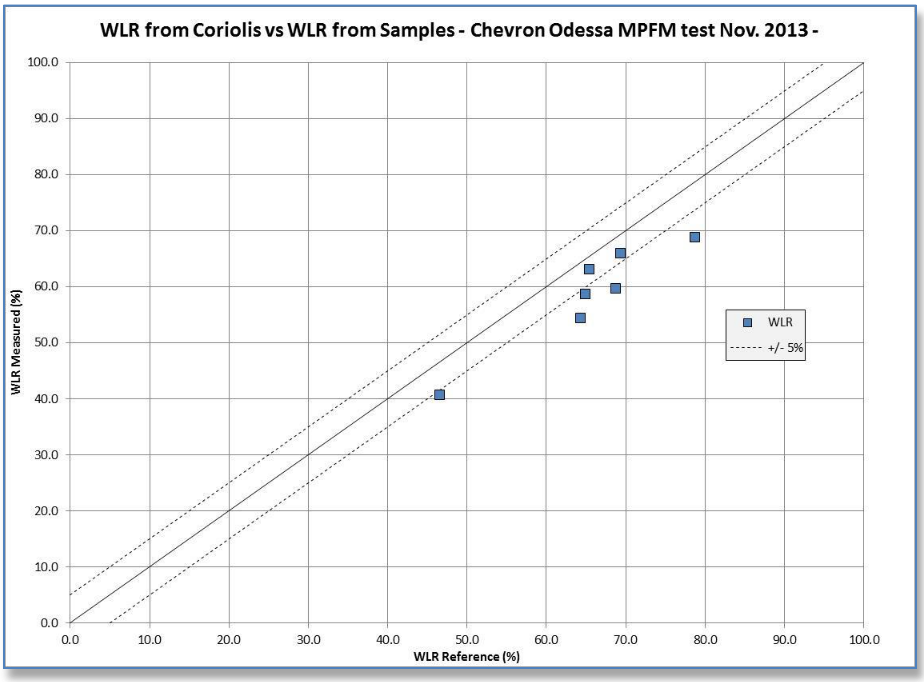
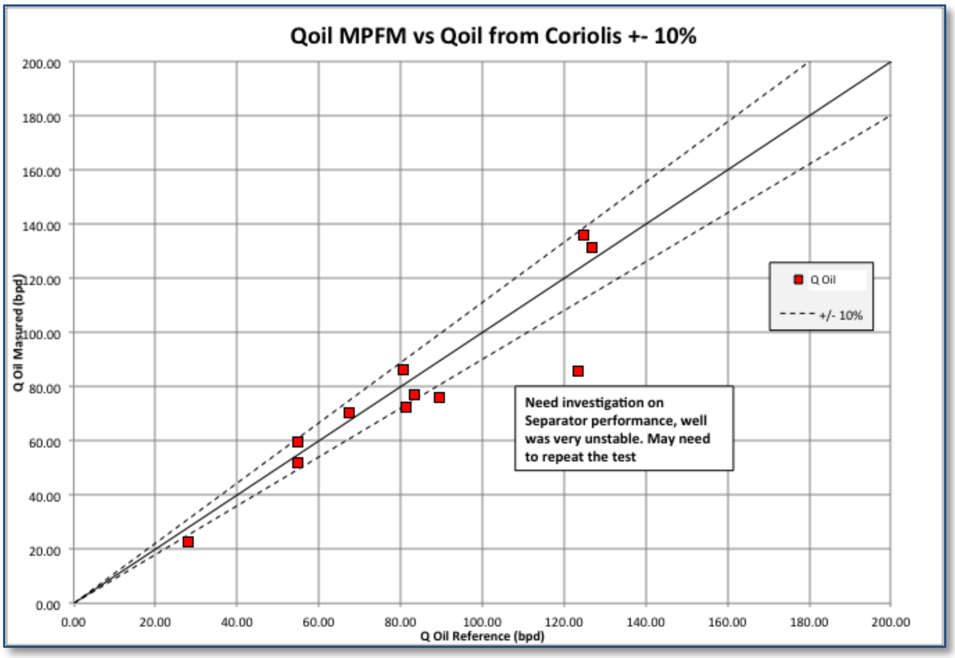


Figure 11: Results from Coriolis measurements on the well test separator are uniformly lower than the sample measurements. This variation between the Coriolis results and sample measurements adds to error in oil and water flow.



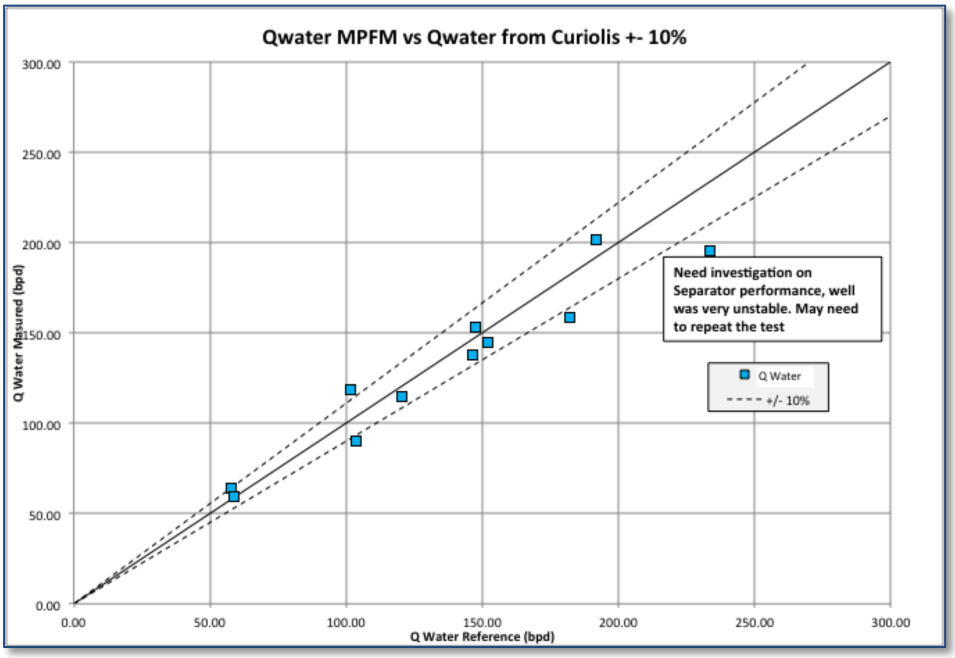
3.3.3 Oil Production Rates

Figure 12: Oil production rates for the MPFM and Coriolis generally matched within 10% with two minor exceptions and larger variation for one well.



3.3.4 Water Production Rates

Figure 13: Water production rates for the MPFM and Coriolis generally matched within 10% with two minor exceptions.



3.3.5 Gas Production Rates

Figure 14: The match between MPFM and Coriolis in measuring gas production rates is within +/- 10% for all wells.

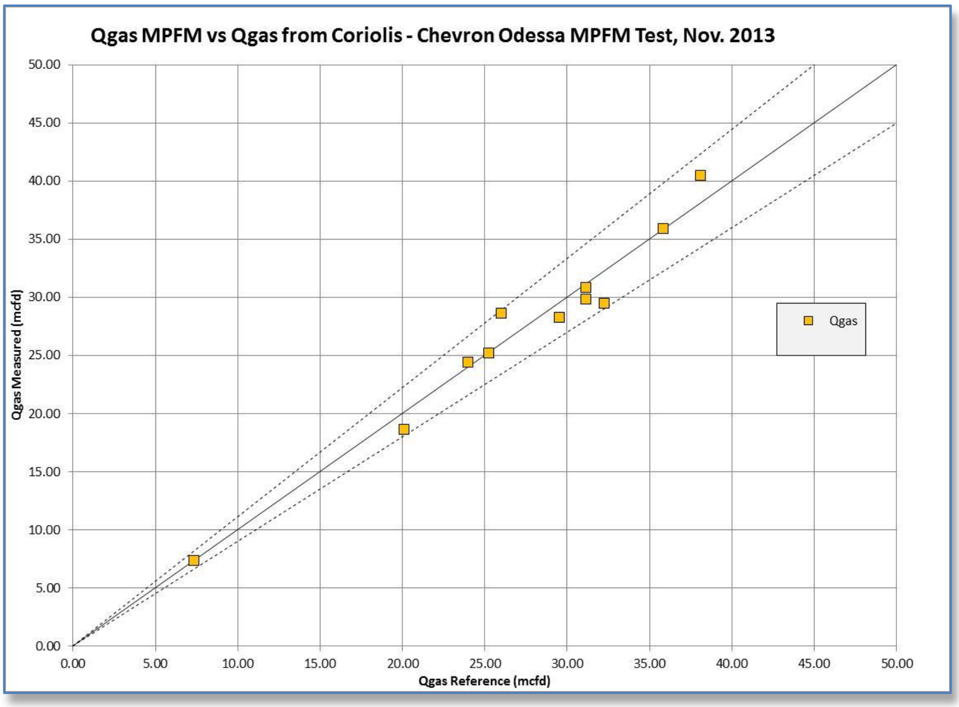
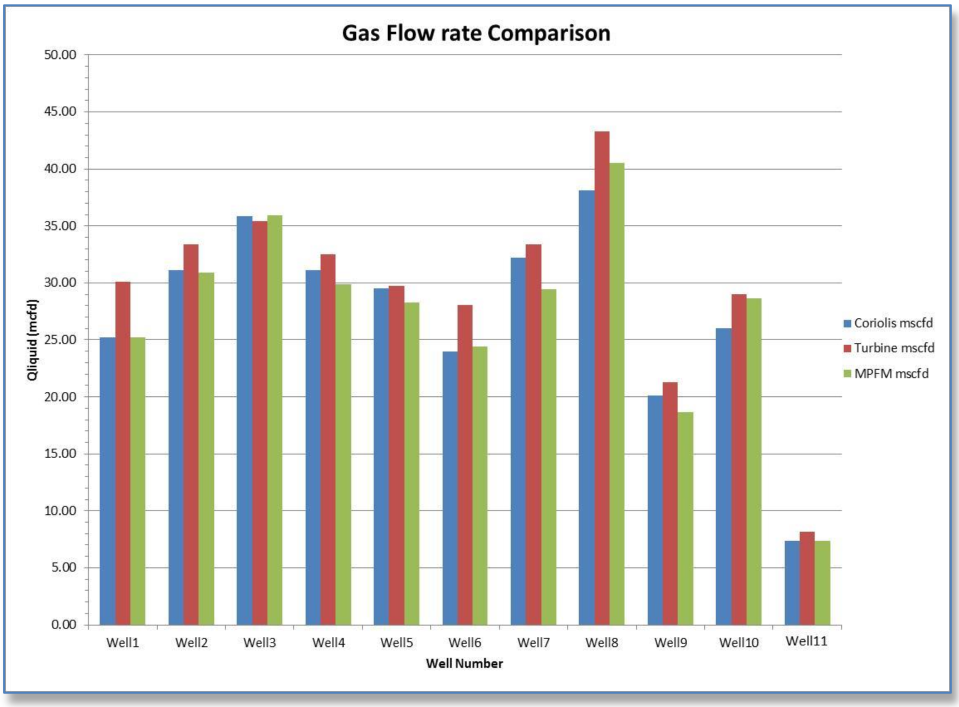


Figure 15: This plot of gas rates measured for all wells by MPFM, Coriolis and Turbine shows that the Turbine Meter often yielded the highest values.



3.4 Examples of Multiphase Continuous Flow Rate Measurement (All wells producing by rod pump. Flow can be quite regular but many wells exhibit high variations in flow rate.)

Figure 16: 15.6 Hour Tests – Uniform rates & slight, slow decline in decline in pressure to a stable level. Was well pumping off? Flow rates stated at Standard Conditions.

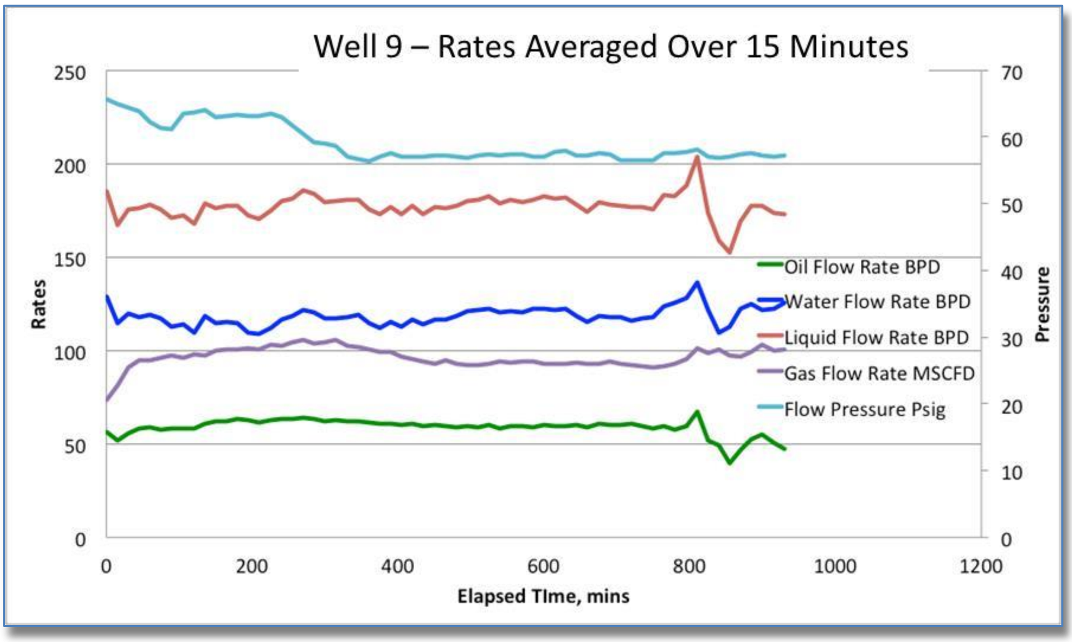


Figure 17: 17.6 Hour Test – Oil and water surges; possible indications that pump is not matched to inflow? Flow rates stated at Standard Conditions.

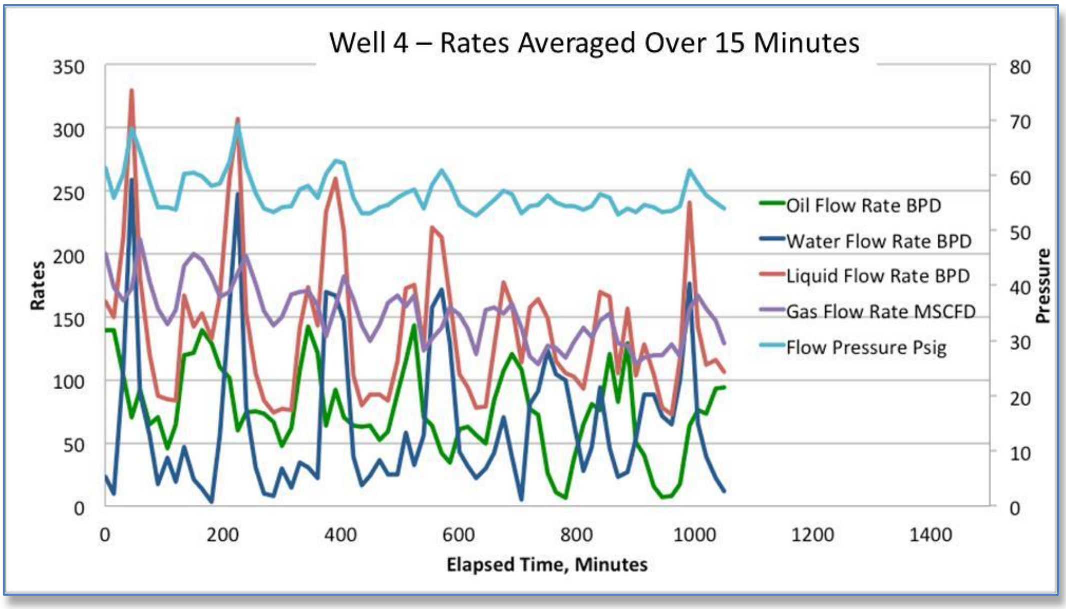


Figure 18: 14.6 Hour Test – Significant pressure & rate buildup after 9 hours of flow. Indication of some type of clean up or fluid build-up in the production system? Flow stated at Standard Conditions.

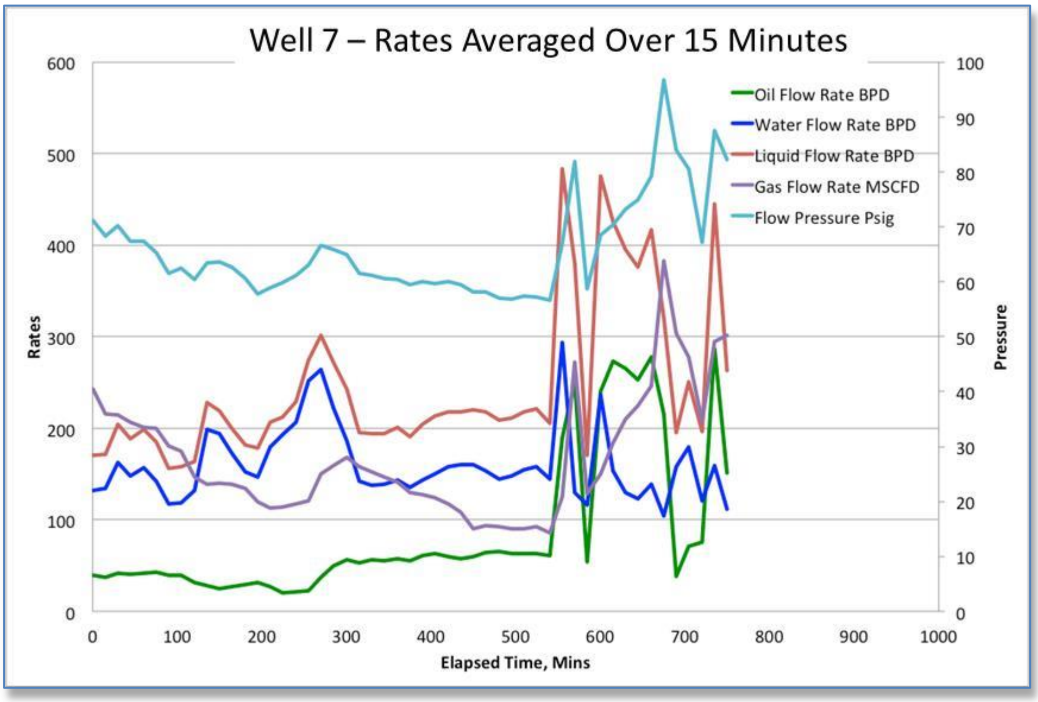
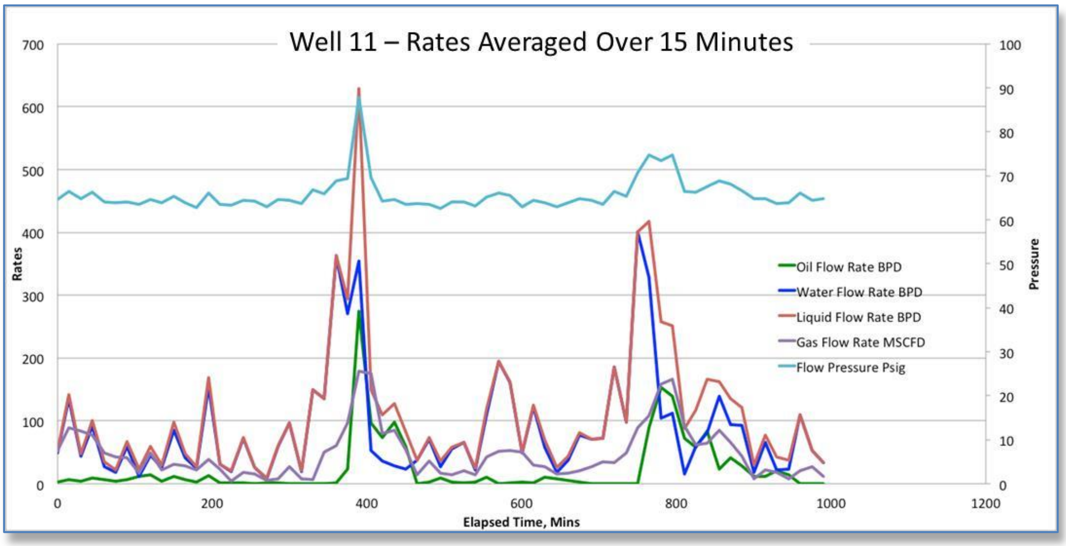


Figure 19: 16.6 Hour Test - Flow rate surges indicating slugging in flow lines? Flow stated at Standard Conditions.



3.3.5 Data Tables

- The tables below shows the production rates, WLR and flow temperatures /pressures during the field trial. The second of the two tables (below) show WLR obtained from samples while the upper table does not. Measurements based on samples were not taken on all wells.

Table 1: Flow Rates, Temperatures, Pressures and Water/Liquid Ratios excluding Water/Liquid Rations measured from sample

					Calculated using WLR from Sample																
		LIQUID FLOW RATE			OIL FLOW RATE			WATER FLOW RATE			GAS FLOW RATE			WLR			SEPARATOR		MPFM	
		Curiolis	Turbine	MPFM	Curiolis	Turbine	MPFM	Curiolis	Turbine	MPFM	Curiolis	Turbine	MPFM	Sample	Turbine	MPFM	P	T	P	T
Well N.	Date of test	bpd	bpd	bpd	bpd	bpd	bpd	bpd	bpd	bpd	mscfd	mscfd	mscfd	%	%	%	psi	DegF	psi	DegF
4207	11-Nov-2013	281.55	281.64	277.46	89.53	143.82	76.03	192.02	137.82	201.43	25.23	30.12	25.19	68.20	48.93	72.60	59.83	58.00	81.39	50.30
4305	12-Nov-2013	272.24	269.99	289.05	124.68	238.79	136.17	147.55	31.20	152.88	31.15	33.41	30.88	54.20	11.56	52.89	61.45	49.80	85.27	40.16
4311	13-Nov-2013	278.81	262.71	276.16	126.86	232.88	131.42	151.95	29.84	144.74	35.85	35.45	35.92	54.50	11.36	52.41	71.44	73.60	94.08	44.98
4312	14-Nov-2013	141.00	135.19	141.23	83.19	77.24	77.00	57.81	57.95	64.22	31.14	32.48	29.85	41.00	42.86	45.48	69.38	81.40	72.23	48.11
4308	15-Nov-2013	126.20	122.98	129.81	67.52	66.78	70.17	58.68	56.20	59.64	29.55	29.72	28.31	46.50	45.70	45.94	71.44	78.42	74.30	60.21
4103	16-Nov-2013	175.10	177.18	166.74	54.75	63.90	52.11	120.35	113.28	114.63	23.97	28.03	24.45	68.73	63.93	68.75	61.30	88.70	72.69	88.36
4215	16-Nov-2013	262.60	264.31	244.80	80.59	112.23	86.30	182.01	152.09	158.50	32.24	33.40	29.46	69.31	57.54	64.75	62.77	64.30	81.93	60.90
4309	17-Nov-2013	227.39	227.68	209.91	81.18	94.00	72.21	146.21	133.68	137.70	38.09	43.29	40.50	64.30	58.71	65.60	65.12	93.10	82.26	93.70
4306	17-Nov-2013	156.40	144.48	178.29	54.90	138.48	59.82	101.50	6.00	118.47	20.08	21.26	18.68	64.90	4.15	66.45	61.89	61.50	74.70	57.05
4304	18-Nov-2013	357.00	368.00	280.97	123.52	121.28	85.68	233.48	246.72	195.29	26.00	28.98	28.65	65.40	67.04	69.51	57.33	57.10	79.42	70.39
4216	20-Nov-2013	132.00	129.90	112.60	28.12	30.24	22.80	103.88	99.66	89.80	7.36	8.14	7.36	78.70	76.72	79.75	70.27	71.08	81.56	65.12

Table 2: Flow Rates, Temperatures, Pressures and Water/Liquid Ratios excluding Water/Liquid Rations measured from sample

					Calculated using WLR from Curiolis																	
		LIQUID FLOW RATE			OIL FLOW RATE			WATER FLOW RATE			GAS FLOW RATE			WLR				SEPARATOR		MPFM	
		Curiolis	Turbine	MPFM	Curiolis	Turbine	MPFM	Curiolis	Turbine	MPFM	Curiolis	Turbine	MPFM	Curiolis	Turbine	MPFM	Sample	P	T	P	T
Well N.	Date of test	bpd	bpd	bpd	bpd	bpd	bpd	bpd	bpd	bpd	mscfd	mscfd	mscfd	%	%	%	%	psi	DegF	psi	DegF
4308	15-Nov-2013	126.20	122.98	129.81	74.86	66.78	70.17	51.34	56.20	59.64	29.55	29.72	28.31	40.68	45.70	45.94	46.50	71.44	78.42	74.30	60.21
4103	16-Nov-2013	175.10	177.18	166.74	70.57	63.90	52.11	104.53	113.28	114.63	23.97	28.03	24.45	59.70	63.93	68.75	68.73	61.30	88.70	72.69	88.36
4215	16-Nov-2013	262.60	264.31	244.80	89.28	112.23	86.30	173.32	152.09	158.50	32.24	33.40	29.46	66.00	57.54	64.75	69.31	62.77	64.30	81.93	60.90
4309	17-Nov-2013	227.39	227.68	209.91	103.71	94.00	72.21	123.68	133.68	137.70	38.09	43.29	40.50	54.39	58.71	65.60	64.30	65.12	93.10	82.26	93.70
4306	17-Nov-2013	156.40	144.48	178.29	64.52	138.48	59.82	91.89	6.00	118.47	20.08	21.26	18.68	58.75	4.15	66.45	64.90	61.89	61.50	74.70	57.05
4304	18-Nov-2013	357.00	368.00	280.97	131.38	121.28	85.68	225.62	246.72	195.29	26.00	28.98	28.65	63.20	67.04	69.51	65.40	57.33	57.10	79.42	70.39
4216	20-Nov-2013	132.00	129.90	112.60	41.18	30.24	22.80	90.82	99.66	89.80	7.36	8.14	7.36	68.80	76.72	79.75	78.70	70.27	71.08	81.56	65.12

Table 3: The deviation from reference data is tabulated below.

					Calculated using WLR from Sample											
		LIQUID FLOW RATE			OIL FLOW RATE			WATER FLOW RATE			GAS FLOW RATE			WLR		
		MPFM vs Curiolis	MPFM vs Turbine	Turbine vs Curiolis	MPFM vs Curiolis	MPFM vs Turbine	Turbine vs Curiolis	MPFM vs Curiolis	MPFM vs Turbine	Turbine vs Curiolis	MPFM vs Curiolis	MPFM vs Turbine	Turbine vs Curiolis	MPFM vs Samples	MPFM vs Turbine	Turbine vs Samples
Well numbe	Date of test	%	bpd	bpd	%	bpd	bpd	%	bpd	bpd	%	bpd	bpd	%	bpd	bpd
4207	11-Nov-2013	-1.45	-1.48	0.03	-15.08	-47.13	60.63	4.90	46.15	-28.23	-0.16	-16.37	19.39	4.40	23.66	-19.27
4305	12-Nov-2013	6.18	7.06	-0.82	9.21	-42.98	91.52	3.61	390.01	-78.85	-0.90	-7.57	7.22	-1.31	41.33	-0.80
4311	13-Nov-2013	-0.95	5.12	-5.77	3.60	-43.57	83.57	-4.75	385.12	-80.37	0.20	1.34	-1.12	-2.09	41.05	-0.80
4312	14-Nov-2013	0.16	4.47	-4.12	-7.44	-0.31	-7.15	11.10	10.83	0.24	-4.14	-8.08	4.28	4.48	2.61	-0.80
4308	15-Nov-2013	2.86	5.55	-2.55	3.94	5.09	-1.10	1.62	6.11	-4.23	-4.17	-4.74	0.60	-0.56	0.24	-0.80
4103	16-Nov-2013	-4.77	-5.89	1.19	-4.82	-18.44	16.70	-4.75	1.19	-5.87	1.98	-12.78	16.93	0.02	4.81	-4.80
4215	16-Nov-2013	-6.78	-7.38	0.65	7.08	-23.10	39.25	-12.92	4.21	-16.44	-8.61	-11.80	3.62	-4.56	7.21	-11.77
4309	17-Nov-2013	-7.69	-7.80	0.13	-11.04	-23.18	15.79	-5.82	3.01	-8.57	6.32	-6.43	13.63	1.30	6.88	-5.59
4306	17-Nov-2013	13.99	23.40	-7.62	8.97	-56.80	152.26	16.71	1874.46	-94.09	-7.01	-12.14	5.84	1.55	62.30	-60.75
4304	18-Nov-2013	-21.30	-23.65	3.08	-30.63	-29.35	-1.82	-16.36	-20.85	5.67	10.17	-1.15	11.46	4.10	2.46	1.64
4216	20-Nov-2013	-14.70	-13.32	-1.59	-18.92	-24.61	7.55	-13.56	-9.89	-4.07	0.02	-9.61	10.66	1.05	3.03	-1.98

					Calculated using WLR from Curiolis											
		LIQUID FLOW RATE			OIL FLOW RATE			WATER FLOW RATE			GAS FLOW RATE			WLR		
		MPFM vs Curiolis	MPFM vs Turbine	Turbine vs Curiolis	MPFM vs Curiolis	MPFM vs Turbine	Turbine vs Curiolis	MPFM vs Curiolis	MPFM vs Turbine	Turbine vs Curiolis	MPFM vs Curiolis	MPFM vs Turbine	Turbine vs Curiolis	MPFM vs Curiolis	MPFM vs Turbine	Turbine vs Curiolis
Well numbe	Date of test	%	bpd	bpd	%	bpd	bpd	%	bpd	bpd	%	bpd	bpd	%	bpd	bpd
4308	15-Nov-2013	2.86	5.55	-2.55	-6.26	5.09	-10.80	16.16	6.11	9.47	-4.17	-4.74	0.60	5.26	0.24	5.02
4103	16-Nov-2013	-4.77	-5.89	1.19	-26.15	-18.44	-9.45	9.65	1.19	8.37	1.98	-12.78	16.93	9.05	4.81	4.23
4215	16-Nov-2013	-6.78	-7.38	0.65	-3.34	-23.10	25.70	-8.55	4.21	-12.25	-8.61	-11.80	3.62	-1.25	7.21	-8.46
4309	17-Nov-2013	-7.69	-7.80	0.13	-30.37	-23.18	-9.36	11.34	3.01	8.09	6.32	-6.43	13.63	11.21	6.88	4.32
4306	17-Nov-2013	13.99	23.40	-7.62	-7.28	-56.80	114.65	28.93	1874.46	-93.47	-7.01	-12.14	5.84	7.70	62.30	-54.60
4304	18-Nov-2013	-21.30	-23.65	3.08	-34.78	-29.35	-7.68	-13.45	-20.85	9.35	10.17	-1.15	11.46	6.30	2.46	3.84
4216	20-Nov-2013	-14.70	-13.32	-1.59	-44.64	-24.61	-26.57	-1.12	-9.89	9.73	0.02	-9.61	10.66	10.95	3.03	7.92

4 Issues for Future Work

Further work to identify ways to improve reservoir management and optimize production based on MPFM results is expected to add value to development in the Permian Basin.

Future work will also focus on MPFM measurements of horizontal hydraulically fractured wells. Flow profile characteristics and reservoir issues presented by horizontal wells are challenging and are expected to benefit from application of MPFM measurements.

5 Definitions

- MPFM: Multiphase flow meter
- Water-cut: Percent of water in a sample of produced fluid
- Q: Symbol for flow rate
- NIR: Near infrared
- GVF%: Gas Void (or Volume) Fraction – the percent of gas of the total flow from the well under flowing conditions

- Standard Conditions: 60° F and 14.7 PSI

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