CHAPTER 5
RESULTS AND DISCUSSION

This chapter discusses on the performance of the inferential coriolis flowmeter which is developed and embedded in the FieldPoint controller, and then tested on the experimental test rig. Since mass flowrate is an estimated value in the inferential coriolis, graphs based on mass flowrate are used to analyze the performance which could be categorized into three types of flows: single pressure flow, continuous pressure flow and multi pressure flow with disturbance.

5.1 Introduction

CNG flow experiment is conducted to study how the transferring of CNG set at higher pressure source would flow from cascaded storage bank to receiver tank. In this experiment, the initial and final pressure of the receiver is measured by a pressure sensor at the receiver tank, whilst the mass flowrate is measured using the inferential coriolis and the Micro Motion coriolis flowmeter.

To validate the mass measured by both methods, a load cell that does a direct weighting is used to measure total mass at the receiver tank. The load cell is made by Mettler Toledo which has been calibrated for measuring CNG. Please refer appendix II for calibration and international accreditation [253].

In following section, Figure 5.1 shows P&ID diagram to validate the inferential coriolis. The experiment for single pressure flow is conducted by transferring CNG from the low bank set at 3600 psig to the receiver tank set at 0 psig. Initially, when the low valve is opened, a spike would occur at initial stage, and then decrease to zero when pressure at the receiver tank is equivalent to pressure at low bank or supply tank. The experiment is repeated with the receiver pressure initially set at 100, 500, 1000, 1500 and finally at 2000 psig.

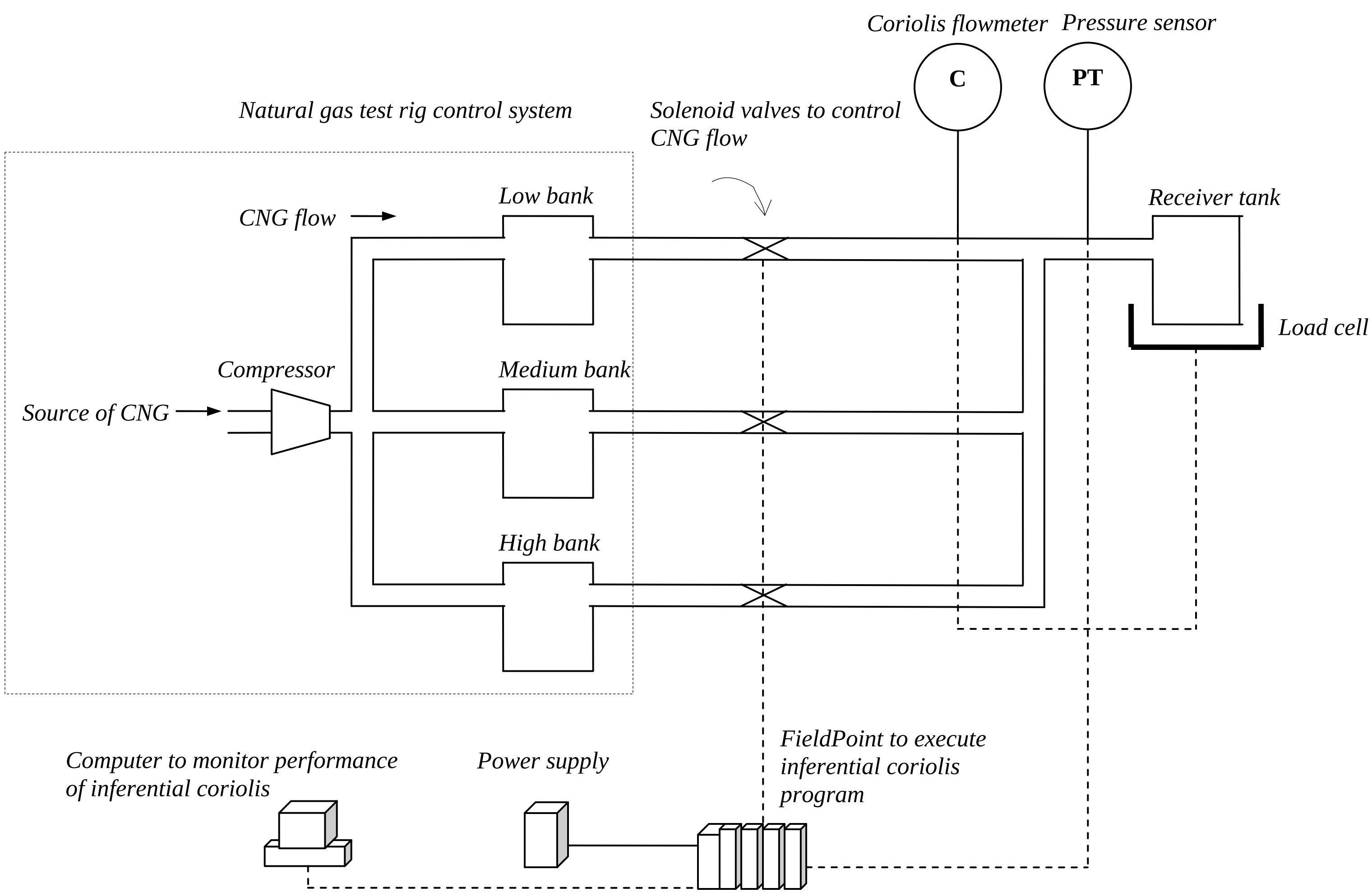

Figure 5.1: P&ID diagram to validate inferential coriolis with Micro Motion flowmeter and load cell

For the experiment of continuous pressure flow, three storage tanks such as the low bank, medium bank and high bank are used to transfer the CNG as shown by the P&ID diagram in Figure 5.1, respectively. The experiment is conducted by transferring the flow from the storage tanks set at 3600 psig to the receiver tank set at 0 psig. During the experiment, when the flow has decreased close to zero, other storage tank is opened, until the receiver tank reaches the maximum capacity or equal to 3000 psig. Like the previous experiment, the continuous pressure flow is repeated by testing the initial receiver pressure at 100, 500, 1000, 1500 and finally at 2000 psig.

Lastly, for the experiment of multi pressure flow, there are three sets of different initial pressures set at the low bank, medium bank and high bank. The experiment is conducted by transferring the CNG from the low bank, medium bank and high bank to the receiver tank set at 20 psig using a natural gas refueling algorithm known as time optimal control. Please refer time optimal control method for details descriptions on optimal switching design for transferring CNG [32].

Whilst, to simulate disturbance in the experiment, solenoid valves at the low bank, medium bank and high bank are randomly switched to develop different types of flow to the receiver tank. Hence, different scenarios of flows could be simulated and tested on the inferential coriolis as well as the Micro Motion flowmeter. For this type of multi pressure flow (with disturbance), there are two experiments to be presented with difference sets of initial pressures at storage tanks, whilst the initial receiver pressure is set at 20 psig.

For all experiments, results of Micro Motion flowmeter, inferential coriolis and load cell measurements are presented in mass flowrate graphs using blue, red and green color graphs, respectively. Whilst, total mass accumulated in the receiver tank is the performance measure to be evaluated with other measurements based on percentage error formula.

$$\text{Percentage error (\%)} = \frac{\text{(Total mass by load cell – total mass by measurement)}}{\text{Total mass by load cell}} \times 100 \qquad (5.1)$$

Please refer to following section for details results on single pressure flow experiment.

5.2 Results of single pressure flow experiment

The purpose of the experiment is to observe the total mass of CNG accumulated at the receiver tank when only a single pressure bank is used such as the low bank. Figure 5.2 shows mass flowrate graphs when initial pressure inside the low bank and receiver tank are set at 3600 psig and 0 psig, respectively.

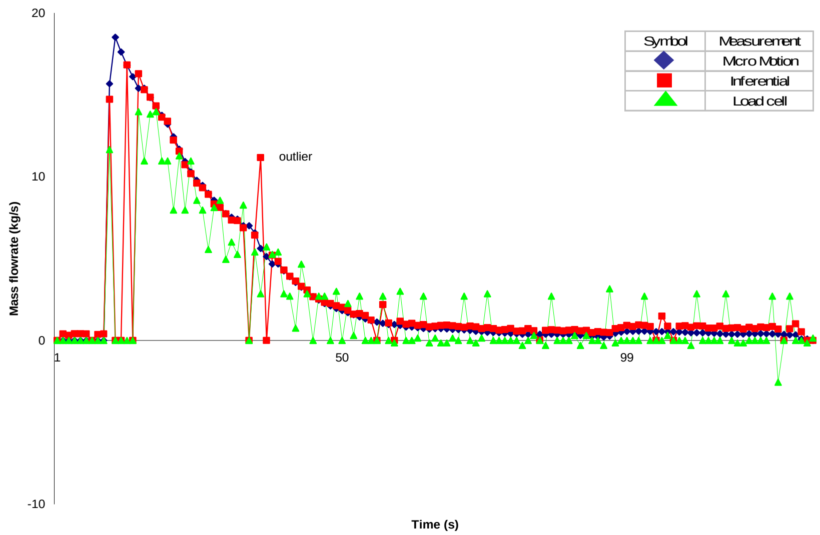

Figure 5.2: Initial receiver pressure 0 psig

Table 5.1: Total mass when initial receiver pressure 0 psig

Measurement	Total Mass (kg)
Micro Motion	6.686
Inferential coriolis	6.760
Load cell	6.963

Based on Table 5.1, the total mass measured by the Micro Motion and inferential coriolis are 6.686 kg and 6.760 kg, whilst, the total mass measured by the load cell is 6.963 kg, respectively. Since, unexpected outlier have been removed using the inferential coriolis program, the final value measured by the inferential coriolis are closed to mass value measured by the load cell which show both curves overlap to each other. From the load cell graph, notice that there are outliers occurs at each sampling time of its measurement. This is due to external disturbance and other noise developed such as wind surrounding and tank vibration, which is susceptible to load cell sensor. For that reason, only total mass of the load cell is used as the performance measure. Further analysis is made by increasing the initial pressure at receiver tank to 100 psig.

Figure 5.3 shows mass flowrate graphs when initial pressure inside the low bank and receiver tank are set at 3600 psig and 100 psig, respectively.

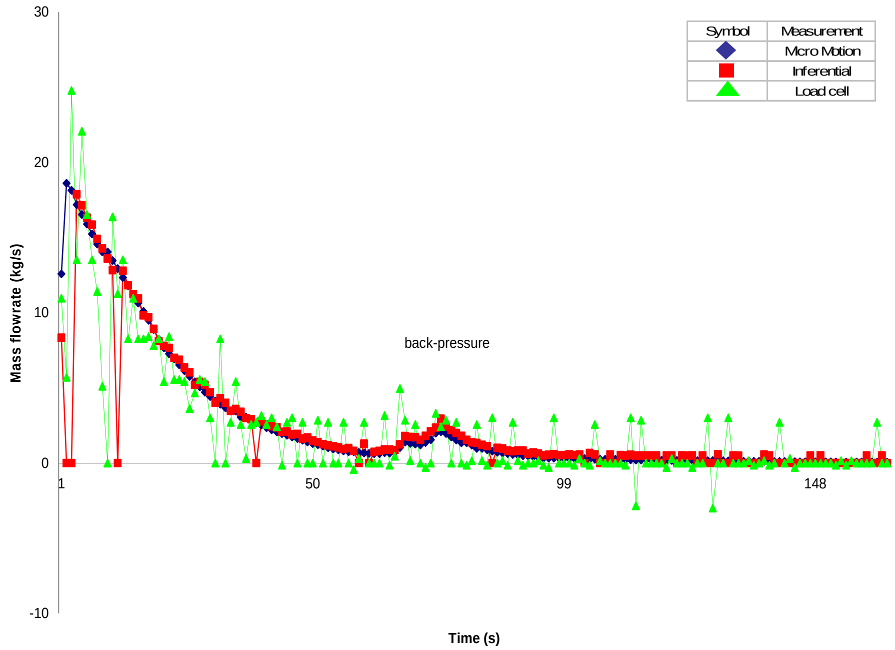

Figure 5.3: Initial receiver pressure 100 psig

Table 5.2: Total mass when initial receiver pressure 100 psig

Measurement	**Total Mass (kg)**
Micro Motion	7.174
Inferential coriolis	6.432
Load cell	6.411

Based on Table 5.2, the total mass measured by the Micro Motion and inferential coriolis are 7.174 kg and 6.432 kg, whilst, the total mass measured by the load cell is 6.411 kg, respectively. Notice that, there is a unique condition occurs known as back-pressure as shown in Figure 5.3. When the back pressure occurs, pressure at the receiver tank is much higher than the pressure at the low bank, in which the pressure is able to push towards the direction of current flow, back to the low bank as indicated by a small peak in Figure 5.3, respectively. However, the occurrence of back-pressure does not affect the final value produced by the inferential coriolis, as compared to a higher reading value recorded by the Micro Motion measurement. Further analysis is made by increasing the initial pressure at receiver tank to 500 psig.

Figure 5.4 shows mass flowrate graphs when initial pressure inside the low bank and receiver tank are set at 3600 psig and 500 psig, respectively.

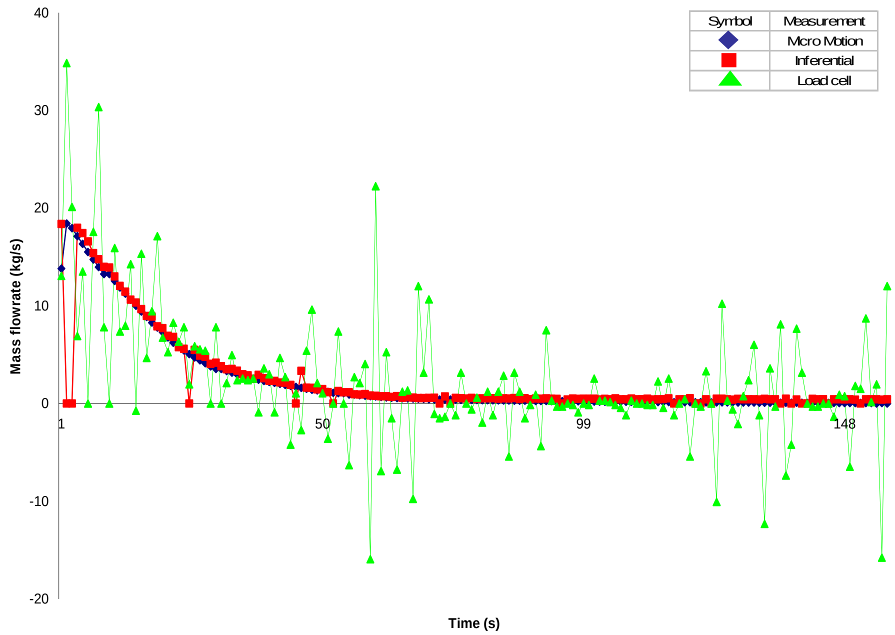

Figure 5.4: Initial receiver pressure 500 psig

Table 5.3: Total mass when initial receiver pressure 500 psig

Measurement	**Total Mass (kg)**
Micro Motion	6.285
Inferential coriolis	6.364
Load cell	6.329

Based on Table 5.3, the total mass measured by the Micro Motion and inferential coriolis are 6.285 kg and 6.364 kg, whilst, the total mass measured by the load cell is 6.329 kg, respectively. Further analysis is made by increasing the initial pressure at receiver tank to 1000 psig.

Figure 5.5 shows mass flowrate graphs when initial pressure inside the low bank and receiver tank are set at 3600 psig and 1000 psig, respectively.

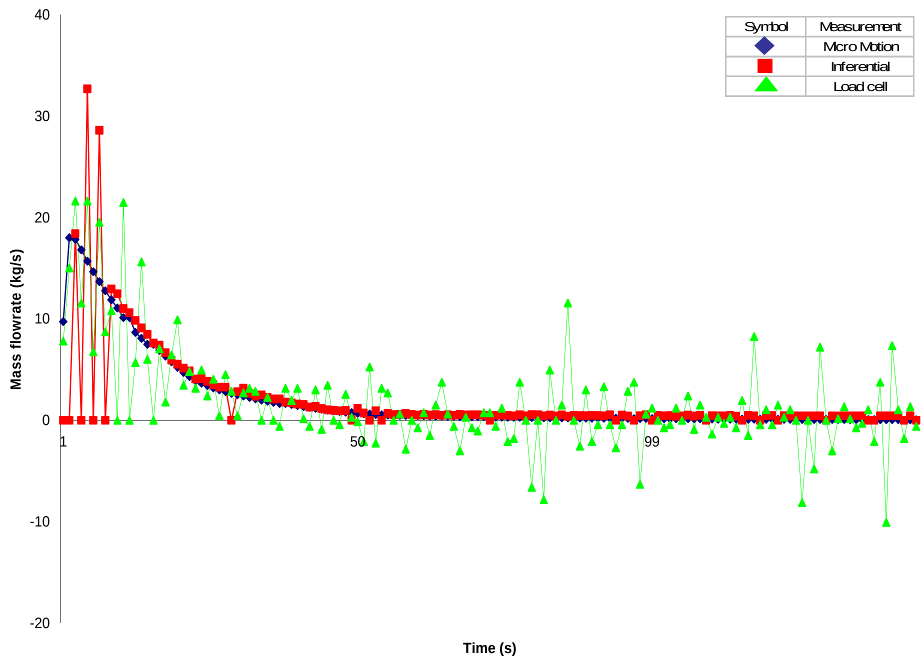

Figure 5.5: Initial receiver pressure 1000 psig

Table 5.4: Total mass when initial receiver pressure 1000 psig

Measurement	**Total Mass (kg)**
Micro Motion	5.029
Inferential coriolis	4.779
Load cell	4.722

Based on Table 5.4, the total mass measured by the Micro Motion and inferential coriolis are 5.029 kg and 4.779 kg, whilst, the total mass measured by the load cell is 4.772 kg, respectively. Further analysis is made by increasing the initial pressure at receiver tank to 1500 psig.

Figure 5.6 shows mass flowrate graphs when initial pressure inside the low bank and receiver tank are set at 3600 psig and 1500 psig, respectively.

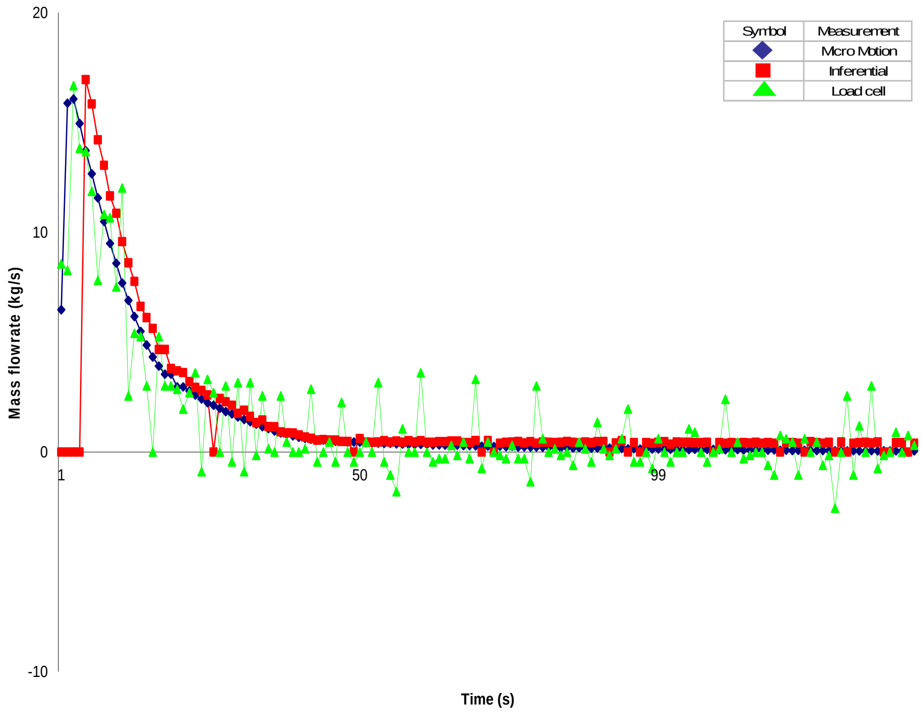

Figure 5.6: Initial receiver pressure 1500 psig

Table 5.5: Total mass when initial receiver pressure 1500 psig

Measurement	**Total Mass (kg)**
Micro Motion	3.719
Inferential coriolis	3.337
Load cell	3.470

Based on Table 5.5, the total mass measured by the Micro Motion and inferential coriolis are 3.719 kg and 3.373 kg, whilst, the total mass measured by the load cell is 3.470 kg, respectively. Further analysis is made by increasing the initial pressure at receiver tank to 2000 psig.

Figure 5.7 shows mass flowrate graphs when initial pressure inside the low bank and receiver tank are set at 3600 psig and 2000 psig, respectively.

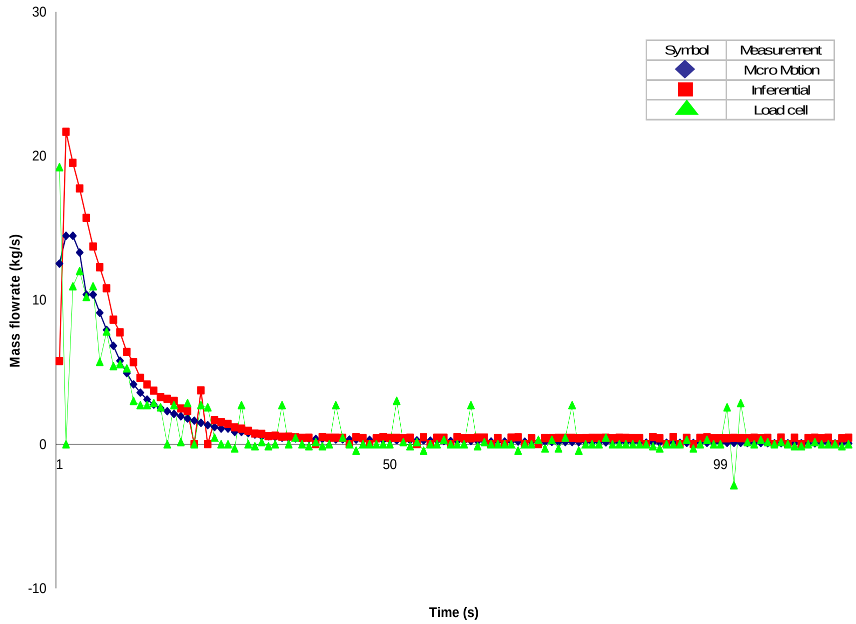

Figure 5.7: Initial receiver pressure 2000 psig

Table 5.6: Total mass when initial receiver pressure 2000 psig

Measurement	Total Mass (kg)
Micro Motion	2.694
Inferential coriolis	2.442
Load cell	2.471

Based on Table 5.6, the total mass measured by the Micro Motion and inferential coriolis are 2.694 kg and 2.442 kg, whilst, the total mass measured by the load cell is 2.471 kg, respectively.

In this section, results of single pressure flow experiments for different initial pressures at the receiver tank have been presented i.e., 0 psig, 100 psig, 500 psig, 1000 psig, 1500 psig and 2000 psig. As depicted in Figure 5.2-5.7, when the single tank valve is opened, the receiver tank receives gas that is gradually flow into the receiver tank. These shows the performances of the inferential coriolis as the initial receiver pressure are at different amount, which indicate, the total mass accumulated in the receiver tank is related to the initial amount of mass in the receiver tank. Please refer to following section for details results on continuous pressure flow experiment.

5.3 Results of continuous pressure flow experiment

The following results are from a set of experiments conducted to observe the behavior of the refueling system when continuous flow is applied. Figure 5.8 shows mass flowrate graphs when initial pressure inside the low bank, medium bank, high bank and receiver tank are set at 3600 psig and 0 psig, respectively.

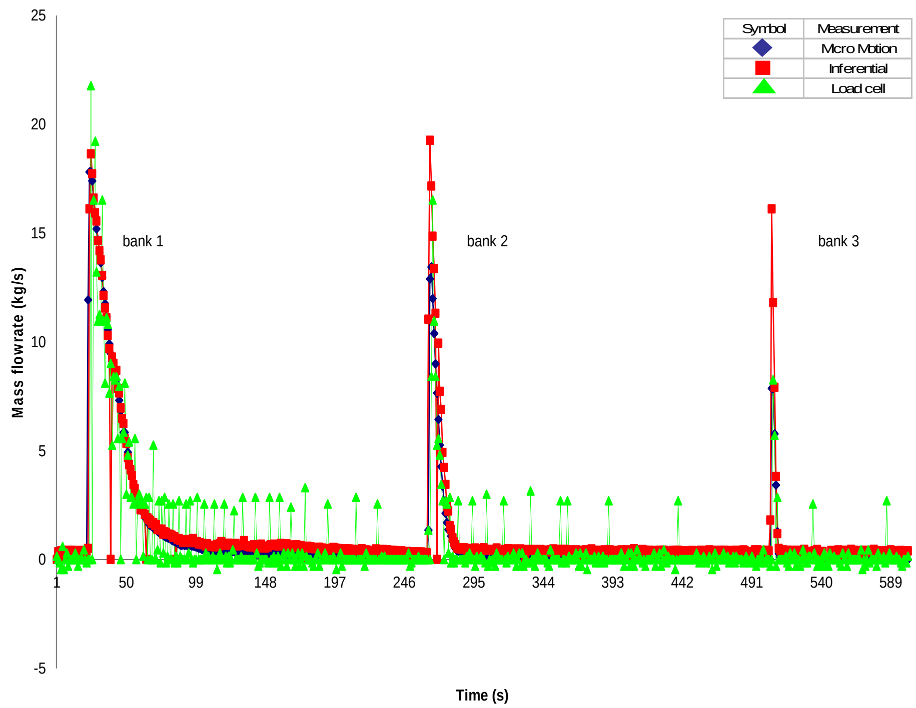

Figure 5.8: Initial receiver pressure 0 psig

Table 5.7: Total mass when initial receiver pressure 0 psig

Measurement	Total Mass (kg)
Micro Motion	9.293
Inferential coriolis	10.125
Load cell	9.906

Based on Table 5.7, the total mass measured by the Micro Motion and inferential coriolis are 9.293 kg and 10.125 kg, whilst, the total mass measured by the load cell is 9.906 kg, respectively. Notice that, when the low bank, medium bank and high bank are opened, there spikes would occur at initial stage before the gas is gradually flow into the receiver tank. Further analysis is made by increasing the initial pressure at receiver tank to 100 psig.

Figure 5.9 shows mass flowrate graphs when initial pressure inside the low bank, medium bank, high bank and receiver tank are set at 3600 psig and 100 psig, respectively.

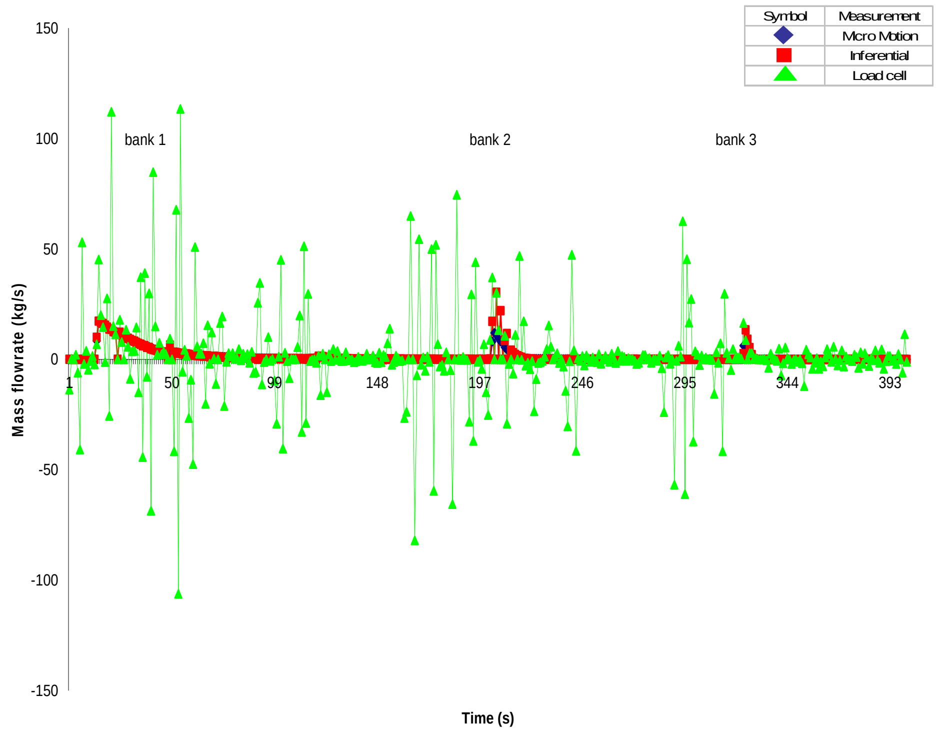

Figure 5.9: Initial receiver pressure 100 psig

Table 5.8: Total mass when initial receiver pressure 100 psig

Measurement	**Total Mass (kg)**
Micro Motion	8.864
Inferential coriolis	9.038
Load cell	9.183

Based on Table 5.8, the total mass measured by the Micro Motion and inferential coriolis are 8.864 kg and 9.038 kg, whilst, the total mass measured by the load cell is 9.183 kg, respectively. Further analysis is made by increasing the initial pressure at receiver tank to 500 psig.

Figure 5.10 shows mass flowrate graphs when initial pressure inside the low bank, medium bank, high bank and receiver tank are set at 3600 psig and 500 psig, respectively.

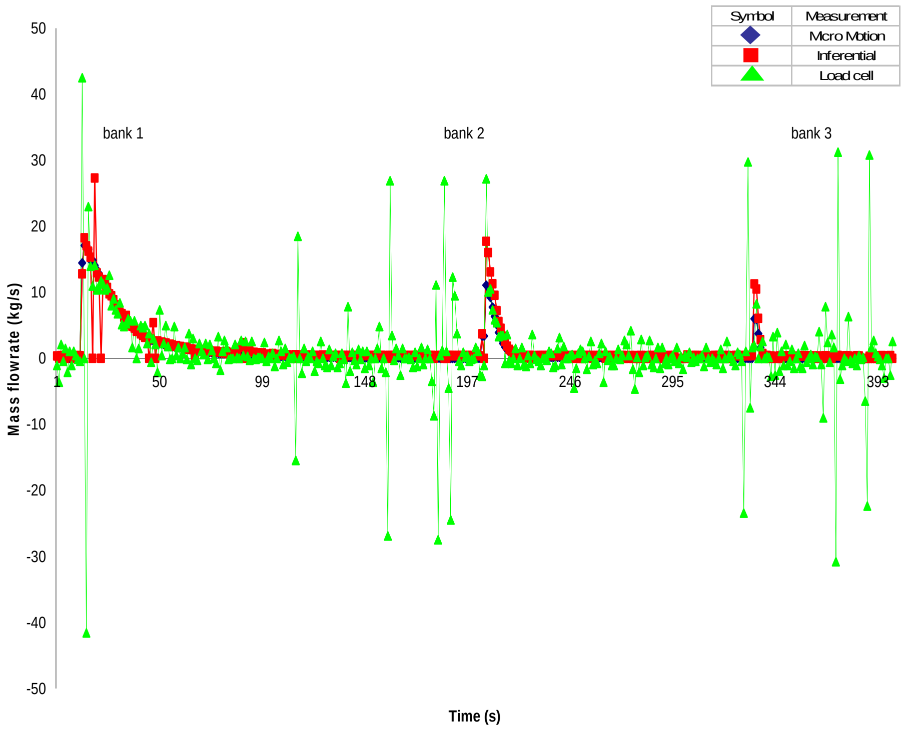

Figure 5.10: Initial receiver pressure 500 psig

Table 5.9: Total mass when initial receiver pressure 500 psig

Measurement	Total Mass (kg)
Micro Motion	7.871
Inferential coriolis	7.172
Load cell	7.090

Based on Table 5.9, the total mass measured by the Micro Motion and inferential coriolis are 7.871 kg and 7.172 kg, whilst, the total mass measured by the load cell is 7.090 kg, respectively. Further analysis is made by increasing the initial pressure at receiver tank to 1000 psig.

Figure 5.11 shows mass flowrate graphs when initial pressure inside the low bank, medium bank, high bank and receiver tank are set at 3600 psig and 1000 psig, respectively.

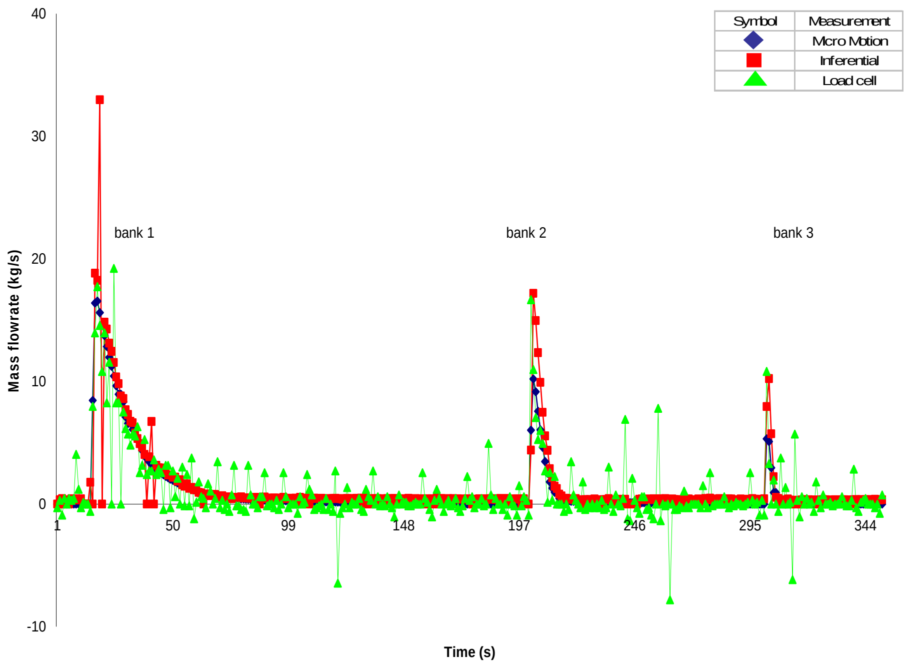

Figure 5.11: Initial receiver pressure 1000 psig

Table 5.10: Total mass when initial receiver pressure 1000 psig

Measurement	**Total Mass (kg)**
Micro Motion	6.163
Inferential coriolis	6.031
Load cell	6.080

Based on Table 5.10, the total mass measured by the Micro Motion and inferential coriolis are 6.163 kg and 6.031 kg, whilst, the total mass measured by the load cell is 6.080 kg, respectively. Further analysis is made by increasing the initial pressure at receiver tank to 1500 psig.

Figure 5.12 shows mass flowrate graphs when initial pressure inside the low bank, medium bank, high bank and receiver tank are set at 3600 psig and 1500 psig, respectively.

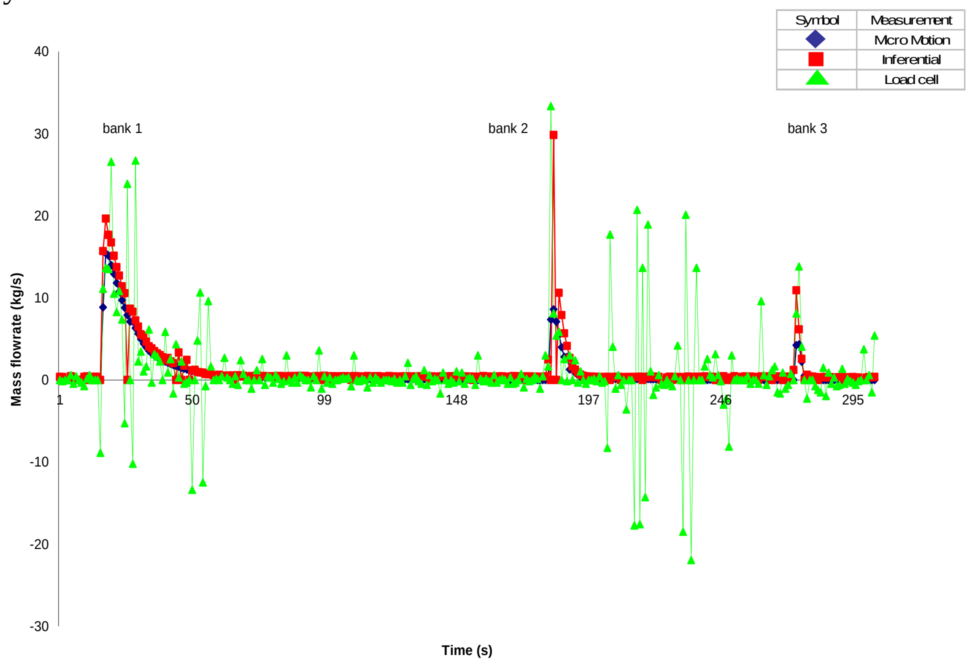

Figure 5.12: Initial receiver pressure 1500 psig

Table 5.11: Total mass when initial receiver pressure 1500 psig

Measurement	**Total Mass (kg)**
Micro Motion	4.585
Inferential coriolis	5.029
Load cell	5.047

Based on Table 5.11, the total mass measured by the Micro Motion and inferential coriolis are 4.585 kg and 5.029 kg, whilst, the total mass measured by the load cell is 5.047 kg, respectively. Further analysis is made by increasing the initial pressure at receiver tank to 2000 psig.

Figure 5.13 shows mass flowrate graphs when initial pressure inside the low bank, medium bank, high bank and receiver tank are set at 3600 psig and 2000 psig, respectively.

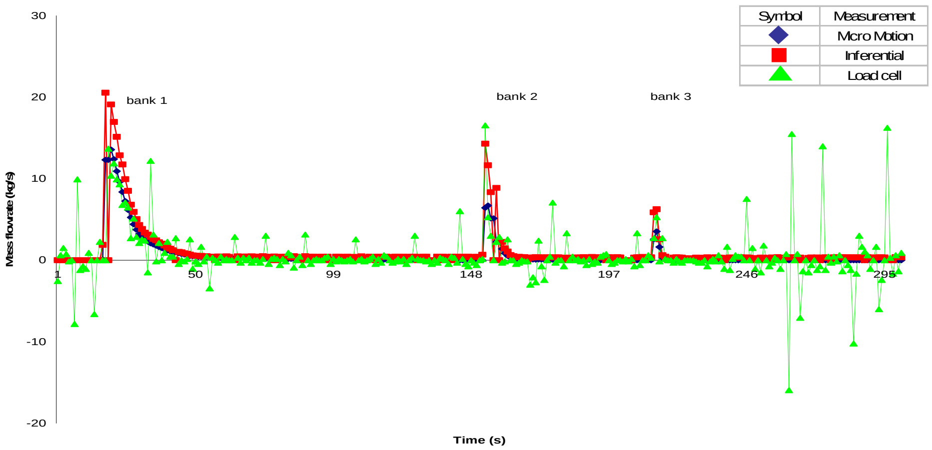

Figure 5.13: Initial receiver pressure 2000 psig

Table 5.12: Total mass when initial receiver pressure 2000 psig

Measurement	Total Mass (kg)
Micro Motion	3.187
Inferential coriolis	3.202
Load cell	3.199

Based on Table 5.12, the total mass measured by the Micro Motion and inferential coriolis are 3.187 kg and 3.202 kg, whilst, the total mass measured by the load cell is 3.199 kg, respectively.

In this section, results of continuous pressure flow experiments for different initial pressures at the receiver tank have been presented i.e., 0 psig, 100 psig, 500 psig, 1000 psig, 1500 psig and 2000 psig. As illustrated in Figure 5.8-5.13, the total mass accumulated in the receiver tank is related to the initial amount of mass in the receiver tank. The pattern of refueling as depicted in Figure 5.8-5.13 suggests that the behavior of the system does match the expectation of the behavior of the inferential coriolis. These also show the performance of the switching between bank 1, bank 2 and followed by bank 3 as the refueling progresses. As would be expected, the switching times required are related to the initial amount of mass in the receiver tank. Please refer to following section for details results on multi pressure flow experiment with disturbance.

5.4 Results of multi pressure flow experiment with disturbance

This section illustrates three experiments of the multi pressure tanks when are used as the source to evaluate how the inferential coriolis behaves as compared to the commercial measuring instrument i.e., Micro Motion. Notably, time optimal control refueling is applied for this experiment. Figure 5.14 is the first example of experiments, which shows result of mass flowrates when initial pressure inside the low bank, medium bank, high bank and receiver tank are set at 2000, 3000, 3600 and 20 psig, respectively.

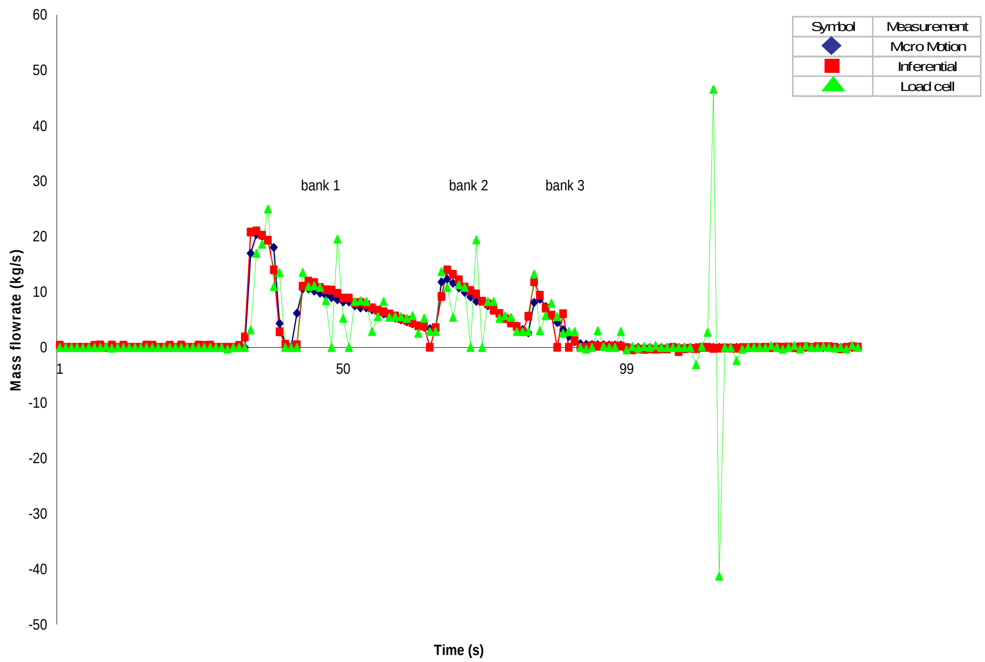

Figure 5.14: Initial source pressure 2000-3000-3600 psig and receiver pressure 20 psig

Table 5.13: Total mass when initial source pressure 2000-3000-3600 psig and receiver pressure 20 psig

Measurement	Total Mass (kg)
Micro Motion	7.726
Inferential coriolis	5.801
Load cell	5.773

Based on Table 5.13, the total mass measured by the Micro Motion and inferential coriolis are 7.726 kg and 5.801 kg, whilst, the total mass measured by the load cell is 5.773 kg, respectively. Further analysis is made using the second experimental data as shown in following section by Figure 5.15.

Figure 5.15 is the second example of experiments, which shows mass flowrate graphs when initial pressure inside the low bank, medium bank, high bank and receiver tank are set at 1000, 2000, 3000 and 20 psig, respectively.

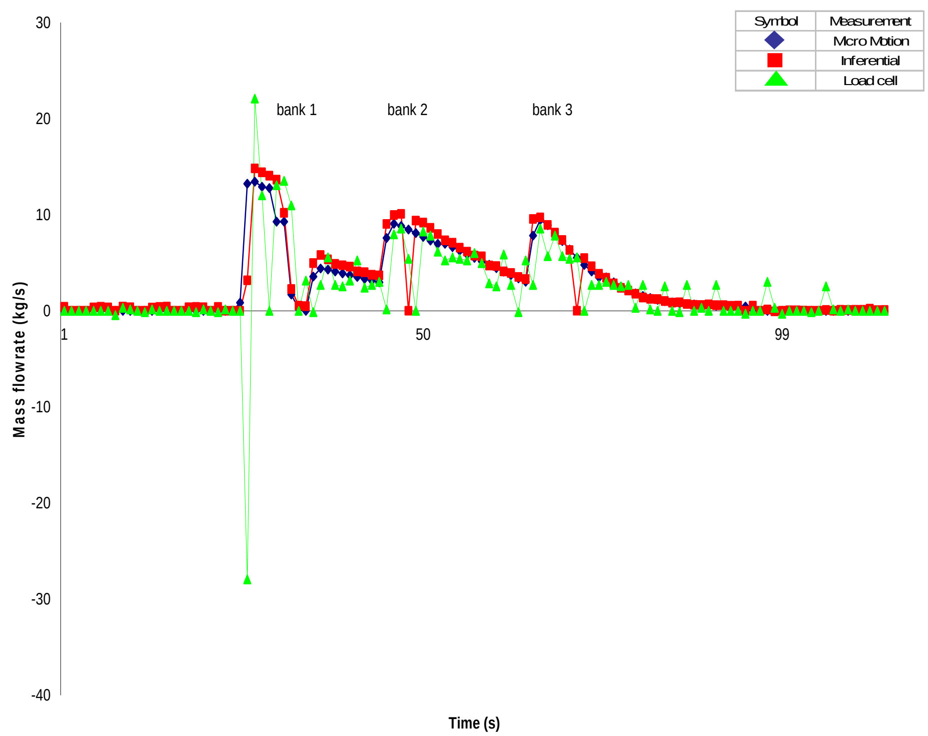

Figure 5.15: Initial source pressure 1000-2000-3000 psig and receiver pressure 20 psig

Table 5.14: Total mass when initial source pressure 1000-2000-3000 psig and receiver pressure 20 psig

Measurement	Total Mass (kg)
Micro Motion	5.414
Inferential coriolis	4.493
Load cell	4.584

Based on Table 5.14, the total mass measured by the Micro Motion and inferential coriolis are 5.414 kg and 4.493 kg, whilst, the total mass measured by the load cell is 4.584 kg, respectively. Further analysis is made using the third experimental data as shown in following section by Figure 5.16.

Figure 5.16 is the third example of experiments, which shows mass flowrate graphs when initial pressure inside the low bank, medium bank, high bank and receiver tank are set at 290, 1450, 3600 and 20 psig, respectively.

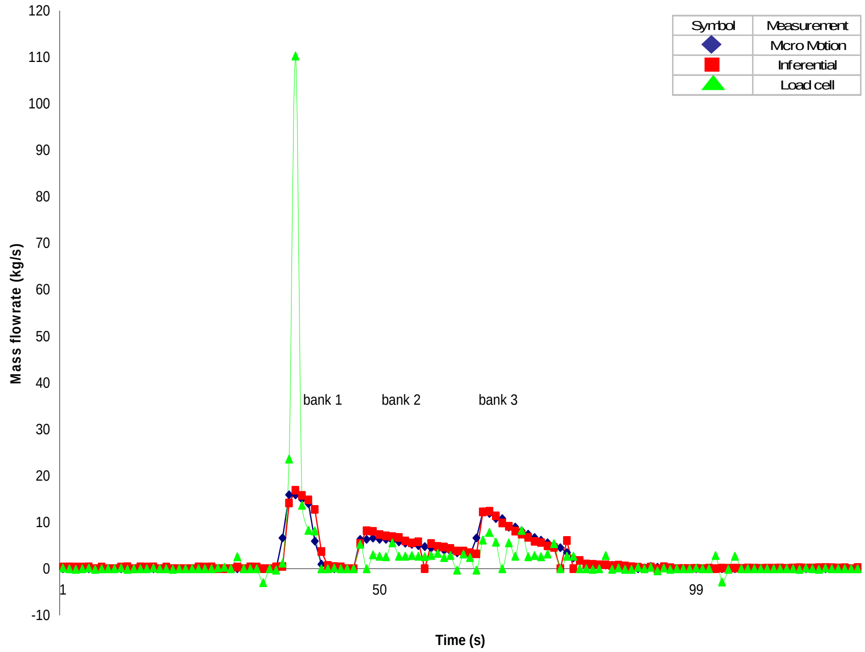

Figure 5.16: Initial source pressure 290-1450-3600 psig and receiver pressure 20 psig

Table 5.15: Total mass when initial source pressure 290-1450-3600 psig and receiver pressure 20 psig

Measurement	**Total Mass (kg)**
Micro Motion	4.874
Inferential coriolis	4.655
Load cell	4.631

Based on Table 5.15, the total mass measured by the Micro Motion and inferential coriolis are 4.874 kg and 4.655 kg, whilst, the total mass measured by the load cell is 4.631 kg, respectively.

In this section, results of multi pressure flow experiments when initial receiver tank is set at 20 psig have been presented based on Figure 5.14 to Figure 5.16. There are similar refueling patterns being observed for all measurement methods. Figure 5.14-5.16 also shows the performance of the inferential coriolis when the initial source pressure is set at different amount, which indicate, the total mass accumulated in the receiver tank is related to the initial amount of mass in the source tanks.

The following results describe two sets of experiments to observe the behavior of the multiple pressure flow when disturbance is applied. As mentioned earlier, disturbance is developed by switching to low bank, medium bank and high bank randomly, for generating different types of flow to receiver tank. Notably, disturbance is presented by a 'sharp' peak in the mass flowrate graphs. Figure 5.17 shows the first results of the experiments when initial pressure inside the low bank, medium bank, high bank and receiver tank are set at 3300 and 20 psig, respectively. The disturbance is applied with 7 times of random switching.

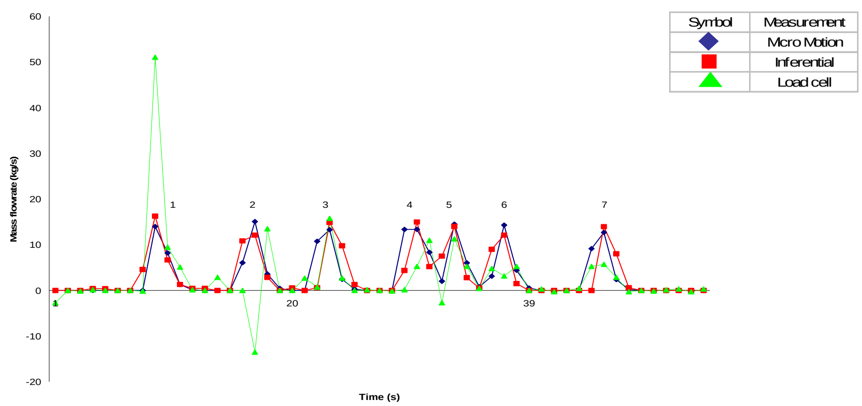

Figure 5.17: Initial source pressure 3300-3300-3300 psig, receiver pressure 20 psig, 7 times of switching

Table 5.16: Total mass when initial source pressure 3300-3300-3300 psig, receiver pressure 20 psig, 7 times of switching

Measurement	Total Mass (kg)
Micro Motion	3.012
Inferential coriolis	2.501
Load cell	2.478

Based on Table 5.16, the total mass measured by the Micro Motion and inferential coriolis are 3.012 kg and 2.501 kg, whilst, the total mass measured by the load cell is 2.478 kg, respectively. These graphs, representing the level of natural gas at the source tanks, indicate that a change at the switching has given rise to a large fluctuation at the source. When each valve is opened, the receiver tank receives natural gas that flows gradually to the receiver tank. As depicted in Figure 5.17, the effect of the source tank to deliver is based on the demand and that the switching pattern shows more frequent switching to meet the demands by the receiver tank. Further analysis is made using the second experimental data as shown in following section by Figure 5.18.

Figure 5.18 shows the results of the second experiments when initial pressure inside the low bank, medium bank, high bank and receiver tank are set at 3300 and 20 psig, respectively, whilst, the disturbance is applied with 22 times of random switching.

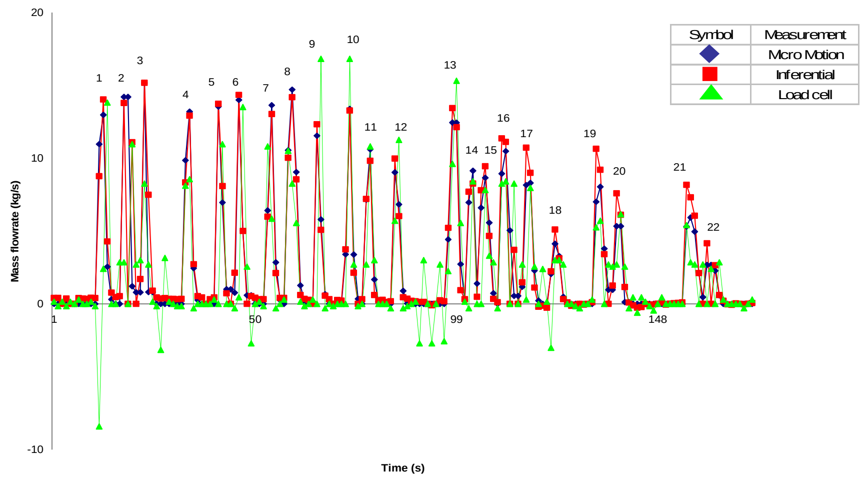

Figure 5.18: Initial source pressure 3300-3300-3300 psig, receiver pressure 20 psig, 22 times of switching

Table 5.17: Total mass when initial source pressure 3300-3300-3300 psig, receiver pressure 20 psig, 22 times of switching

Measurement	**Total Mass (kg)**
Micro Motion	7.726
Inferential coriolis	5.801
Load cell	5.773

Based on Table 5.17, the total mass measured by the Micro Motion and inferential coriolis are 7.726 kg and 5.801 kg, whilst, the total mass measured by the load cell is 5.773 kg, respectively.

In this section, results of multi pressure flow experiments with disturbance have been presented based on Figure 5.17 to Figure 5.18. From the figure, it indicates that higher sets of source tanks pressure are used to supply different requirements at the receiver tank. Figure 5.17 to Figure 5.18 also illustrate the performance of the inferential coriolis as the valve-switching are set at different settings. With the initial source pressure kept similar, and the receiver tank at the same initial pressure, the total mass accumulated in the receiver tank is related to the valve-switching patterns: more frequent valve-switching allows more total mass being accumulated. Please refer to following section for analysis of percentage error based on single pressure flow experiment.

5.5 Analysis of percentage error for single pressure flow

Table 5.18 and Table 5.19 show table of comparisons to analyze percentage error developed by inferential coriolis and Micro Motion in single pressure flow experiment. The performance measure, which is the total mass, is compared to load cell based on percentage error formula. Please refer the percentage error equation shown in the introduction section 5.1.

Table 5.18: Percentage error for inferential coriolis

Experiment	Source pressure	Receiver pressure			Total mass		Percentage error (%)
	Bank1 (psig)	Initial (psig)	Final (psig)	Difference (psig)	Inferential (kg)	Load cell (kg)	
1	3600	0	2400	2400	6.760	6.963	2.915
2	3600	100	2400	2300	6.432	6.411	-0.328
3	3600	500	2500	2000	6.364	6.329	-0.553
4	3600	1000	2600	1600	4.779	4.772	-0.147
5	3600	1500	2800	1300	3.373	3.470	2.795
6	3600	2000	3000	1000	2.442	2.471	1.174
						Average	0.976

Table 5.19: Percentage error for Micro Motion

Experiment	Source pressure	Receiver pressure			Total mass		Percentage error (%)
	Bank1 (psig)	Initial (psig)	Final (psig)	Difference (psig)	Micro Motion (kg)	Load cell (kg)	
1	3600	0	2400	2400	6.686	6.963	3.978
2	3600	100	2400	2300	7.174	6.411	-11.901
3	3600	500	2500	2000	6.285	6.329	0.695
4	3600	1000	2600	1600	5.029	4.772	-5.386
5	3600	1500	2800	1300	3.719	3.470	-7.176
6	3600	2000	3000	1000	2.694	2.471	-9.025
						Average	-4.802

Based on Table 5.18 and Table 5.19, the average of percentage error for inferential coriolis and Micro Motion as compared to load cell is 0.976 % and -4.802 %, respectively. Since the percentage error by the inferential coriolis measurement is closer to 0 %, the inferential coriolis is found to have better performance as compared to the Micro Motion's performance. Further analysis on the percentage error developed by inferential coriolis could be referred from variation of percentage error shown in Figure 5.19.

Figure 5.19 shows variation of percentage error based on results of single pressure flow experiment. The curve is developed by values from difference of receiver pressure and percentage error shown in Table 5.18 and Table 5.19, as x-axis and y-axis, respectively.

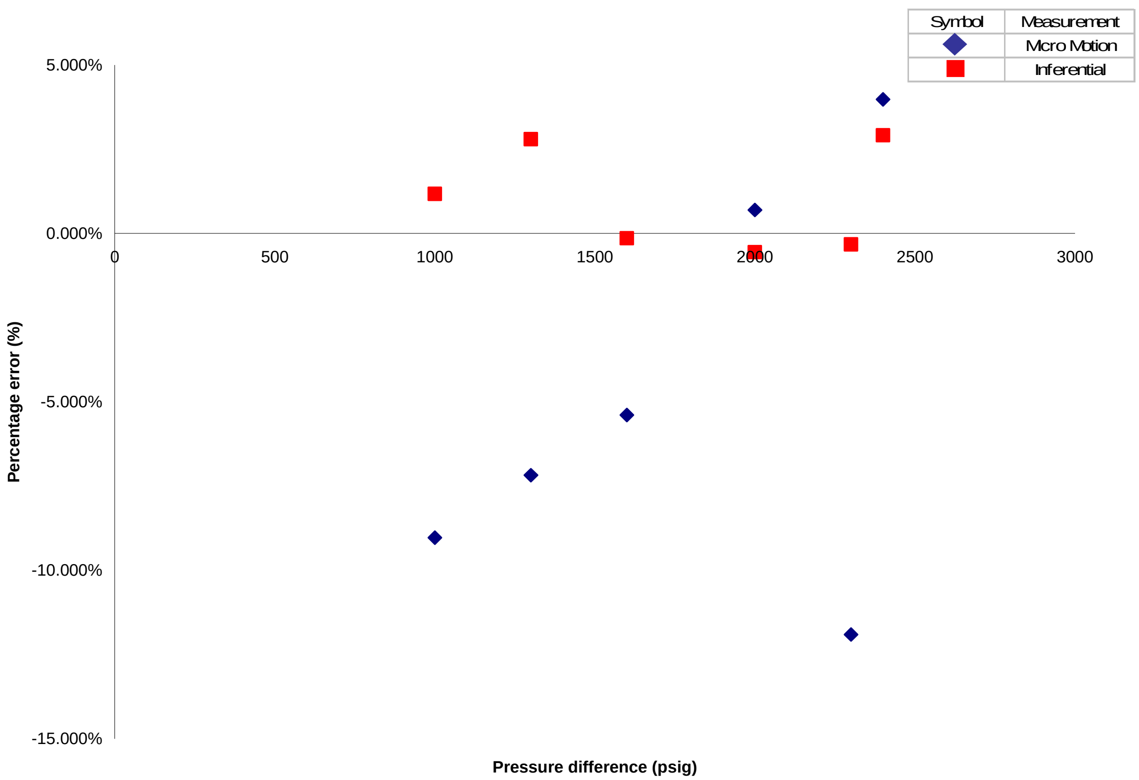

Figure 5.19: Variation of percentage error for single pressure flow experiment

Based on Figure 5.19, it shows the percentage error varies for inferential coriolis and Micro Motion measurements, in which, the accuracy of inferential coriolis is valid at the range of 0 % to 5 %, whilst the accuracy of Micro Motion is valid at the range of 0 % to 15 %, respectively. The smaller range of percentage error developed by the inferential coriolis indicates that the performance is consistent and reliable in the wide range of pressure difference for single pressure flow of CNG refueling. Please refer to following section for analysis of percentage error based on continuous pressure flow experiment.

5.6 Analysis of percentage error for continuous pressure flow

Table 5.20 and Table 5.21 show table of comparisons to analyze percentage error developed by inferential coriolis and Micro Motion in continuous pressure flow experiment. Similarly, the performance measure is the total mass which is compared to the load cell measurement based on percentage error formula.

Table 5.20: Percentage error for inferential coriolis

Experiment	Source pressure			Receiver pressure			Total mass		Percentage error (%)
	Bank1 (psig)	Bank2 (psig)	Bank3 (psig)	Initial (psig)	Final (psig)	Difference (psig)	Inferential (kg)	Load cell (kg)	
1	3600	3600	3600	0	3200	3200	10.125	9.906	-2.211
2	3600	3600	3600	100	3200	3100	9.038	9.183	1.579
3	3600	3600	3600	500	3200	2700	7.172	7.090	-1.157
4	3600	3600	3600	1000	3200	2200	6.031	6.080	0.806
5	3600	3600	3600	1500	3200	2700	5.029	5.047	0.357
6	3600	3600	3600	2000	3200	1200	3.202	3.199	-0.094
								Average	-0.120

Table 5.21: Percentage error for Micro Motion

Experiment	Source pressure			Receiver pressure			Total mass		Percentage error (%)
	Bank1 (psig)	Bank2 (psig)	Bank3 (psig)	Initial (psig)	Final (psig)	Difference (psig)	Micro Motion (kg)	Load cell (kg)	
1	3600	3600	3600	0	3200	3200	9.293	9.906	6.188
2	3600	3600	3600	100	3200	3100	8.864	9.183	3.474
3	3600	3600	3600	500	3200	2700	7.871	7.090	-11.016
4	3600	3600	3600	1000	3200	2200	6.163	6.080	-1.365
5	3600	3600	3600	1500	3200	2700	4.585	5.047	9.154
6	3600	3600	3600	2000	3200	1200	3.187	3.199	0.375
								Average	1.135

Based on Table 5.20 and Table 5.21, the average of percentage error for inferential coriolis and Micro Motion as compared to load cell is -0.120 % and 1.135 %, respectively. In each refueling, the values are compared to the load cell measurement, in which, from the results, it shows that the percentage error of the inferential coriolis is better than the Micro Motion's performance. Since the percentage error is closer to 0 %, the inferential coriolis is expected to have better performance as compared to the Micro Motion in the continuous pressure flow of CNG. Further analysis on the percentage error developed by inferential coriolis could be referred from variation of percentage error shown in Figure 5.20.

Figure 5.20 shows graph of percentage error based on results of continuous pressure flow experiment. The curve is developed by values from difference of receiver pressure and percentage error shown in Table 5.20 and Table 5.21, as x-axis and y-axis, respectively.

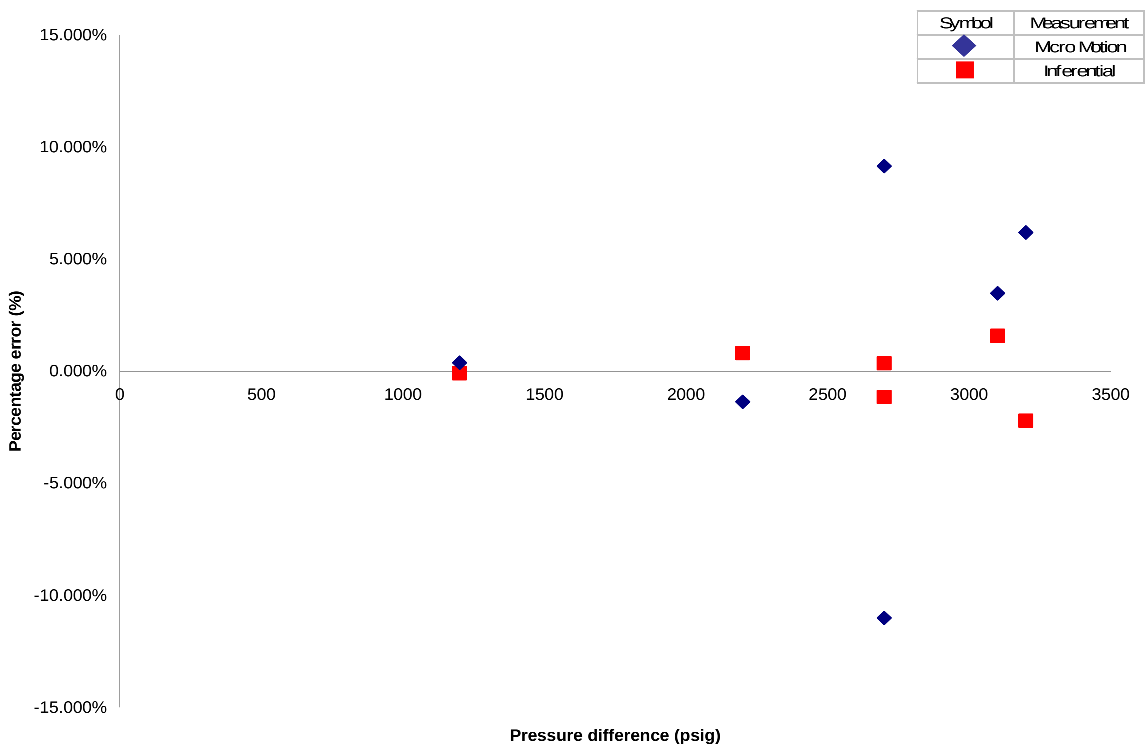

Figure 5.20: Variation of percentage error for continuous pressure flow experiment

Based on Figure 5.20, variation of percentage errors could be analyzed for inferential coriolis and Micro Motion, in which, the analysis shows the accuracy of inferential coriolis is valid at the range of 1 % to -2 %, whilst the accuracy of Micro Motion is valid at the range of 10 % to -15 %, respectively. Notice that, the smaller range of percentage error developed by the inferential coriolis indicates that the performance is consistent and reliable in the wide range of pressure difference for continuous pressure flow of CNG refueling. Please refer to following section for analysis of percentage error based on multi pressure flow experiment with disturbance.

5.7 Analysis of percentage error for multi pressure flow with disturbance

Table 5.22 and Table 5.23 show table of comparisons to analyze percentage error developed by inferential coriolis and Micro Motion in multi pressure flow experiment with disturbance. As described by the previous experiments, the performance measure is the total mass, which is compared to load cell based on percentage error analysis.

Table 5.22: Percentage error for inferential coriolis

Experiment	Source pressure			Receiver pressure			Total mass		Number of valves switching	Percentage error (%)
	Bank1 (psig)	Bank2 (psig)	Bank3 (psig)	Initial (psig)	Final (psig)	Difference (psig)	Inferential (kg)	Load cell (kg)		
1	2000	3000	3600	20	2400	2380	6.893	6.914	0	0.304
2	1000	2000	3000	20	1800	1780	4.493	4.584	0	1.985
3	290	1450	3600	20	1600	1580	4.655	4.631	0	-0.518
4	3300	3300	3300	20	1000	980	2.501	2.478	7	-0.928
5	3300	3300	3300	20	2500	2480	5.801	5.773	22	-0.485
									Average	0.071

Table 5.23: Percentage error for Micro Motion

Experiment	Source pressure			Receiver pressure			Total mass		Number of valve switching	Percentage error (%)
	Bank1 (psig)	Bank2 (psig)	Bank3 (psig)	Initial (psig)	Final (psig)	Difference (psig)	Micro Motion (kg)	Load cell (kg)		
1	2000	3000	3600	20	2400	2380	7.273	6.914	0	-5.192
2	1000	2000	3000	20	1800	1780	5.414	4.584	0	-18.106
3	290	1450	3600	20	1600	1580	4.874	4.631	0	-5.247
4	3300	3300	3300	20	1000	980	3.012	2.478	7	-21.550
5	3300	3300	3300	20	2500	2480	7.726	5.773	22	-33.830
									Average	-16.785

Based on Table 5.22 and Table 5.23, the average of percentage error for inferential coriolis and Micro Motion as compared to load cell is 0.071 % and -16.785 %, respectively. Interestingly, the observation is similar with the performance shown in single pressure flow and continuous pressure flow experiment, in which, it shows the percentage error is closer to 0 %. Since the percentage error is closer to 0 %, the inferential coriolis has better performance than the Micro Motion also when disturbance is applied in multi pressure flow of CNG. Further analysis on the percentage error developed by inferential coriolis could be referred from variation of percentage error shown in Figure 5.21.

Figure 5.21 shows graph of percentage error based on results of multi pressure flow experiment with disturbance. The curve is developed by values from difference of receiver pressure and percentage error shown in Table 5.22 and Table 5.23, as x-axis and y-axis, respectively.

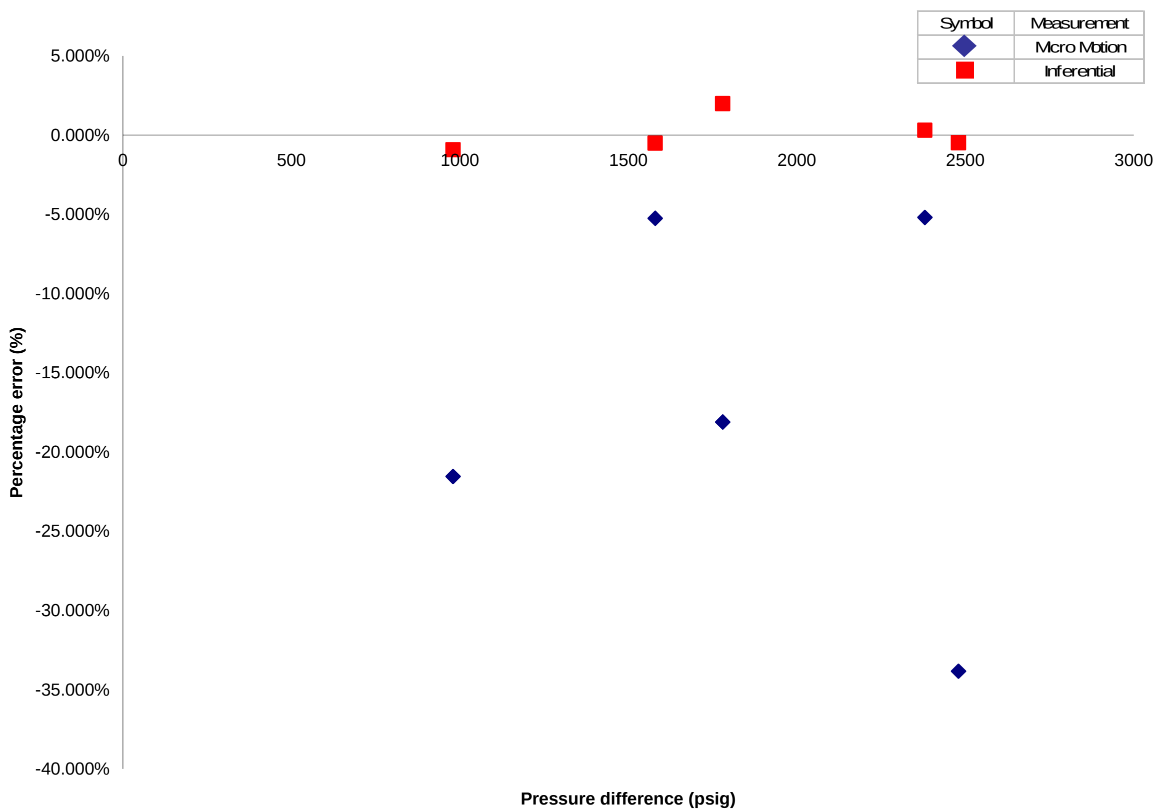

Figure 5.21: Variation of percentage error for multi pressure flow experiment with disturbances

Based on Figure 5.21, further justification on performance of inferential coriolis and Micro Motion could be made. Notice that, the inferential coriolis has a smaller variation of error as compared to the Micro Motion, in which, the accuracy of inferential coriolis is valid at the range of -1 % to 2 %, whilst the accuracy of Micro Motion is valid at the range of 0 % to -35 %. As depicted in Table 5.22 and 5.23, the results verify that the inferential coriolis performs better than the Micro Motion flowmeter in various flow of CNG also when disturbance is applied. A similar phenomenon is also observed for the case of the single pressure flow as well as the continuous pressure flows; see Tables 5.18 and 5.19, and Table 5.20 and 5.21, respectively.

The results as shown in sections 5.2 to 5.7 provide an indication that the proposed inferential coriolis is performing as expected, that is by,

a) Visual checks: the model output graphs do suggest that the inferential coriolis performs correctly, and
b) Inspection of results: the performance of the inferential coriolis does match the performances of the standard coriolis used in practical.

5.8 Discussion

Based on results tabulated in Table 5.18 and Table 5.19 from a single pressure flow experiment, the average percentage error by the inferential coriolis and the Micro Motion are 0.976 % and -4.802 %, respectively. Likewise, based on Table 5.20 and Table 5.21 of continuous pressure flow experiment, the average percentage error of the inferential coriolis and the Micro Motion are -0.120 % and 1.135 %, respectively. Similarly, based on Table 5.22 and Table 5.23 of multi pressure flow experiment with disturbance, the average percentage error by the inferential coriolis and the Micro Motion are 0.071 % and -16.785 %, respectively. During these experiments, the occurrences of unexpected events, such as an abnormal pulse, a temporary sensor failure, or transmitter failure, could corrupt the data samples. One of the examples could be seen from the load cell graph. Load cell is a very accurate device that the signals measured are susceptible to noise such as wind surrounding and tank vibration due to gas flow. It would be expected that these disturbances i.e., also defined as outliers by [30], could severely distort the resulting graphs. A green spark shown in Figure 5.2 is a typical example for an outlier in load cell measurement. Apart of that, there is a unique condition occurs known as back pressure as shown in Figure 5.3.When back pressure occurs, receiver pressure is much higher than the storage pressure, in which the pressure is able to push towards the direction of current flow, as indicated by a small peak in Figure 5.3, respectively. However, outliers have been filtered for the final mass analysis. As a conclusion, basically all measurements by the inferential coriolis approaches to zero percentage error indicating that it measures with less error compares to Micro Motion, which could be seen from variation of percentage error shown in Figure 5.19, Figure 5.20 and Figure 5.21, respectively.

5.9 Summary

This chapter reports the functional and the performance of the inferential coriolis flowmeter, specially embedded in the FieldPoint controller and then tested on an experimental test rig. Pressure flow test is an experiment to observe the transferring of higher pressure natural gas from cascaded storage tank to the receiver tank. In the experiment, the receiver pressure is measured by a pressure sensor, whilst the mass flowrate is measured using the inferential coriolis developed and the Micro Motion coriolis flowmeter. To validate the mass measured by both methods, a load cell is used as the reference value. The performances are compared which is based on three types of flow conditions: single pressure flow; continuous pressure flow; multi pressure flow with disturbance. Interestingly, all measurements by the inferential coriolis approach to zero percentage error indicating the algorithm used is capable of providing smaller percentage error compares to the one used in the practical case. The inferential coriolis technique implemented here are also able to provide cost saving for the CNG refueling companies and operators.

Even though the inferential coriolis developed in this works was limited to the situations that have been discussed in this thesis, other practical application of this inferential technique would be worth investigated. Its development would be similar and straightforward to what that has been presented.