CMC
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VERIFICATION OF
QUANTITATIVE OPTICAL GAS IMAGING SYSTEM
(QOGI)

PREPARED FOR
SASKATCHEWAN RESEARCH COUNCIL (SRC)

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1. Executive Summary

The objective of this report is to provide an independent verification of a quantitative optical gas imaging (QOGI) technology developed by Providence Photonics based on the requirements of ISO-14034 for Environmental Technology Verification Standard.

The Saskatchewan Research Council (SRC) has completed the initial controlled field trial (fall 2017), and the verification testing campaign (spring 2018) of Quantitative Optical Gas Imaging System with the QL320 quantification tool developed by Providence Photonics. The details of the test have been collected in two reports made by SRC. CMC Research Institutes is providing its evaluation of those test results in this document, which is a complementary to SRC data analysis efforts.

This project received financial support from the Alberta Upstream Petroleum Research Fund (AUPRF), managed by Petroleum Technology Alliance Canada (PTAC).

2. Identification of the Verifier

Third party verification is conducted by CMC Research Institutes, having its office located in 3535 Research Road, NW, Calgary, Alberta, Canada, T2L 2K8, hereinafter is referred to as “CMCRI”.

3. Identification of the applicant

Technology is developed by Providence Photonics, having its office located at 1201 Main Street, Baton Rouge, LA, US, 70802. Providence Photonics is specialized in the development and utilization of advanced technologies for optical gas imaging and developed a new technology for quantitative optical gas imaging.

4. Identification of the report and date of issue

This report is written by CMCRI on September 2018 based on the data collected by SRC during the initial controlled field trial campaign (fall 2017), and the verification testing campaign (spring 2018).

5. Date of verification

Third party verification by CMCRI was conducted in August and September of 2018.

6. Description of the technology

Technology is based on US Patent and Trademark Office Patent No. 9,225,915 B2 [1]. The QL320 quantitative optical gas imaging technology is designed to work with FLIR GF320/GFx320 handle-held gas detection cameras to provide a quantitative measurement of the leak rates for most of the hydrocarbons. The QL320 analyzes the infrared image from the FLIR camera and analyzes the picture intensity, on a pixel by pixel basis. Each plume pixel is a representative of a gas column between the camera and the background. At a given temperature difference between the plume and the background, pixel intensity is proportional to the molecules in the gas column; hence it can be used to predict the quantity of the gas. References [1] and [2] provide comprehensive details on the technology.

7. Field experimental data

Experimental results of the both campaigns are presented in Appendix 14.1.

8. Verification

The objective of the field tests was to measure the volumetric flow rate of the gas leak using QL320 in conjunction with FLIR GFx320 cameras to validate the results under various conditions. The initial controlled field trial campaign was conducted during fall of 2017. All tests were performed at SRC's outdoor test facility in Saskatoon, SK. A controlled release of methane was simulated using piping and a valve. Ambient temperature was measured on site using a thermometer and wind speed data were collected from SRC's climate reference station at the proximity of the testing facility.

The verification testing campaign was conducted by SRC at an operational battery, located at about 85 km southeast of Regina, SK, during May 29th to June 27th, 2018.

8.1. Methodology

Combination of statistical and data visualization methods are employed to analyze and interpret the experimental data. Experimental design and conditions were selected by SRC based on the stakeholder's input.

Verification is conducted on the available data and to examine for the following:

- Measurement repeatability of the readings for one gas.
- Investigate the significant effect of variables and their combinations during the initial controlled field trial campaign.
- Evaluate whether the measured values were within the accuracy range of ± 30% of the actual value.
- Measurement reliability considering the environmental variables for each gas.
- Check for the effect of environmental variables when the tests were conducted at different times of the day.
- Evaluate the response when various gas types are tested.
- Investigate the effect of notching on the readings.
- Evaluate the operational conditions and limitations in the field.

8.2. Test conditions

8.2.1. Initial controlled field trial campaign

During the initial controlled field trial campaign, combinations of two levels of flow rates and distance were tested at various environmental conditions (i.e., temperature and wind speed). Limits of variables were selected prior to the campaign, however it is not possible to control environmental conditions, therefore wind speed and temperature were measured and considered as co-variants in the statistical analysis. A summary of the experimental design is listed in Table 1.

Table 1 Experimental design of the initial controlled field trial campaign

Flow rate (cm^3/min)[1]	2000, 10,000
Distance (m)	2, 4
ΔT (°C)	5 and 20
Temperature (°C)	-5 and +5
Wind speed (km/h)	<8 and >8

8.2.2. Verification testing campaign

Three types of gas including methane and two gas mixtures were tested. The specification of the mixed gases is presented in Table 2.

Table 2 Composition of mixed gases

Composition (wt %)	A Natural Gas – Fuel Gas	C Crude Oil-light/ med vapor
Nitrogen	1.1	4.0
Carbon Dioxide	1.5	10.0
Methane	84.2	55.5
Ethane	9.3	11.5
Propane	2.6	10.0
Butane	1.1	6.0
Pentane	0.2	3.0

1) Flow rate: Tests were conducted at three flow rate levels of 1000, 5000, and 10,000 cm^3/min.
2) Distance: The distance between the camera and the emission source was kept constant at 2m.
3) Temperature and wind direction and wind speed are monitored and recorded as the environmental variables during the test.

The experiment provided a basis for evaluation and verification of the technology for three different gas types and three levels of flow rates at a

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[1] 1000 cm^3/min equals to 1 L/min (lpm)

constant distance of 2m from the leak source and at the known environmental conditions.

The results collected during week one showed a high level of noise and low level of signal due to the reflectance of pipes insulation present at the field. The reflectance resulted in an unstable background during the readings and made it hard to extract the plume signals, particularly at the lower flow rates. Therefore, the results of week one are excluded from the majority of the analysis.

In order to minimize the effect of reflectance, "Notch boundary" setting that excludes the area of the insulation from the measurement ring was also investigated (notching practice).

8.3. Highlights of the results from initial controlled field trial campaign

8.3.1. Analysis of variance (ANOVA)

ANOVA was used in order to determine whether the differences between the group means are statistically significant at $\alpha = 5\%$.

The null hypothesis is stated as H_0: Flow rate mean-values are equal in each test run, and H_a: Flow rate mean-values are not equal in each test run. The results are presented in Tables 3 and 4.

Table 3 ANOVA results at the flow rate of 2(L/min)

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1114484782	21	53070703.9	18.30819	1.18E-23	1.677223678
Within Groups	255089240	88	2898741.364			
Total	1369574022	109				

Table 4 ANOVA results at the flow rate of 10(L/min)

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	15717841438	31	507027143.2	44.27739	5E-54	1.541769135
Within Groups	1454296235	127	11451151.46			
Total	17172137673	158				

The results showed at both flow rates of 2000(cm^3/min) and 10,000(cm^3/min), the probability (P) is significantly lower than the significance level α (0.05), and $F_{statistics} > F_{critical}$, therefore, the null hypothesis is rejected and the difference between the group mean-values is statistically significant, confirming the effect of various test conditions on the results at the both studied flow rates.

8.3.2. Analysis of co-variance (ANCOVA)

Analysis of covariance was used to test for the significant effect of the independent variables (considered to be ΔT and distance), their combinations on the measured flow rate (dependent variable) and to account for the effect of co-variants (considered to be wind speed and ambient temperature) during the measurements.

- **Tests of Between-Subjects Effects**

As it can be seen in Table 5, the probability of ΔT, distance and their combination is less than 0.05, therefore they have the significant effect on the response, while the probability of wind speed and temperature is higher than 0.05, which shows they don't have a significant effect (or their effect is corrected during the ANCOVA process). Moreover, F-test showed for temperature, $F(33,1)= 250.09>F_{statistics} = 0.278$, for wind speed, $F(33,1) = 250.09 > F_{statistics} =0.703$, for distance $F(33,1)=250.09>F_{statistics} = 8.5$ therefore, the effect of temperature, wind speed and distance are not significant. For ∆T, $F(33,24) = 1.98 < F_{statistics} = 8.14$, and for the combination of ΔT and distance, $F(33,6)=3.8<F_{statistics} = 7.8$, therefore ∆T and its combination with distance have both significant effect.

Table 5 ANCOVA results

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	7104119448.048^a	33	215276346.911	7.076	.000
Intercept	200480617.180	1	200480617.180	6.590	.015
Temperature	8444738.169	1	8444738.169	.278	.602
Wind-Speed	21380917.751	1	21380917.751	.703	.408
∆T	5939953503.131	24	247498062.630	8.135	.000
Distance	260775239.907	1	260775239.907	8.572	.006
∆T * Distance	1425328261.360	6	237554710.227	7.808	.000
Error	1034393277.198	34	30423331.682		
Total	11527870465.250	68			
Corrected Total	8138512725.246	67			

- **Levene's Test of Equality of Error Variances**

This tests the null hypothesis that the error variance of the dependent variable is equal across the groups. According to the results presented in Table 6, $F(30,30)=1.84 <F_{statistics} = 9.7$, therefore there is not enough evidence to support the null hypothesis, therefore null hypothesis is rejected and the error is not equal across the groups.

Table 6 Levene's Test of Equality of Error Variances

F	df1	df2	Sig.
9.788	31	36	.000

- **F-Test for Heteroskedasticity**

This tests the null hypothesis that the variance of the errors does not depend on the values of the independent variables. The results showed, F(1,60) = 4 >$F_{statistics}$=0.925, therefore the null hypothesis cannot be rejected, meaning the variance of error does not depend on the values of the independent variables (Table 7). In other words, it can be concluded that the measurement shows various levels of error when various combinations of conditions are tested.

Table 7 Results of F test for Heteroskedasticity

F	df1	df2	Sig.
.925	1	66	.340

8.3.3. Key findings from controlled field trail results

1) Reviewing the results showed, when the absolute value of ∆T =5 and 4 °C, the flow rate of 2000 (cm^3/min) didn't have an outcome and the measured value was zero in most of the cases. This shows the instrument doesn't provide an appropriate response at the low flow rate of 2000 (cm^3/min) and at the mentioned range of ∆T.
2) The difference between the group mean-values is proven to be statistically significant that restates the effect of independent variables (i.e., distance and ∆T) and also the ambient environmental conditions on the results.
3) ∆T, distance and their combination showed a significant effect on the results that emphasize the impact of appropriate environmental conditions during measurements and consideration of distance as an operational parameter during measurements.
4) The error is not equal across the groups and its variance doesn't depend on the values of the independent variables. Hence, it is important to detect the possible sources of error and try to eliminate it during the experiments.

8.4. Analysis of the results of the verification testing campaign

8.4.1. The variability in the results

In order to understand the variability in the results, graphs showing measured flow rates versus the actual flow rates for the three studied gases are shown in Figures 1 - 3. The graphs do not include the data collected during week one.

As the graphs show, the measured flow rates are broadly spread in gas types A and methane but less variability is observed in gas type C. The distribution of data is the broadest in gas type A with the measured values higher than three times of the actual flow rate. Gas type C showed the less variability across the sample groups. This could be simply due to the system calibration and the mismatch between the camera's spectral window and the gas's IR absorption peak.

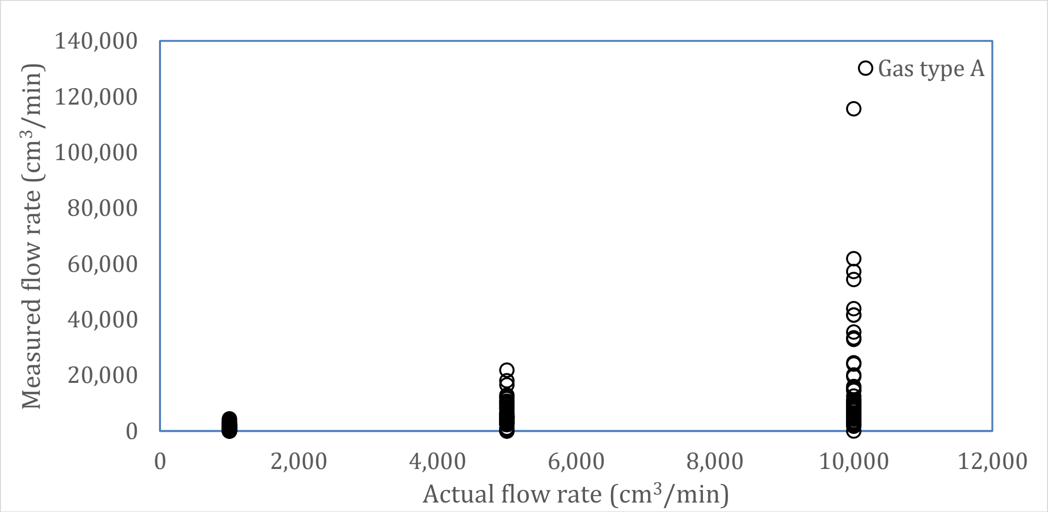


Figure 1 Measured flow rates vs. the actual flow rates of gas A

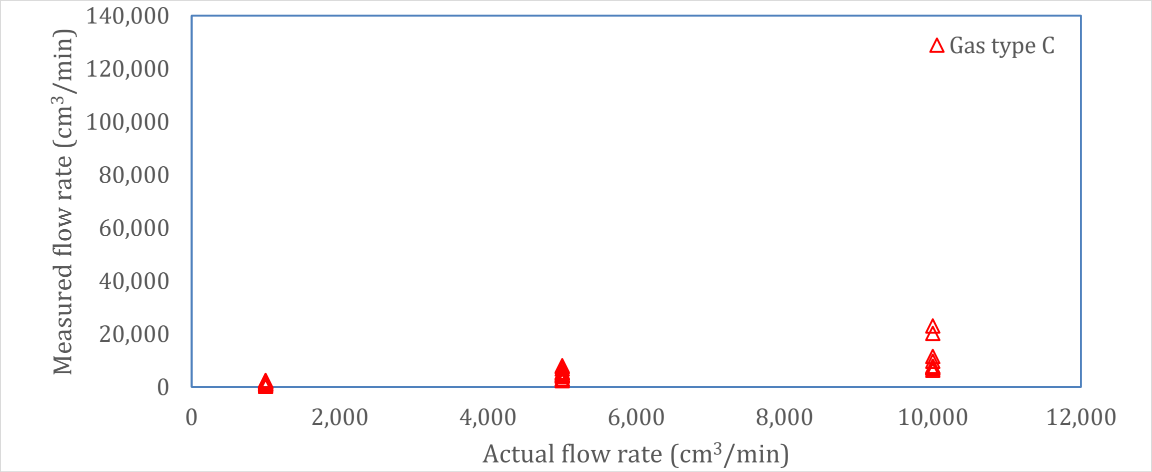


Figure 2 Measured flow rates vs. the actual flow rates of gas C

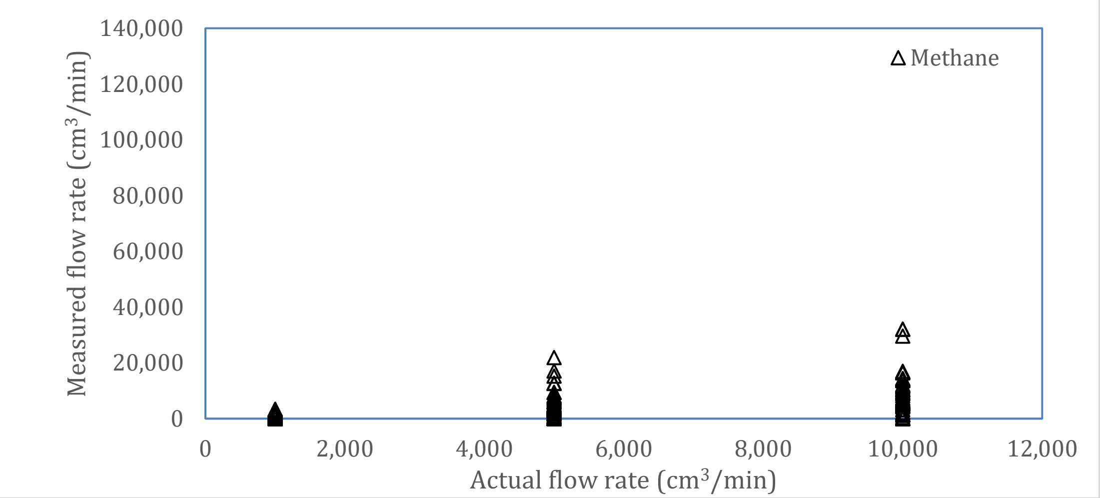


Figure 3 Measured flow rates vs. the actual flow rates of Methane

The range of recorded flow rates is presented in Table 8.

Table 8 Range of the recorded flow rates

Gas Type	Maximum flow rate (cm^3/min)			Minimum measured flow rate
	Measured (Including week one)	Measured (Excluding week one)	Actual	
A	115,710	115,710	10,000	0
C	22,932	-	10,000	270
Methane	50,006	-	5,000	0
Methane	-	32,208	10,000	0

As it is observed in Table 8, the highest recorded flow rate for gas types A (on June 21st) and methane are approximately ten times higher than the actual flow rates. In gas type C, the highest recorded value is about two times higher than the actual flow rate. When the first-week data are excluded from the range study, the results were the same in gas type A, but in methane, the highest measured flow rate was approximately three times higher than the actual flow rate. These numbers can be considered as outliers due to the effect of a random variable in the measurement process as any measurement technique might present variability in the results. However, an accuracy range of ± 30% of the actual flow rate for ambient flow rate measurements is tested in the next section to verify whether the majority of the readings are within a ± 30% range.

8.4.2. Examination of ±30% accuracy range

Histograms are generated for each gas type and the flow rates. The criteria to develop histograms was to check the ±30% of the actual flow rate and evaluate whether the majority of the results are within the specified range for each gas type /flow rate. The study was performed on the data including the results of week 1 and without the results of week 1 and notching. The results are presented in Tables 9 and 10, and the histograms are shown in Appendix 14.2.

Table 9 Frequency distribution of the measurements across various groups

(Reported in percentage and includes the results of the first week)

Flow rate (cm^3/min) - (Including week 1)		1,000	5,000	10,000
Frequency distribution between the accuracy range (±30%)	Gas type A	22	47	28
	Gas type C	N/A	N/A	N/A
	Methane	19	42	24

Table 10- Frequency distribution of the measurements across various groups

(Reported in percentage and excludes the results of the first week and notching)

Flow rate (cm^3/min) – (Excluding week 1)		1,000	5,000	10,000
Frequency distribution between the accuracy range (±30%)	Gas type A	24	55	29
	Gas type C	36	72	75
	Methane	24	50	24

It is expected that 95% of the readings be within the ± 30% accuracy range of the value of the actual flow rate.

As indicated in the tables, in gas types A and methane, the frequency distribution of the within the range readings are the highest at the flow rate of 5000 cm^3/min (i.e., 47% and 42 % in Table 9 and 55% and 50% in Table 10). No measurement is available for gas type C during the first week, and it shows a higher frequency percentage of 72% and 75% at the flow rates of 5000 cm^3/min, and 10,000 cm^3/min. When the results of the first week are excluded, the percentage of the readings within the range of ± 30% increased for both gas types A and methane. In gas type C, at the flow rate of 5000cm^3/min and 10,000cm^3/min the percentage is above 70%, meaning the majority of readings are within the accuracy range. For methane, although the number improved after notching, it is still below the limit.

***Key findings**:*

1) Notching improved quality of the measurements with regards to increasing the frequency distribution of the readings that were within the accuracy

range. For gas type A and methane, the frequency distribution of the underestimated or overestimated readings are still below 70%.

2) Notching improved the frequency distribution of readings for the flow rates of 5000 cm^3/min and 10,000 cm^3/min that were within the ± 30% accuracy range in gas type C.
3) The resulted higher frequency for the flow rate of 5,000 cm^3/min in all gas types, shows the suitability of using this technology for such high flow rates.
4) Given the low-frequency distribution for the flow rate of 1000 cm^3/min, it can be concluded that it might be below the operational limit of the instrument at its condition/setting during the measurement.
5) Different gas types provide different results. This indicates that calibration and proper tuning of the camera and data processing are crucial for reliable results.

Recommendations:

1) When gas mixtures are targeted, calibration of the algorithm based on gas compositional analysis might improve the accuracy of the results. Therefore, it would be useful to have gas compositions analyzed and information stored in the software archive, prior flow rate measurements. This will make sure the response is more accurate as the readings seem to be sensitive to the gas type.
2) To evaluate the detection limit of the methodology, the flow rate of 5000 cm^3/min might be an appropriate starting point as the middle point for a statistical experimental design.
3) The results of the initial controlled field trial campaign (fall 2017), and the measurements during the verification testing campaign (spring 2018) showed a significant difference between the actual and measured flow rates of 1000 cm^3/min and 2000 cm^3/min. This finding necessitates the adjustment of the distance for low flow rates and to make it a key aspect of the technology/user manual. Ideally, the lower detection limit of the instrument should be well defined.
4) Since reflection from pipes and insulation affects the readings, it might worth considering to work with the instrument during certain hours of the day when the light reflection is weak and to appropriately adjust the position of the camera to minimize sunlight reflection.

8.4.3. Evaluating the effect of notching on the results

A t-test was conducted to evaluate whether the difference in the mean-values of measurements was statistically significant with or without notching. The hypothesis is set as:

$$H_0: \mu_1 = \mu_2$$

$$H_1: \mu_1 \neq \mu_2$$

Methane: Three sets of samples, each of which included five readings are selected for t-test (15 readings in total). The test was conducted separately on the flow rates of 5,000 cm^3/min and 10,000 cm^3/min. The results are presented in Tables 11 and 12.

Table 11 t-test results to evaluate the effect of notching on methane at the flow rate of 5000 cm^3/min

	Variable 1 (Flow rate without notching)	*Variable 2 (Flow rate after notching)*
Mean	6474.00	5722.67
Variance	61440168.57	16616006.67
Observations	15.00	15.00
Pearson Correlation	-0.15	
Hypothesized Mean Difference	0.00	
df	14.00	
t Stat	0.31	
P(T<=t) one-tail	0.38	
t Critical one-tail	1.76	
P(T<=t) two-tail	0.76	
t Critical two-tail	2.14	

Table 12 t-test results to evaluate the effect of notching on methane at the flow rate of 10,000 cm^3/min

	Variable 1 (Flow rate without notching)	*Variable 2 (Flow rate after notching)*
Mean	8726.00	10996.67
Variance	25584240.00	54539052.38
Observations	15.00	15.00
Pearson Correlation	-0.20	
Hypothesized Mean Difference	0.00	
df	14.00	
t Stat	-0.90	
P(T<=t) one-tail	0.19	
t Critical one-tail	1.76	
P(T<=t) two-tail	0.38	
t Critical two-tail	2.14	

At the both flow rates, $t_{stat} > -t_{critical}$ two tail. Therefore, H_0 cannot be rejected. It can be claimed that there is not enough evidence to conclude the average number of two runs significantly differ. This shows notching did not affect the quality of the measured data, however, when the results of notching are added to the whole data set, the frequency of acquiring the results that are within the accuracy range is improved.

Gas type A:

Three sets of samples, each of which included five readings are selected for t-test (15 readings in total). The test was conducted separately on the flow rates of 1000 cm^3/min and 10,000 cm^3/min. The results are shown in Tables 13 and 14.

Table 13 t-test results to evaluate the effect of notching on gas type A at the flow rate of 1000 cm^3/min

	Variable 1 (Flow rate without notching)	Variable 2 (Flow rate after notching)
Mean	1792.00	3251.33
Variance	487102.86	1805883.81
Observations	15.00	15.00
Pearson Correlation	-0.40	
Hypothesized Mean Difference	0.00	
df	14.00	
t Stat	-3.24	
P(T<=t) one-tail	0.00	
t Critical one-tail	1.76	
P(T<=t) two-tail	0.01	
t Critical two-tail	2.14	

t_{stat} (-3.23) < $-t_{critical}$ two tail (-2.14) and P<α, therefore there is insufficient evidence that the mean-values are equal, meaning there is not enough evidence to accept the null hypothesis, which means notching affected the quality of data.

Table 14 t-test results to evaluate the effect of notching on gas type A at the flow rate of 10,000 cm^3/min

	Variable 1 (Flow rate without notching)	Variable 2 (Flow rate after notching)
Mean	2835.333	12408.67
Variance	5340698	89527084
Observations	15	15
Pearson Correlation	0.006237	
Hypothesized Mean Difference	0	
df	14	
t Stat	-3.81219	
P(T<=t) one-tail	0.000952	
t Critical one-tail	1.76131	

P(T<=t) two-tail	0.001904
t Critical two-tail	2.144787

t_{stat}(-3.81)<-$t_{critical}$ (-1.7) and P<α , therefore there is insufficient evidence to accept the null hypothesis, which means notching affected the quality of data. There is not any notching data available for gas type C.

***Key findings**:*

1) The difference between the mean-values was statistically significant in gas type A, suggesting notching affected the quality of data in gas type A and at both flow rates of 1000 cm^3/min and 10,000 cm^3/min.
2) In methane, the comparison between the results of the hypothesis test and the histogram study, showed similar results at the flow rate of 10,000 cm^3/min, suggesting that notching did not improve the quality of the measurements.
3) At the flow rate of 5000 cm^3/min in methane, the histogram showed notching increased the number of readings that were within the accuracy range. Whereas, the statistical t-test which is a direct comparison, showed the data does not provide sufficient evidence to reject the null hypothesis. Therefore, it cannot be concluded that the mean-values of various measurements differ significantly.

8.4.4. Analysis of the temporal light reflectance variation

The effect of light reflection/ interference during measurements might vary when solar angle changes during the day. The primary objective of this test was to figure out whether the quality of recordings varied in the mornings and evenings during week one when light reflectance interfered the measurements. In addition to temperature and wind speed variations that always happening, solar angle is another variable which may affect the light reflection from the background material such as pipes insulation. The comparison was conducted on gas type A, between morning and afternoon of the May 30th, and between measurements on the May 30th and 31st, at the flow rate of 1000cm^3/min.

Null hypothesis (H_0): $\mu_1 - \mu_2 = 0$
Alternative hypothesis (H_a): $\mu_1 - \mu_2 \neq 0$

Table 15 t-test results on the data collected during the morning and afternoon of May 30th, at the flow rate of 1000 (cm^3/min)

	Variable 1 (Flow rate in the morning)	*Variable 2 (Flow rate in the afternoon)*
Mean	1594.00	1251.00
Variance	8239705.60	1483135.60

Observations	6.00	6.00
Pearson Correlation	0.49	
Hypothesized Mean Difference	0.00	
df	5.00	
t Stat	0.33	
P(T<=t) one-tail	0.38	
t Critical one-tail	2.02	
P(T<=t) two-tail	0.75	
t Critical two-tail	2.57	

$t_{stat} > -t_{critical}$, therefore, H_0 is accepted, meaning mean-values are equal during the two tests runs.

Table 16 t-test results on the data collected on May, 30th and 31st, at the flow rate of 1000 (cm^3/min)

	Variable 1 (Flow rates on the 30th)	*Variable 2 (Flow rates on the 31st)*
Mean	1422.50	4569.50
Variance	4451559.36	33711210.27
Observations	12.00	12.00
Pearson Correlation	-0.01	
Hypothesized Mean Difference	0.00	
df	11.00	
t Stat	-1.76	
P(T<=t) one-tail	0.05	
t Critical one-tail	1.80	
P(T<=t) two-tail	0.11	
t Critical two-tail	2.20	

$t_{stat} > -t_{critical}$, therefore, H_0 cannot be rejected, suggesting mean-values are equal during the two tests runs.

It can be concluded that the results presented here do not show a statistical difference between the measurements in the morning and evening.

8.4.5. Effect of the range of ΔT on the results

A hypothesis test is conducted at different values for ΔT with the objective to evaluate whether the value (or the range) of ΔT affects the quality of the readings. This test is only conducted on the gas type A. In the other gas types, the majority of the recordings were acquired at ΔT below 10, and there is not much data available for statistical comparison. The results are presented in Tables 17 and 18.

Table 17 t-test results on ΔT<5 and ΔT>10, at the flow rate of 5000 cm³/min

	Flow rate at ΔT<5	*Flow rate at ΔT*>5
Mean	5946.67	6558.67
Variance	3243123.00	14252163.00
Observations	9.00	9.00
Pearson Correlation	-0.18	
Hypothesized Mean Difference	0.00	
df	8.00	
t Stat	-0.41	
P(T<=t) one-tail	0.35	
t Critical one-tail	1.86	
P(T<=t) two-tail	0.69	
t Critical two-tail	2.31	

Table 18 t-test results on ΔT<5 and ΔT>10, at the flow rate of 10,000 cm³/min

	Flow rate at ΔT<5	*Flow rate at ΔT*>5
Mean	6351.11	11526.67
Variance	30615777.11	15747810.00
Observations	9.00	9.00
Pearson Correlation	-0.04	
Hypothesized Mean Difference	0.00	
df	8.00	
t Stat	-2.24	
P(T<=t) one-tail	0.03	
t Critical one-tail	1.86	
P(T<=t) two-tail	0.06	
t Critical two-tail	2.31	

At the both flow rates, t_{stat} <-$t_{critical}$ two tail, therefore the null hypothesis cannot be rejected. It can be concluded that *ΔT* below five or above ten does not affect the mean-values at both flow rates of 5000 cm^3/min and 10,000 cm^3/min.

8.4.6. A comparison between gas types

8.4.6.1. Analysis of Variance (ANOVA)

Analysis of variance (ANOVA) is used to determine whether there is a statistically significant difference between the mean-values of the studied groups. The objective of ANOVA was to test the null hypothesis that the mean-values of several populations (i.e., each gas type at a similar flow rate) are all equal ($\mu_1 = \mu_2 = \mu_3$). The study is conducted on the flow rates of 5000 cm^3/min and 10,000 cm^3/min, excluding the results of week one and notching. The results are presented in Appendix 14.3.

The results of F-test showed at the flow rate of 5000 cm^3/min, $F_{statistics}(3.40) > F_{crit}$ (3.18), therefore there is not enough evidence to accept the null hypothesis. It can be stated that the mean-values of the three populations are not all equal, meaning at least one of the mean-values is different. The probability (P) was 0.04 that is less than the significance level of 0.05, therefore not all the population mean-values are equal. In order to identify where the difference is, a t-Test is required to test each pair of mean-values.
At the flow rate of 10,000 cm^3/min, $F(1.57) < F_{critical}$ (3.28) and the probability is 0.22 which is higher than the significance value of 0.05. Therefore, we cannot reject the null hypothesis, meaning the differences between the group mean-values are not statistically significant. Therefore, gas type didn't make a difference at the flow rate of 10,000 cm^3/min. However, paired comparisons are also conducted on the flow rate of 10,000 cm^3/min.

8.4.6.2. Paired comparisons (t-test)

Paired comparisons of the studied groups (i.e., each gas type at a similar flow rate) are conducted using t-test at the confidence level of α=0.05 and assuming unequal variances. T-test assuming unequal variances is used to identify where the difference in group mean-values lie. The results are presented in Appendix 14.4 and are summarized in Table 19.

Table 19 Results of t-test on the two-by-two comparisons of gas types

Flow rate (cm^3/min)	5000	10,000
A and C	Rejected	Rejected
A and methane	Not rejected	Not rejected
C and methane	Rejected	Not rejected

The results showed that there is statistically significant difference between the group mean-values in gas type A and methane at the both flow rates of 5000 and 10,000. Group mean-values are not statistically different in gas types A and C at the studied flow rates. At the flow rate of 5000 cm^3/min, group mean-values are statistically different between gas types C and methane, whereas the difference is not statistically significant at the flow rate of 10,000 cm^3/min.

8.4.6.3. Comparison between ANOVA and t-test results

ANOVA results on the flow rate of 5000 cm^3/min, showed at least one group mean-value is statistically different, but the difference between the group mean-values is not statistically significant at the flow rate of 10,000 cm^3/min.

However, the paired comparison using t-test did not provide similar results at the flow rate of 10,000 cm^3/min, where the difference between the group mean-values of gas type A and C was statistically significant.

However, it should be noted that one major difference between ANOVA and t-test is the difference in the degree of freedom, due to the limited number of measurements in gas type C. In ANOVA, to compare mean-values in three groups, 18 measurements at the flow rate of 5,000 cm^3/min and 12 measurements at the flow rate of 10,000 cm^3/min were used that provided less degree of freedom compared to the paired comparisons in t-test.

9. Constraints

1) Ambient environmental conditions are the major constraints of this technology. As wind speed and its direction vary frequently, and randomly affecting the gas plume shape and concentration, it becomes critical for the operation of QL320 to be properly adjusted for an optimum view-angle and camera's position.
2) Another uncontrolled variable is ambient temperature. However, if a measurement is conducted quickly, the effect of temperature change under ambient environmental conditions might be negligible.
3) Reflection from background material, shiny insulations, and surrounding environment affect the quality of the readings, making it necessary to adjust boundary setting and utilizing advanced features of the QL320 for data processing.
4) Gas type and limited measurements will also are influential to the accuracy of quantitative gas imaging.

10. Limitations

1) Instrument limitation: QL320 technology analyzes the image from a FLIR camera. Various gases have different light absorption constants and QL320 is able to measure the flow rate of the different gases that are included in its algorithm. In addition to the gas type and concentration that impact the intensity of the pixels, the results showed gas composition should also be considered as anther variable that plays an important role in the resulted signal.
2) Seasonal variations: The imaging technology is claimed to be dependent on temperature differential (ΔT) and pixels intensity. Since temperature differential is a function of temporal variations on a specific geographical location, it becomes important to consider the ambient environmental conditions for planning any field testing campaign.
3) Testing environment and infrastructures around the emission source affects the reflection and the pixel intensity of images that implies applying of the boundary setting feature (notching).

11. Conclusions

Initial controlled field trial campaign

1) The flow rate of 2000 cm^3/min resulted in a zero response in most of the measurements at the absolute ΔT value of 5 °C and 4 °C, suggesting the low flow rate of 2000 cm^3/min might be below the instrument detection limit at those ΔTs.
2) Analysis of Co-Variance (ANCOVA) showed that distance, ΔT and their combination have a significant effect on the measurements. The changes in the ambient temperature, cause variations in ΔT. This phenomenon restates that environmental conditions should be taken into account for planning field campaigns.
3) Moreover, the value of the error across the groups does not depend on the amount of the independent variables (i.e., distance and ΔT), making it essential to find the root causes of the error to minimize or delete it.

Verification testing campaign

1) To evaluate the accuracy of the measurements, a ±30% deviation range was used. The frequency distribution of the results in gas type C showed more than 70% of the measurements at the flow rates of 5000 to 10,000 cm^3/min were within the accuracy range.
2) Regardless of the gas type and composition, the percentage of the results that are within the accuracy range is higher at the flow rates of 5000 and 10,000 cm^3/min (i.e., 72% and 75% respectively in the gas type C), suggesting the higher accuracy of the technology for such flow rates.
3) Notching improved the quality of the readings in gas types A and methane, but the percentage of the frequency distribution of the results is still below 70% of the actual value.
4) A t-test showed the mean values of the results with and without notching are not statistically equal in gas type A, at the flow rate of 1000 and 10,000 cm^3/min. This finding suggests notching affected the quality of the data. In methane, t-test did not provide sufficient evidence to confirm the improvement of the results using the notching technique.
5) A paired comparison for evaluating the effect of temporal variation of sunlight reflectance did not show a statistically significant difference between the measurements in the morning and the afternoon.
6) ANOVA was used to determine whether there is a statistically significant difference between the gas types at the identical flow rates. The results showed a difference between the group means at the flow rate of 5000 cm^3/min, whereas the difference was not statistically significant at the flow rate of 10,000 cm^3/min. Further evaluation of the results using a paired comparison (t-test), showed the instrument is less likely to differentiate between the gas types at the higher tested flow rate of 10,000 cm^3/min.

12. Recommendations for future studies

1) Testing the QL320 technology for various (and possible) field gas compositions on site and adding that feature to the existing algorithm that already includes various gas types.
2) Testing to identify the operational range (i.e., the lower limit of the measurements), and to develop a standard operating procedure which may require a particular experimental design.

13. Approval

S. Odendahl

Name: Sandra Odendahl (P.Eng, CFA)
Position: President and CEO
CMC Research Institutes
Date: December 11, 2018

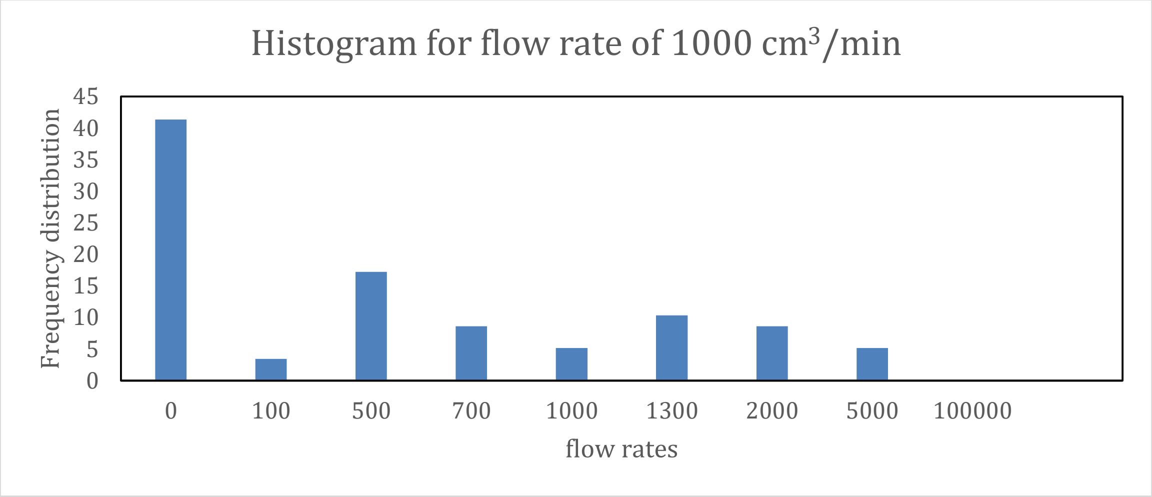
14. Appendices

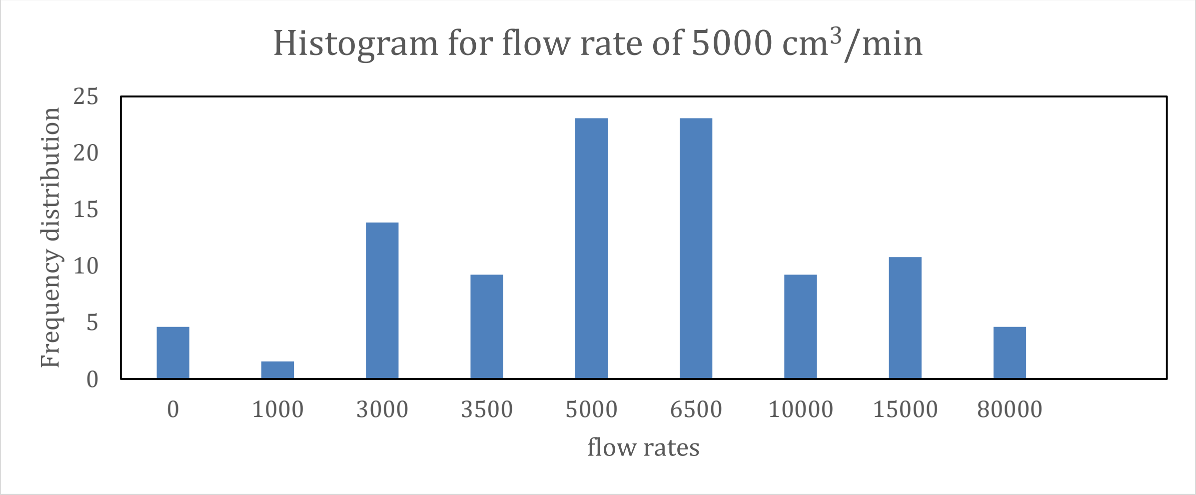
14.1. Test results

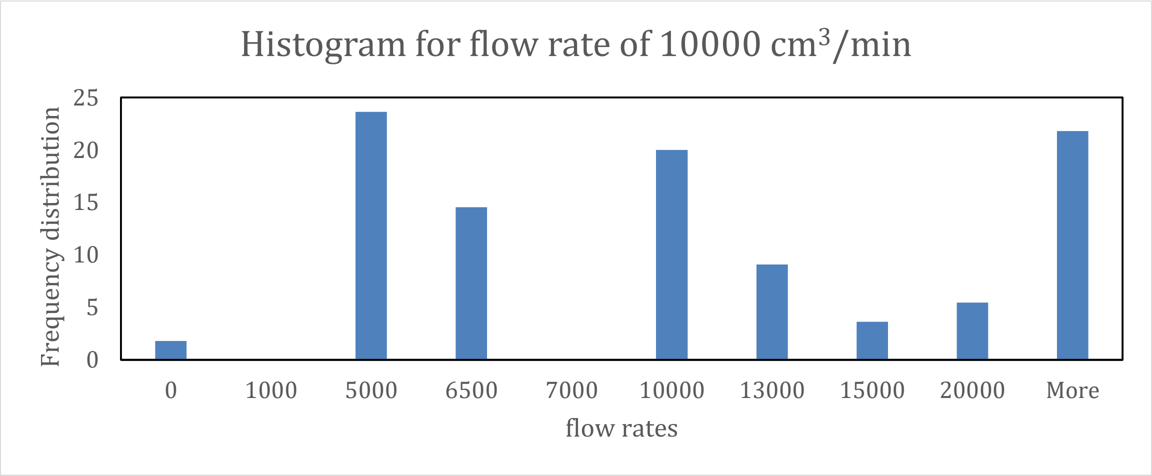
The original data sets can be requested from SRC.

14.2. Histograms

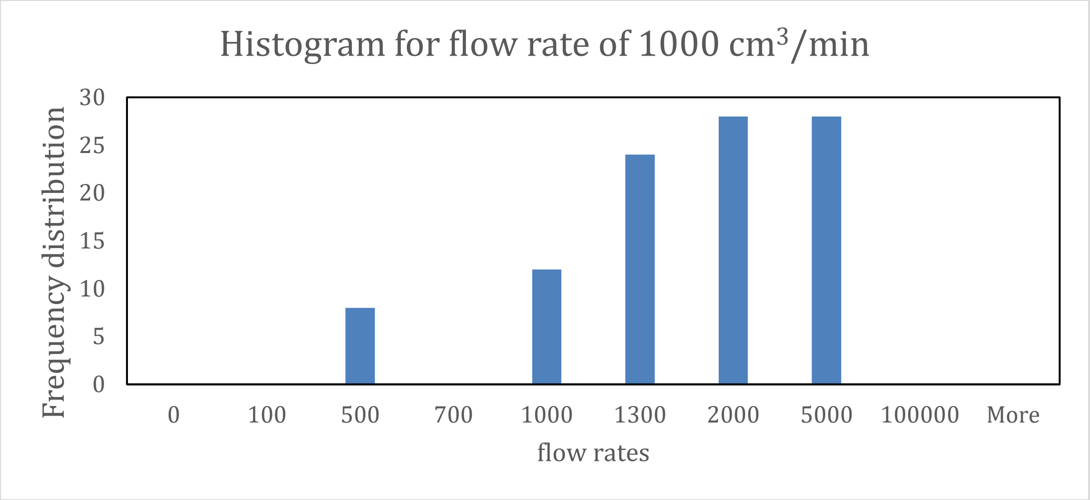
Gas type A:

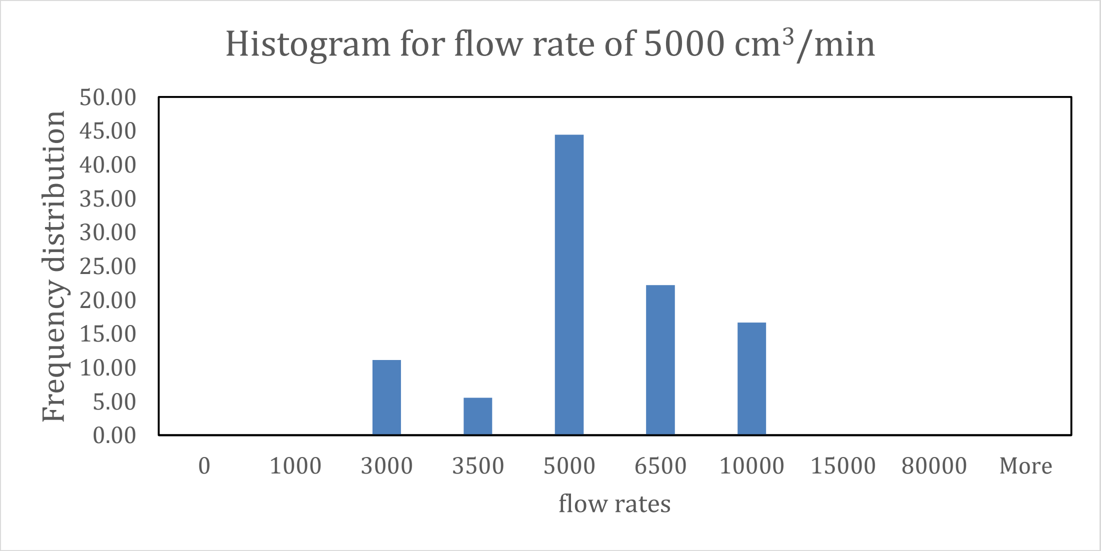


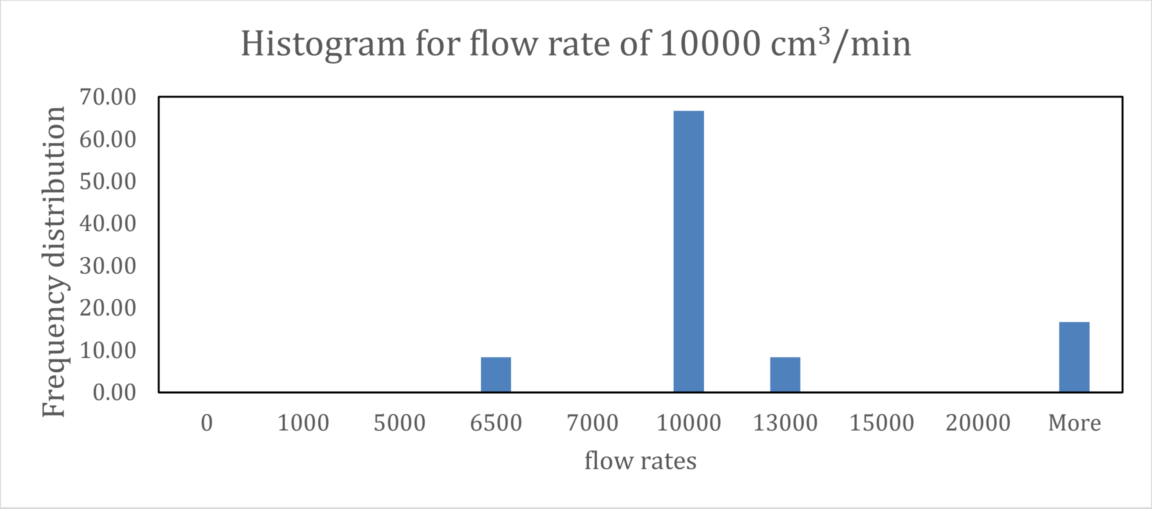



Histogram for flow rate of 10000 cm³/min
Frequency distribution
25
20
15
10
5
0
0
1000
5000
6500
7000
10000
13000
15000
20000
More
flow rates

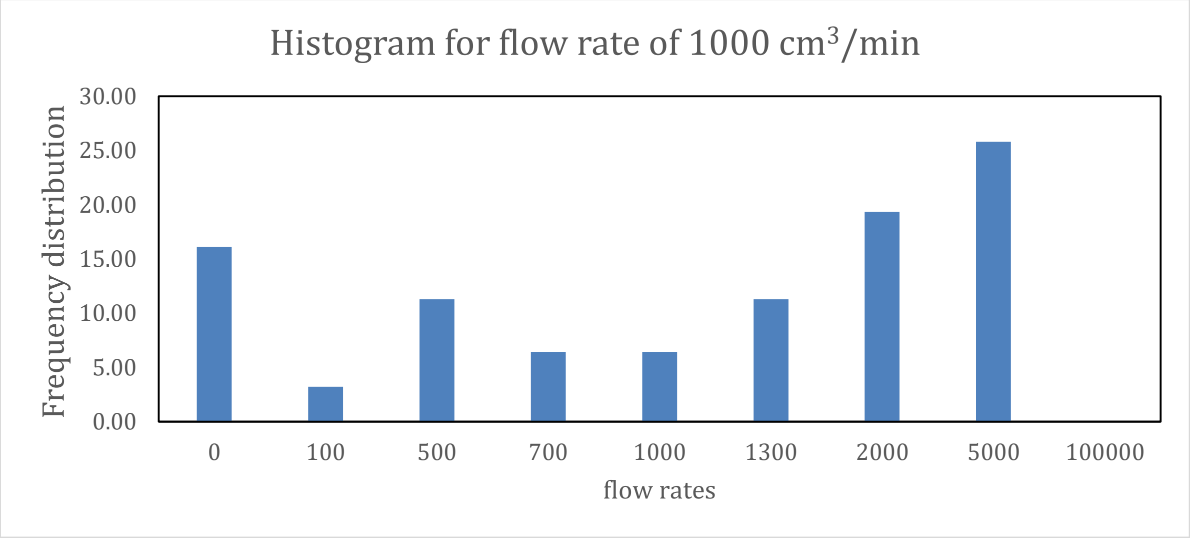
Gas type C:

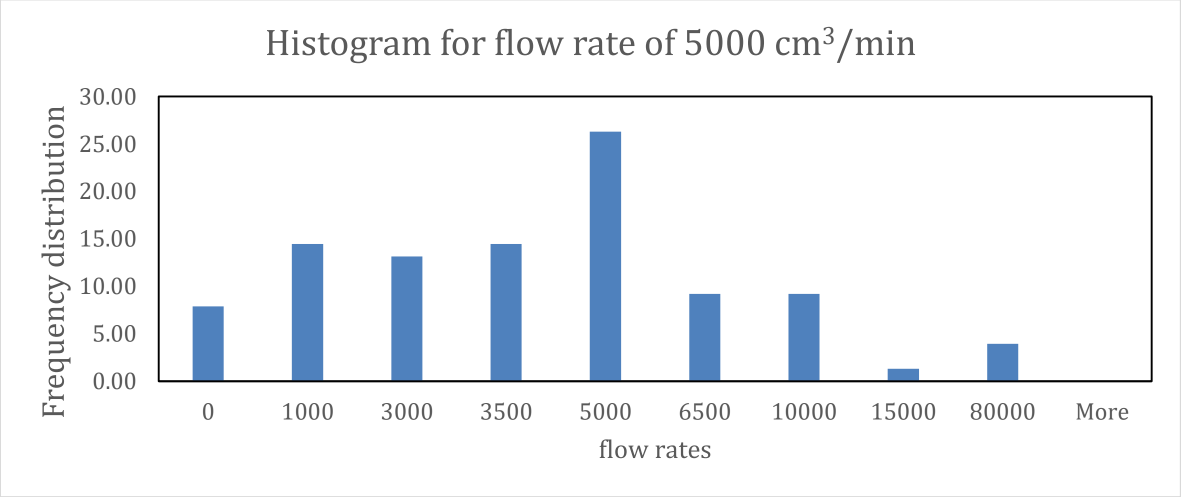

Histogram for flow rate of 1000 cm³/min
Frequency distribution
30
25
20
15
10
5
0
0
100
500
700
1000
1300
2000
5000
100000
More
flow rates

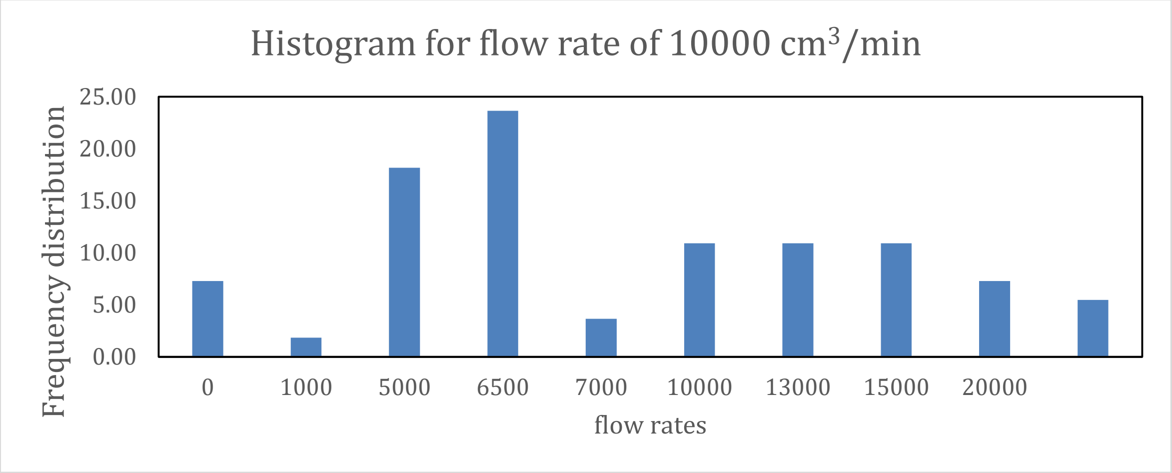

Histogram for flow rate of 5000 cm³/min
Frequency distribution
50.00
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
0
1000
3000
3500
5000
6500
10000
15000
80000
More
flow rates


Histogram for flow rate of 10000 cm3/min
Frequency distribution
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
0
1000
5000
6500
7000
10000
13000
15000
20000
More
flow rates

Methane:


Histogram for flow rate of 1000 cm3/min
Frequency distribution
30.00
25.00
20.00
15.00
10.00
5.00
0.00
0
100
500
700
1000
1300
2000
5000
100000
flow rates





14.3. ANOVA Results

Flow rate = 5000

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Gas type A	18	110708	6150.44	24499323.08
Methane	18	61837	3435.39	2593562.49
Gas type C	18	87310	4850.56	2223404.61

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	66383606.93	2	33191803	3.40	0.04	3.18
Within Groups	498376933.2	51	9772097			
Total	564760540.1	53				

Flow rate = 10000

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Gas type A	12	85446	7120.5	5975314.27
Methane	12	102354	8529.5	19133628.45
Gas type C	12	122662	10221.83	30275953.06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	57870166.22	2	28935083	1.57	0.22	3.28
Within Groups	609233853.7	33	18461632			
Total	667104019.9	35				

14.4. t-test results (Two by two gas comparison)

Gas type A and methane

t-Test: Two-Sample Assuming Unequal Variances

Gas types A and methane -FL=5000

	Gas type A	*Methane*
Mean	5817.82	4359.68
Variance	17396337.34	15582904.47
Observations	65.00	65.00
Hypothesized Mean Difference	0.00	
df	128.00	
t Stat	2.05	
P(T<=t) one-tail	0.02	
t Critical one-tail	1.66	
P(T<=t) two-tail	0.04	
t Critical two-tail	1.98	

t-Test: Two-Sample Assuming Unequal Variances

Gas types A and methane -FL=10000

	Gas type A	*Methane*
Mean	16117.71	8709.67
Variance	411324265.40	52894533.59
Observations	55.00	55.00
Hypothesized Mean Difference	0.00	
df	68.00	
t Stat	2.55	
P(T<=t) one-tail	0.01	
t Critical one-tail	1.67	
P(T<=t) two-tail	0.01	
t Critical two-tail	2.00	

Gas types A and C

t-Test: Two-Sample Assuming Unequal Variances

FL=5000

	Gas type A	*Gas type C*
Mean	6150.44	4850.56
Variance	24499323.08	2223404.61
Observations	18.00	18.00
Hypothesized Mean Difference	0.00	
df	20.00	
t Stat	1.07	
P(T<=t) one-tail	0.15	
t Critical one-tail	1.72	
P(T<=t) two-tail	0.30	
t Critical two-tail	2.09	

t-Test: Two-Sample Assuming Unequal Variances
FL=10,000

	Gas type A	*Gas type C*
Mean	7120.50	10221.83
Variance	5975314.27	30275953.06
Observations	12.00	12.00
Hypothesized Mean Difference	0.00	
df	15.00	
t Stat	-1.78	
P(T<=t) one-tail	0.05	
t Critical one-tail	1.75	
P(T<=t) two-tail	0.09	
t Critical two-tail	2.13	

Gas type C and Methane

t-Test: Two-Sample Assuming Unequal Variances
FL=5000

	Methane	*Gas type C*
Mean	3435.39	4850.56
Variance	2593562.49	2223404.61
Observations	18.00	18.00
Hypothesized Mean Difference	0.00	
df	34.00	
t Stat	-2.74	
P(T<=t) one-tail	0.00	
t Critical one-tail	1.69	
P(T<=t) two-tail	0.01	
t Critical two-tail	2.03	

t-Test: Two-Sample Assuming Unequal Variances
FL=10,000

	Methane	*Gas type C*
Mean	8529.50	10221.83
Variance	19133628.45	30275953.06
Observations	12.00	12.00
Hypothesized Mean Difference	0.00	
df	21.00	
t Stat	-0.83	
P(T<=t) one-tail	0.21	
t Critical one-tail	1.72	
P(T<=t) two-tail	0.41	
t Critical two-tail	2.08	

15. References

[1] Yousheng Zeng, Jon Morris, Calibration and quantification method for gas imaging camera, US9225915B2
[2] Yousheng Zeng, White Paper on A Calibration/Verification Device for Gas