Reproducibility of Liquid Micro-Flow Measurements

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FLOMEKO
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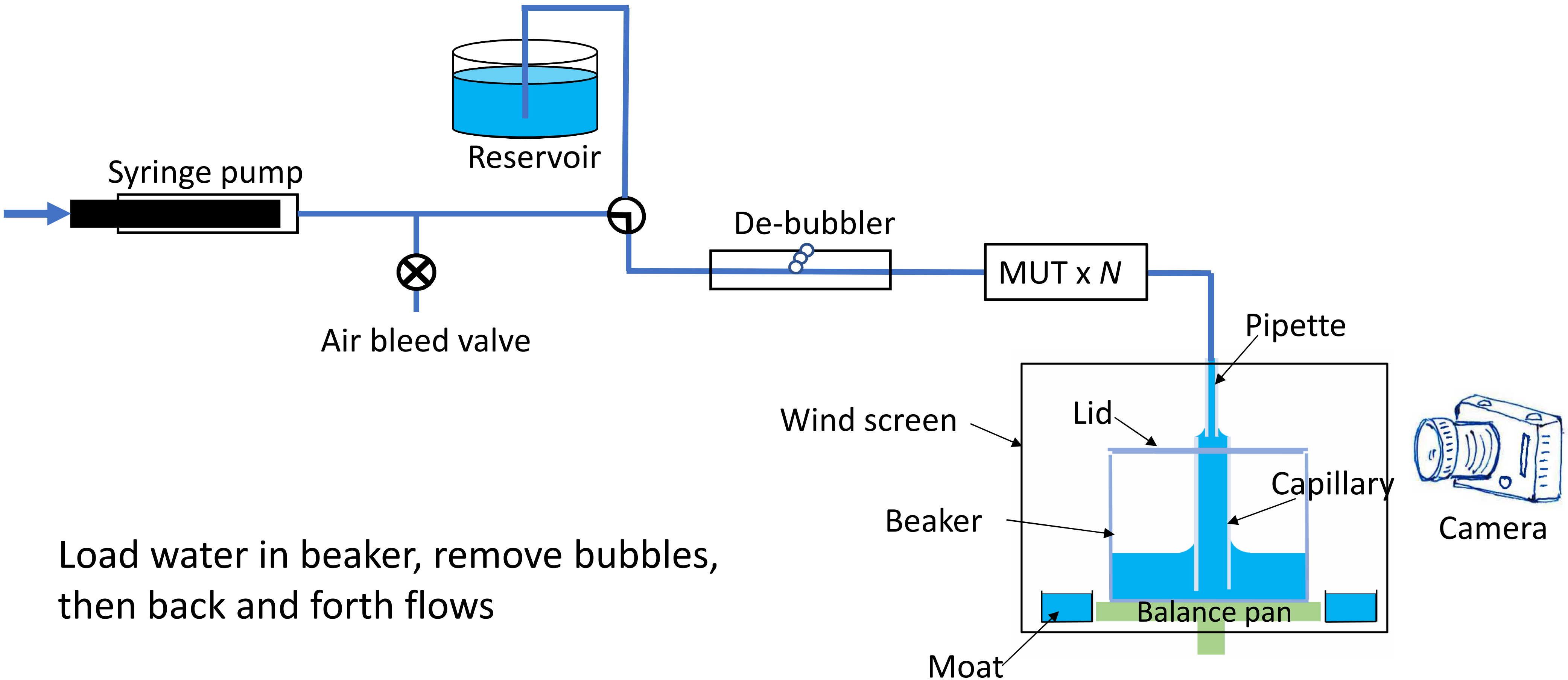
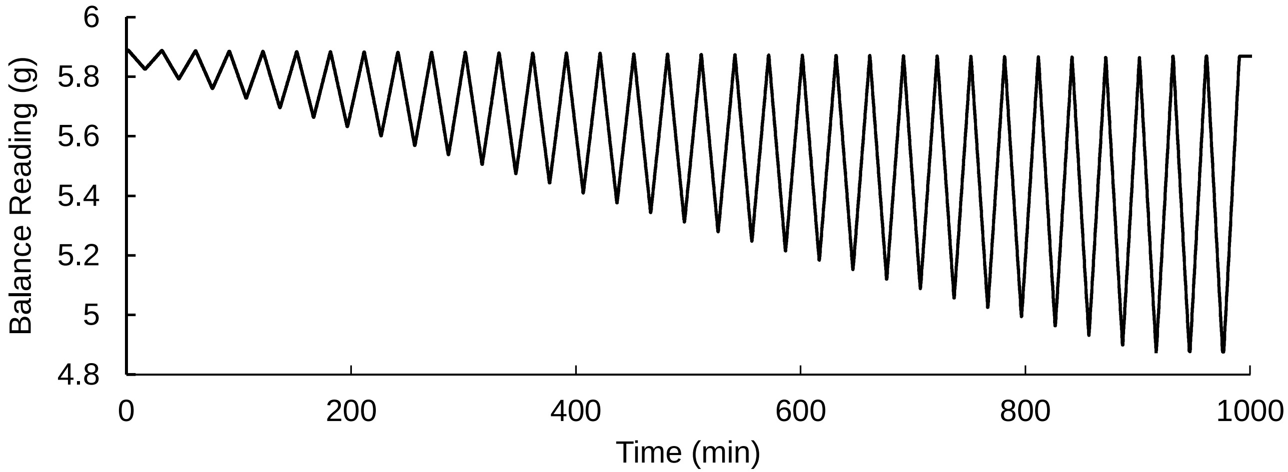
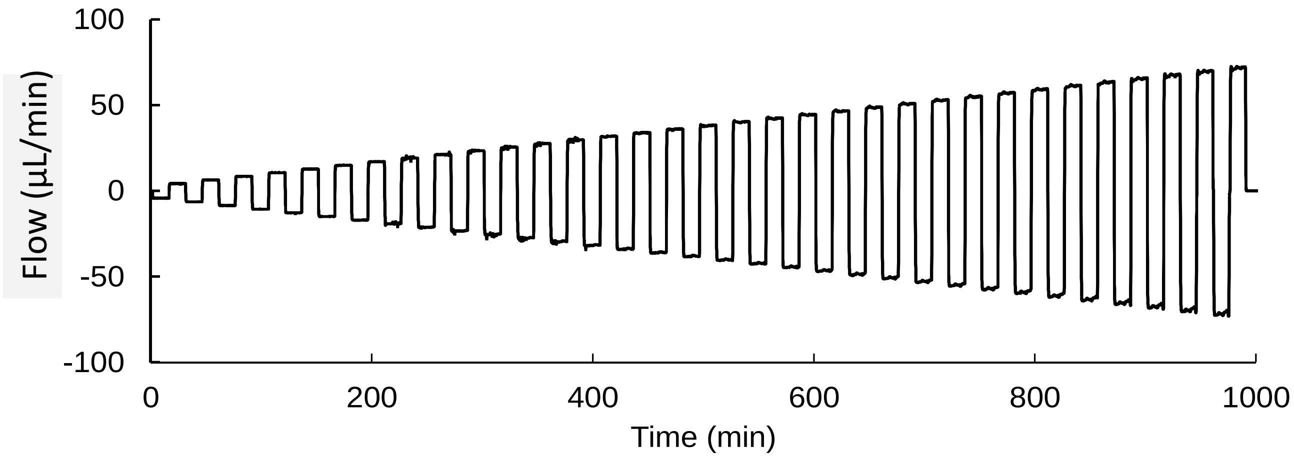
Schematic of Dynamic Gravimetric Flow Standard



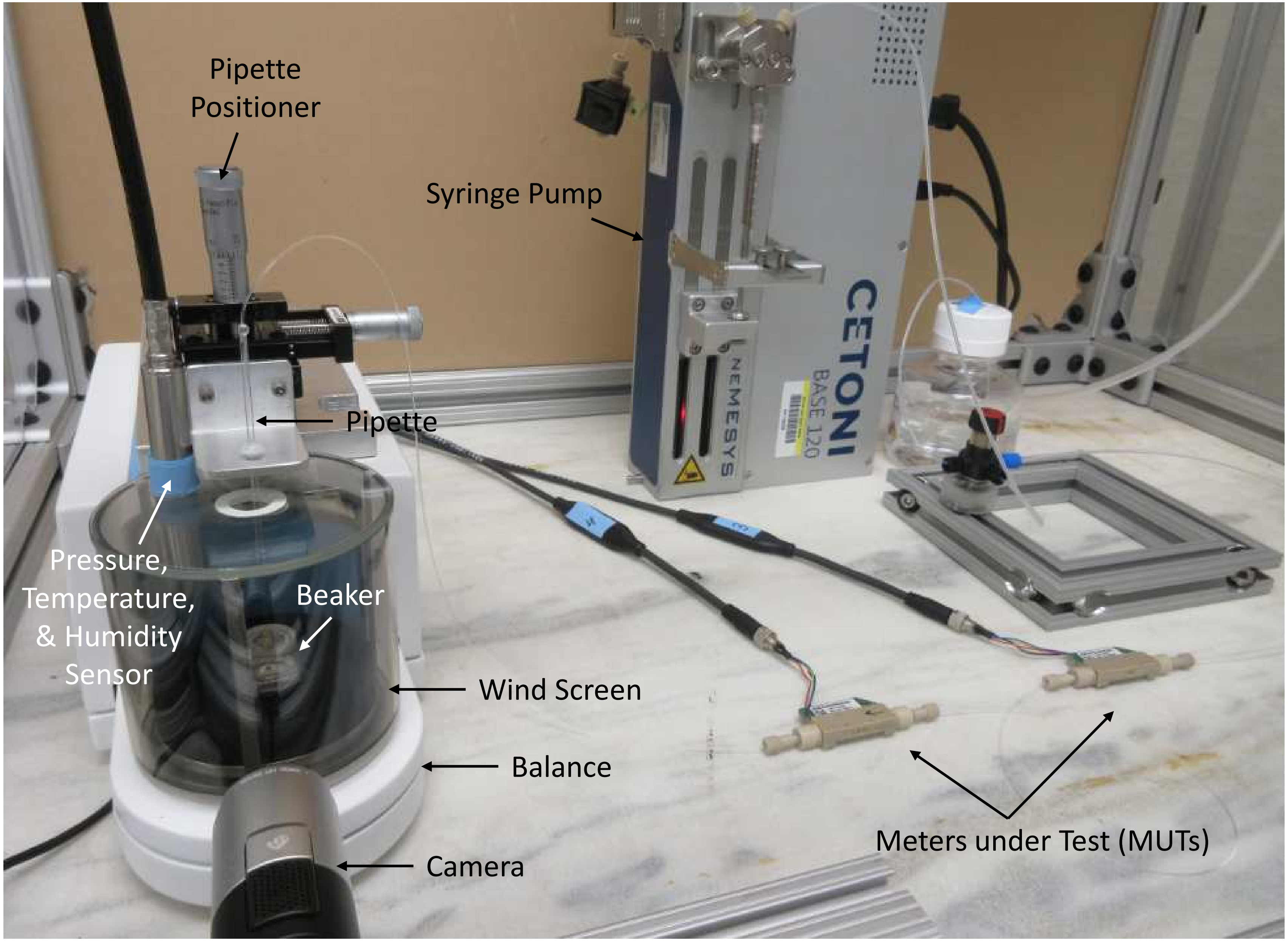
Load water in beaker, remove bubbles, then back and forth flows

Sample Data Set: Mass and It’s Time Derivative

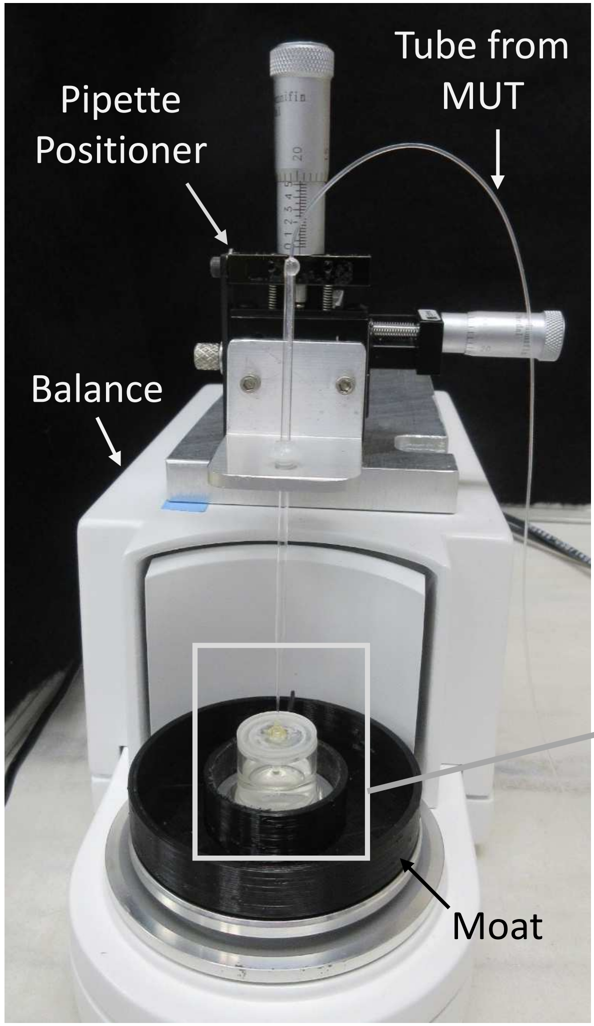


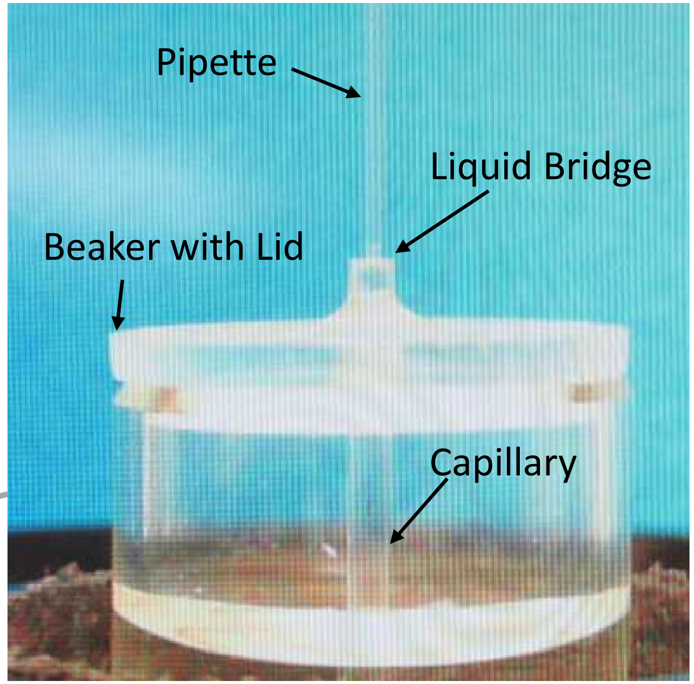


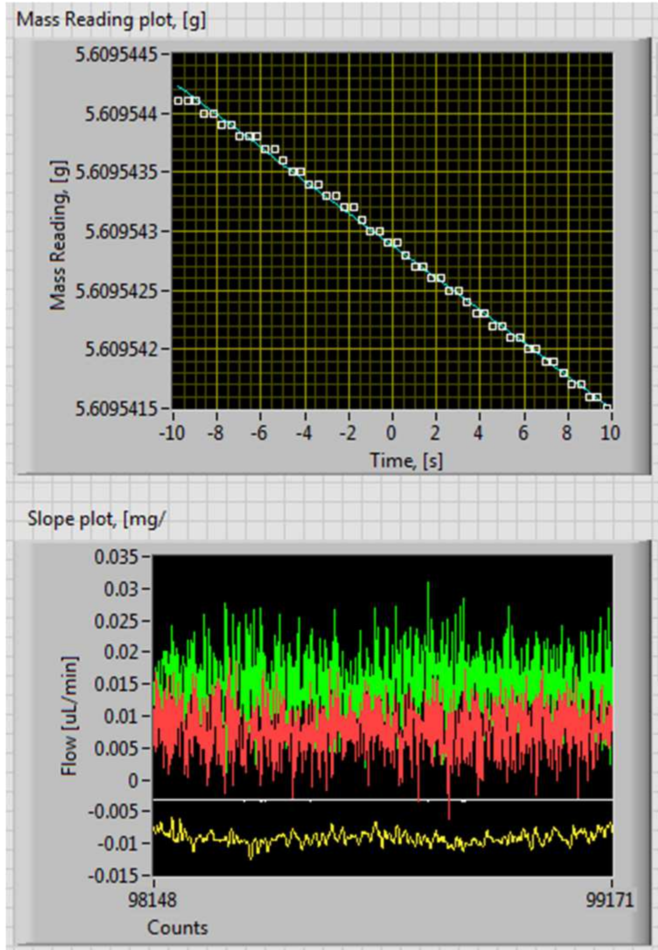
back and forth flows


Pipette
Positioner
Syringe Pump
Pipette
Pressure,
Temperature,
& Humidity
Sensor
Beaker
Wind Screen
Balance
Camera
Meters under Test (MUTs)
CETONI
BASE 120
NEMESYS

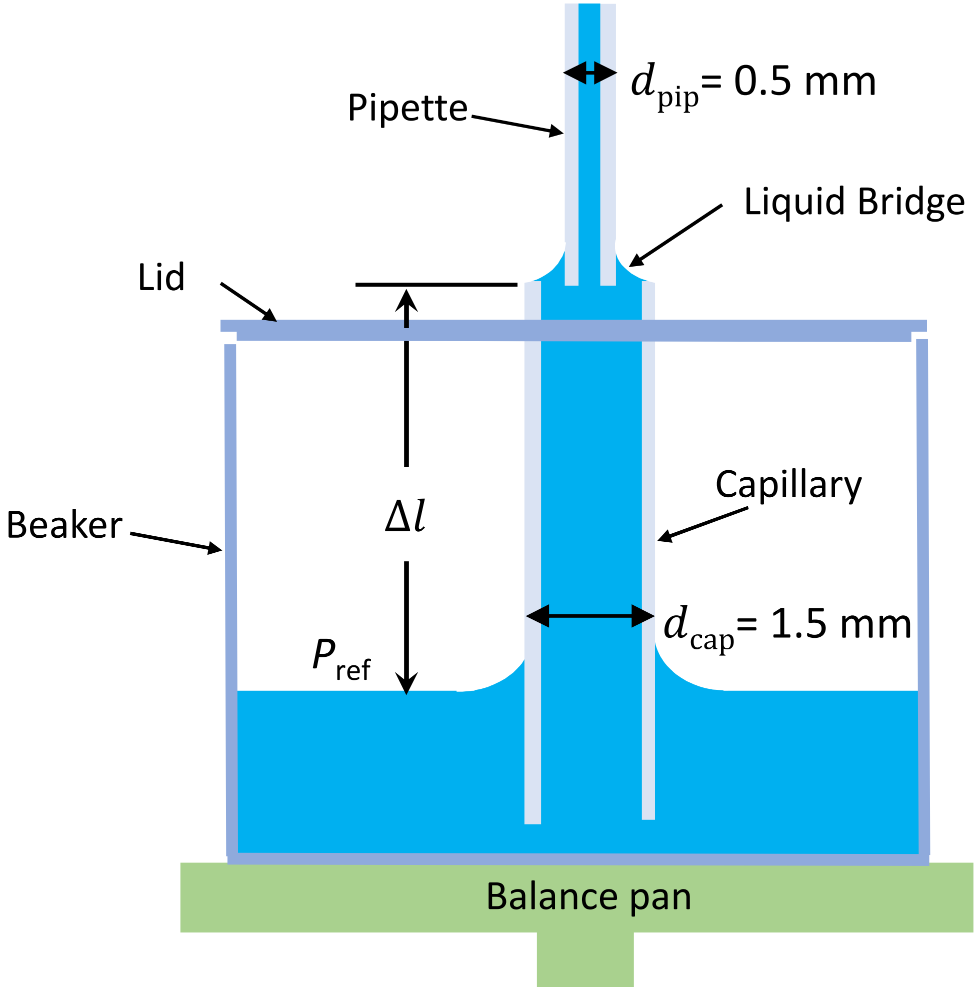
Collection Beaker on a 6 g Balance



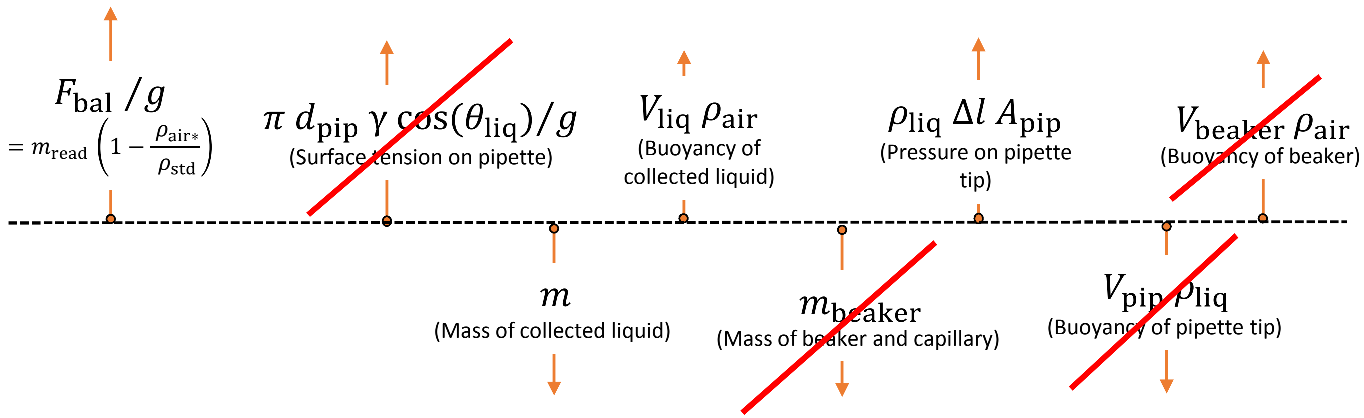




Collection Beaker with “Liquid Bridge”



Mass Flow Equations



$$\hat{m} = m_{\mathrm{read}} \frac{\left(1-\frac{\rho_{\mathrm{air*}}}{\rho_{\mathrm{std}}}\right)}{\left(1-\frac{\rho_{\mathrm{air}}}{\rho_{\mathrm{liq}}}\right)}$$

1) Buoyancy corrections

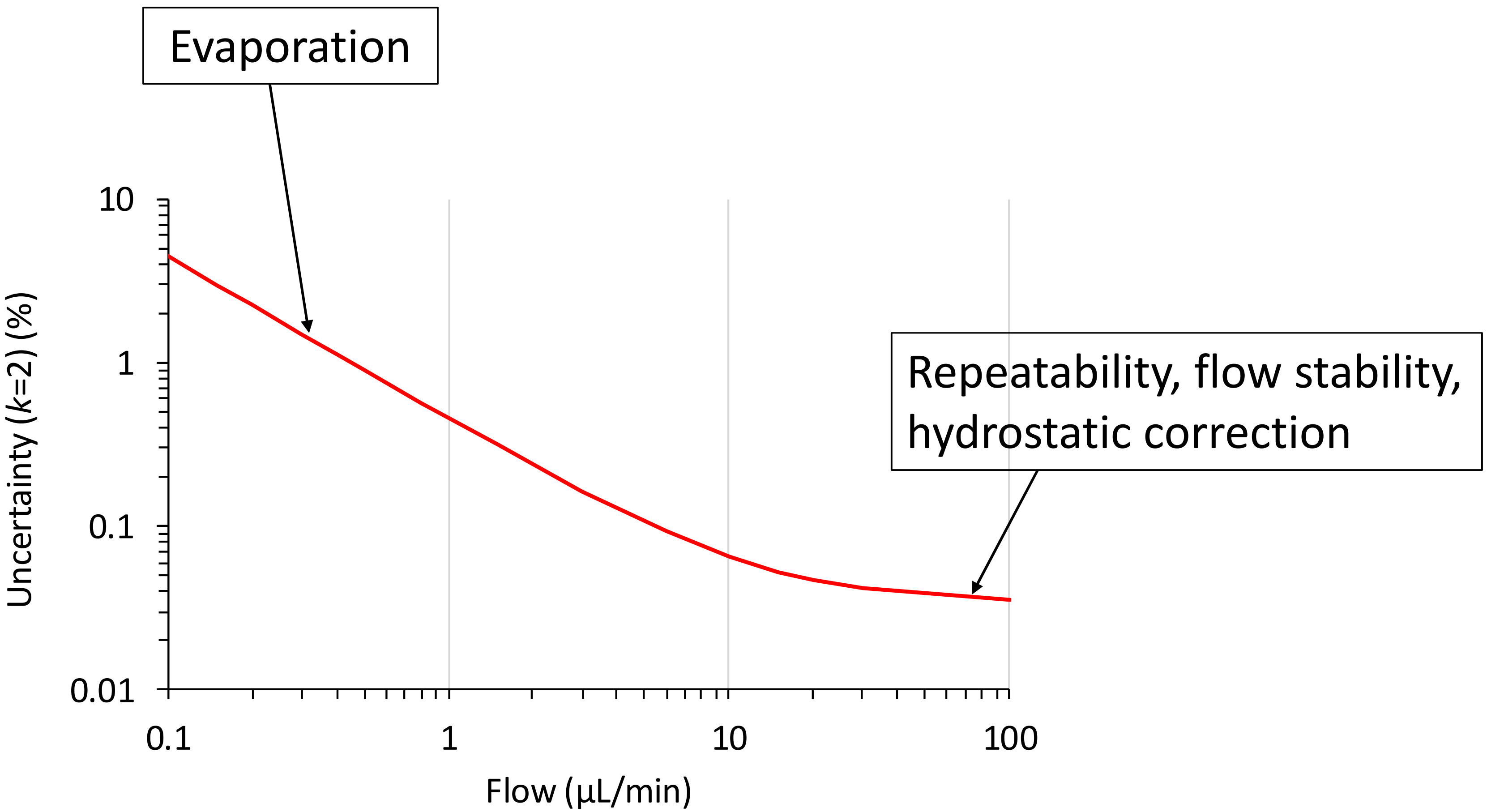
$$\dot{m}_0 = \frac{d\hat{m}}{dt} \cong \frac{N\sum_{j=1}^{N} t_j \hat{m}_j - \sum_{j=1}^{N} t_j \sum_{j=1}^{N} \hat{m}_j}{N\sum_{j=1}^{N} t_j^2 - \left(\sum_{j=1}^{N} t_j\right)^2}$$

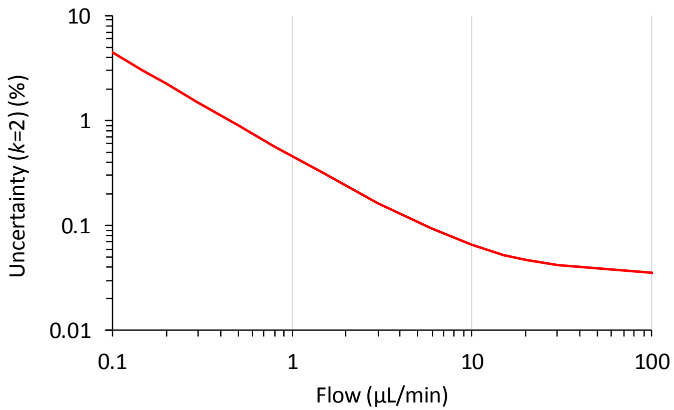
2) Least squares best-fit ($N \geq 150$)

$$\dot{m} = \dot{m}_0 \left[1 - \frac{A_{\mathrm{pip}}}{\left(A_{\mathrm{beaker}} - A_{\mathrm{cap}}\right)}\right] + \frac{dm_{\mathrm{evap}}}{dt}$$

3) Hydrostatic and evaporation corrections

Uncertainty Analysis





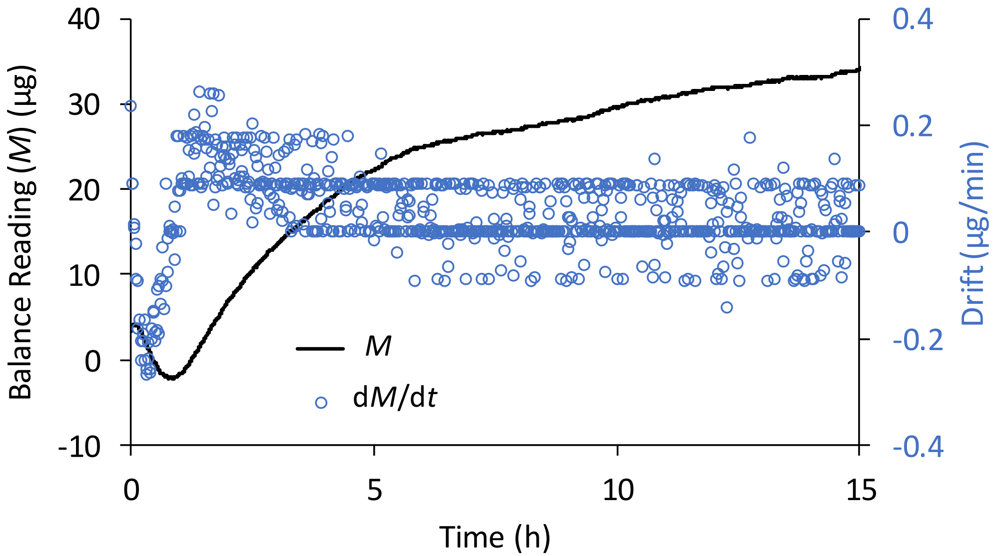
Uncertainty Analysis

For 100 µL/min…

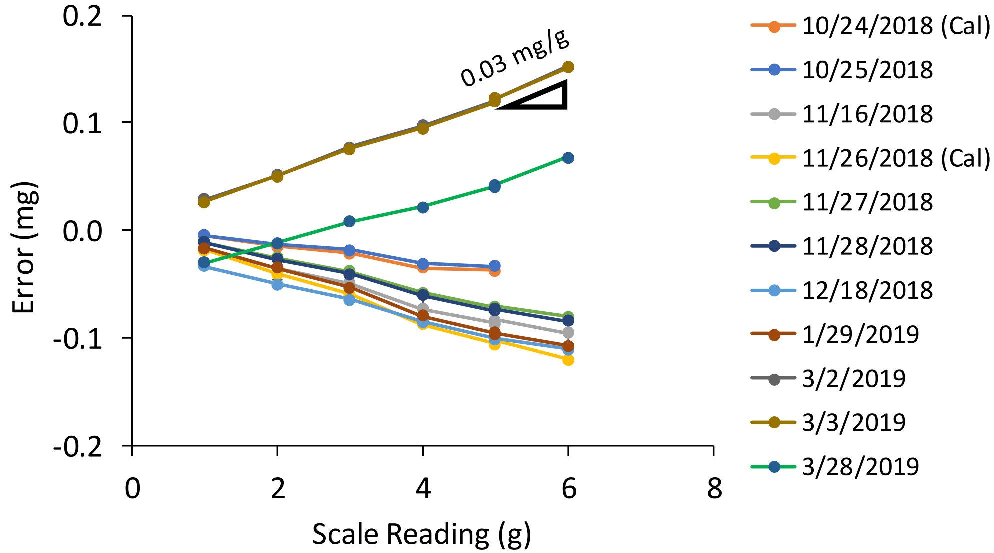
Uncertainty category	Value	Units	Standard unc. (*k* = 1)	Contrib.
			(%)	(%)
ΔMass with buoyancy corr.	0.1	[g]	0.003	0
ΔTime	1	[min]	0.002	0
Pipette hydrostatic corr.	0.999	[-]	0.008	19
Slope calculation	0	[g/min]	0	0
Evaporation	-0.01	[µL/min]	0.002	1
Water density	0.998	[g/cm^3]	0.005	0
Repeatability & flow stability	0.1	[g/min]	0.016	79
Expanded uncertainty (*k* = 2)	0.04	[µL/min]	0.04	

Change in Mass (with Buoyancy Corrections)

At low flows: balance zero drift (0.16 µg/min)



At high flows: balance calibration (0.03 mg/g)

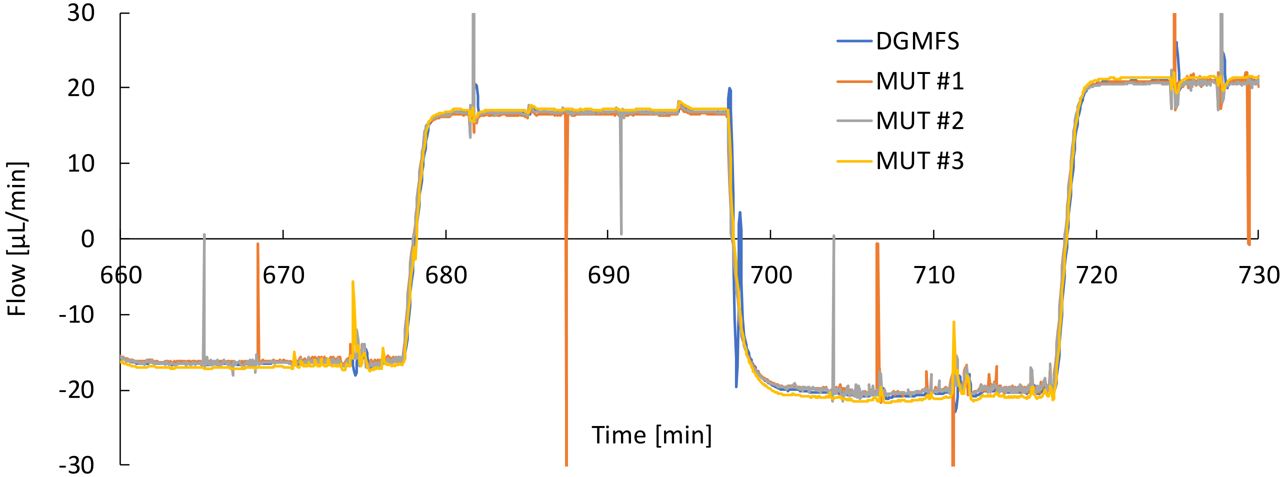


Small mass components:

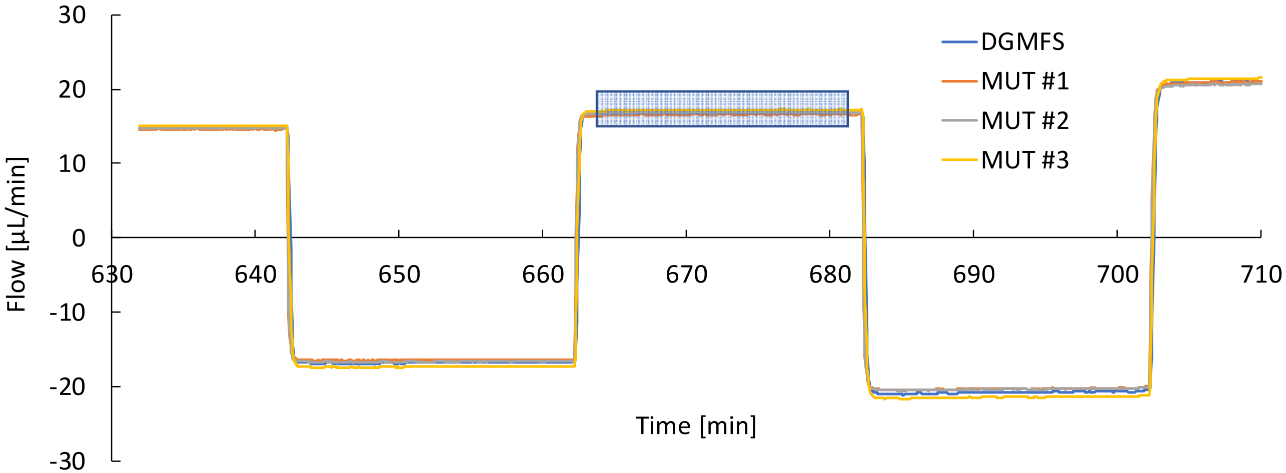
- Resolution (0.1 µg) and
- Buoyancy (correction is 0.12 %, but uncertainty only 5 PPM)

k = 1 values

Flow Stability

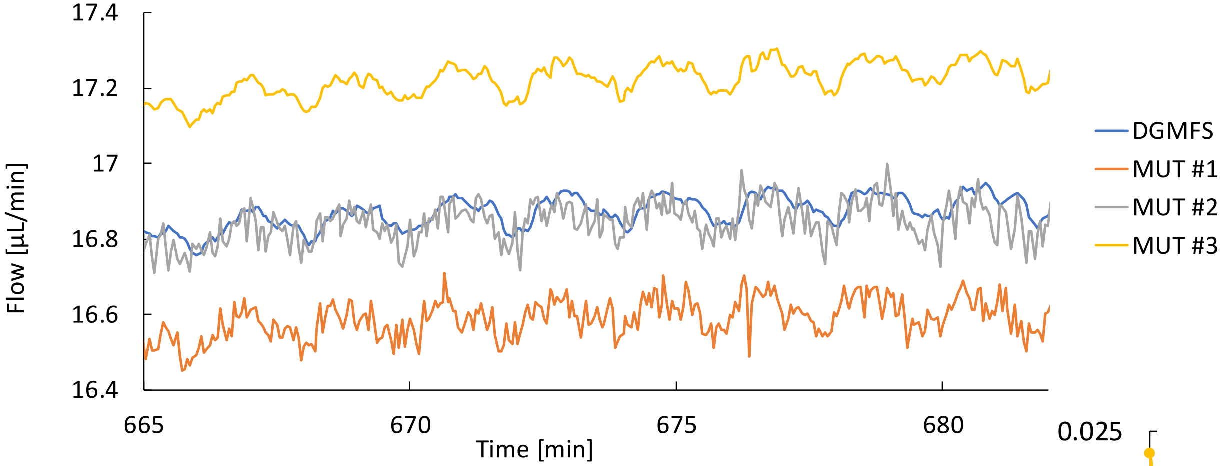


Air bubbles present

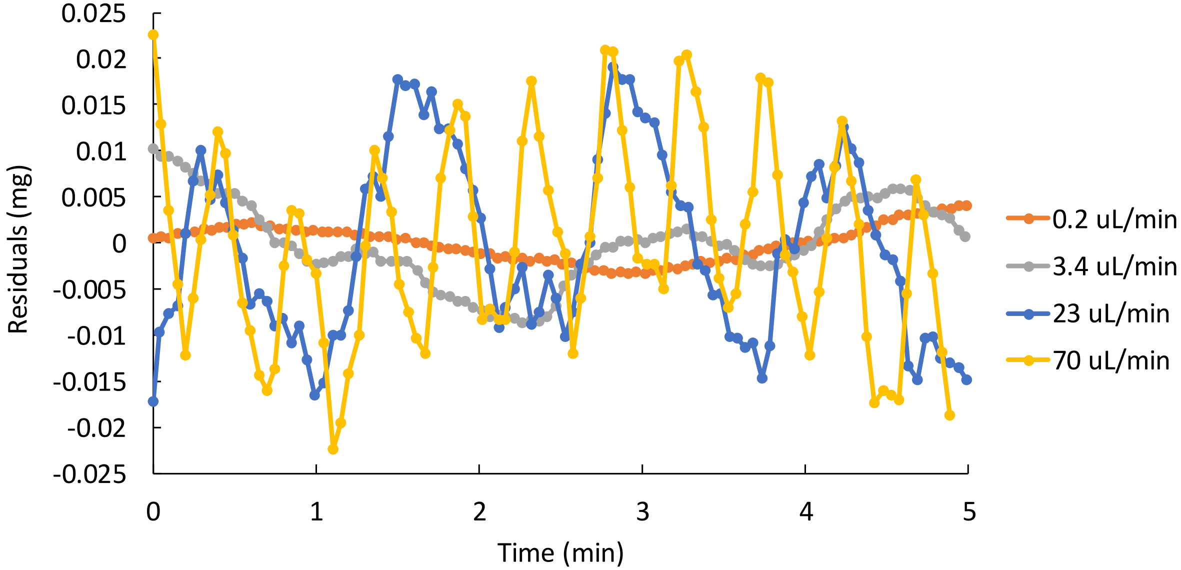


No air bubbles

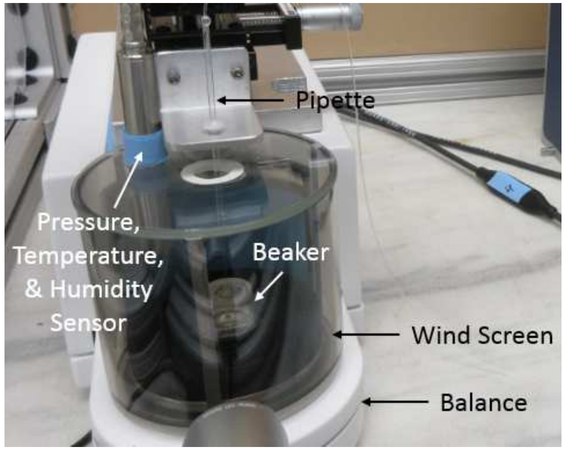
Flow Stability

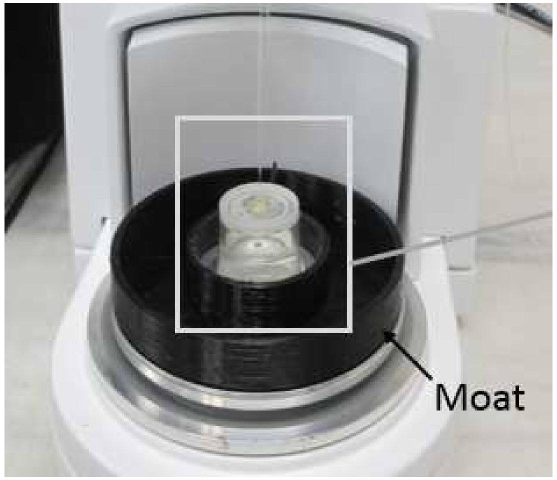


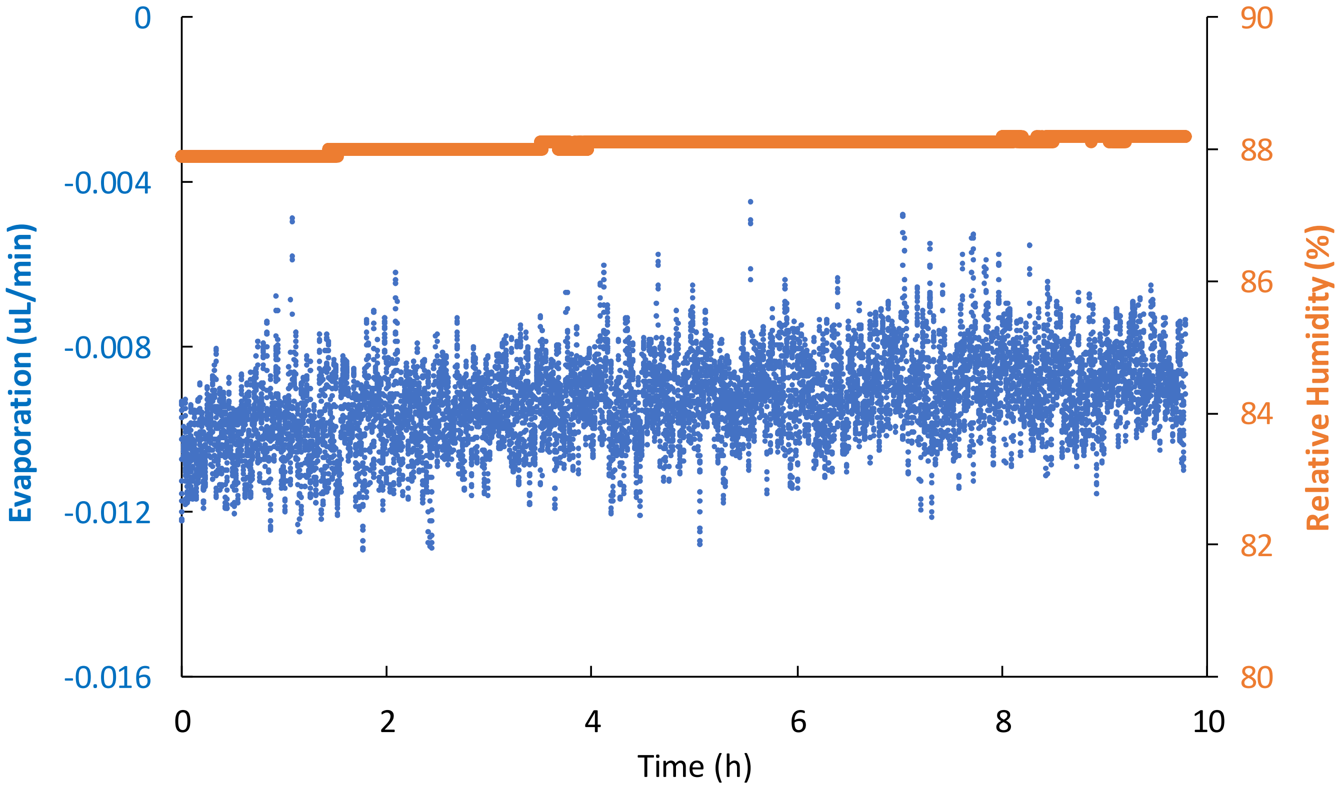
Type A repeatability:
standard deviation of 5 averages



Evaporation Correction

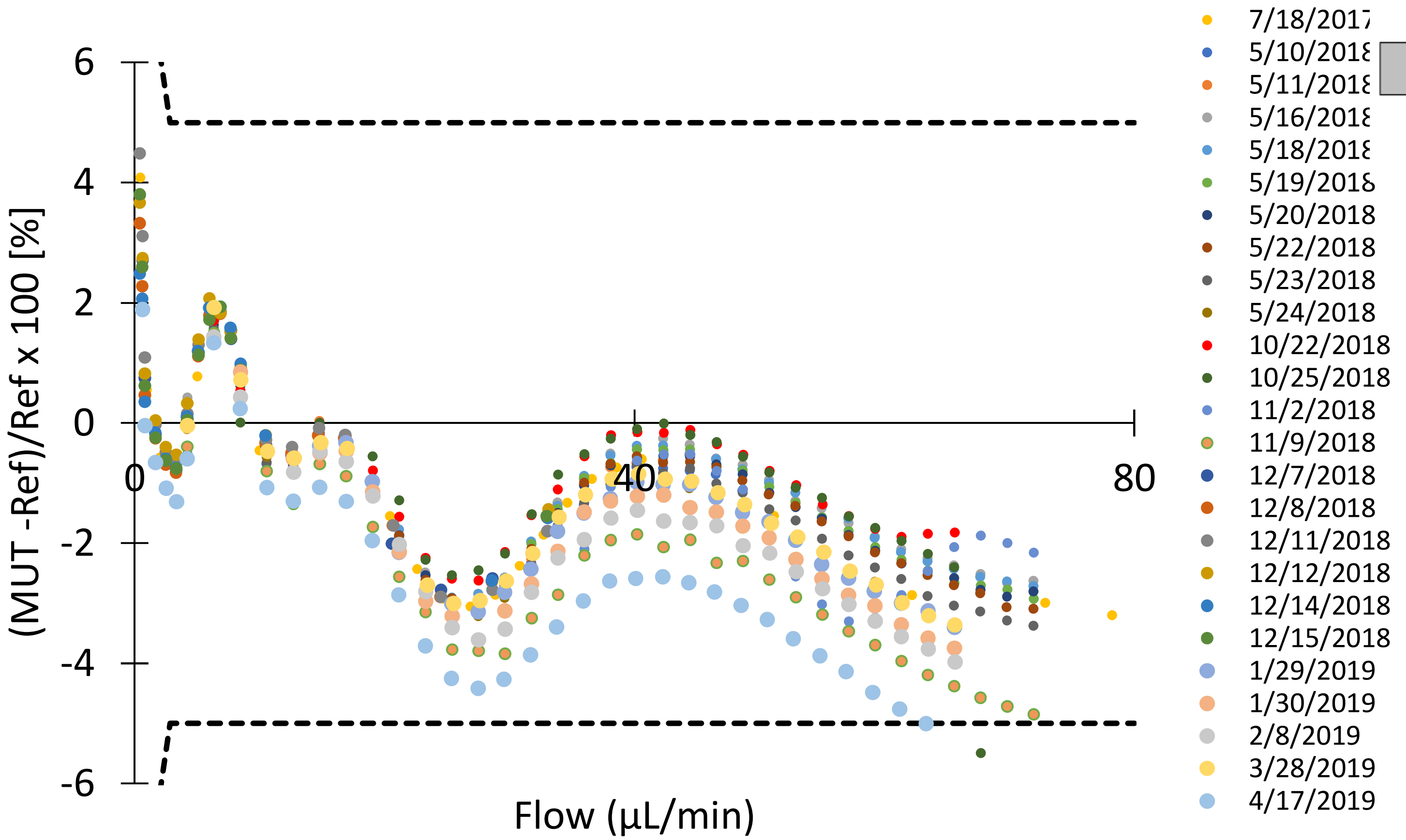


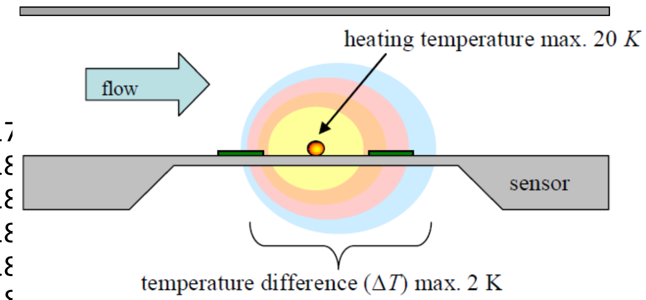




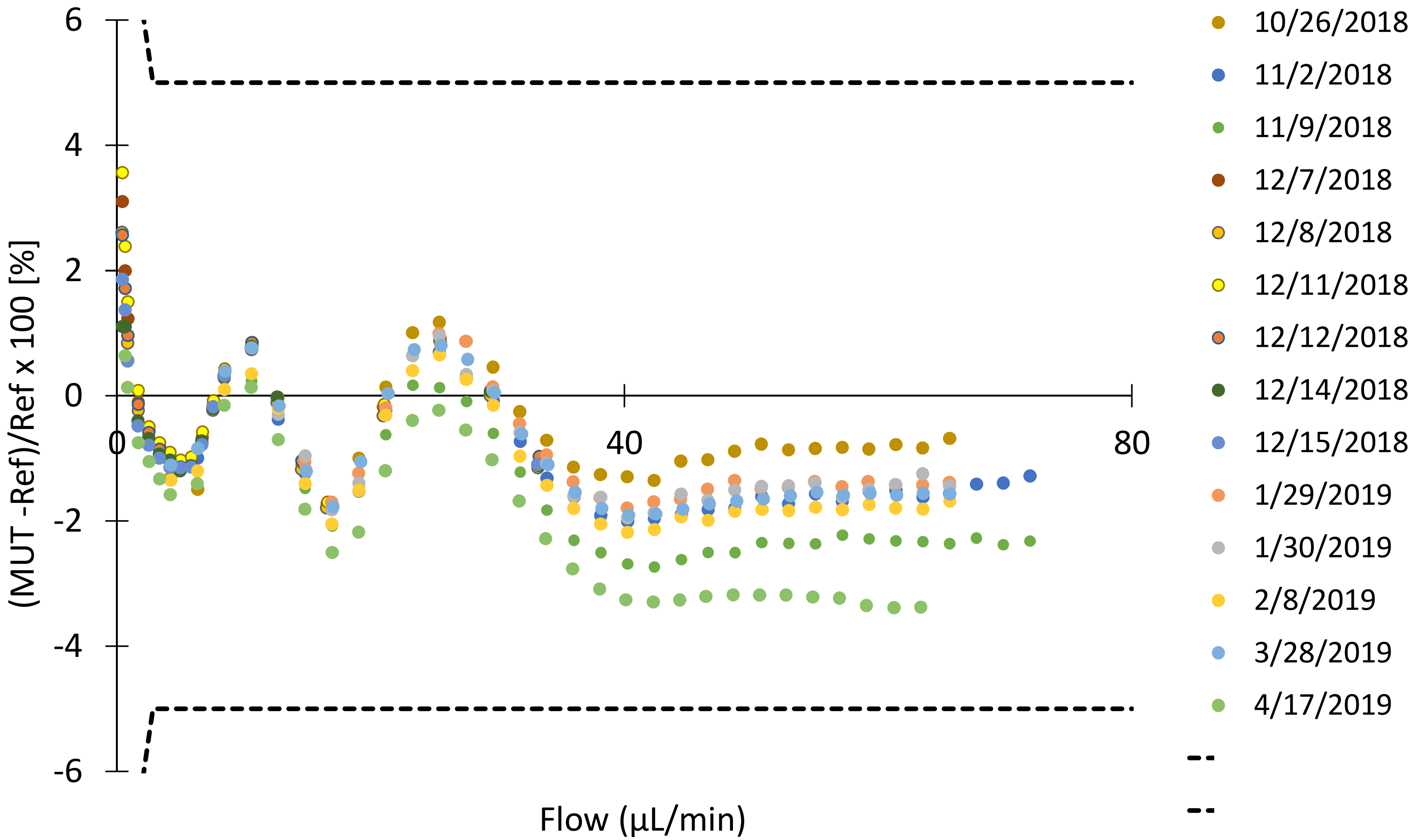
Correction ~ -0.01 µL/min, standard uncertainty = 0.002 µL/min

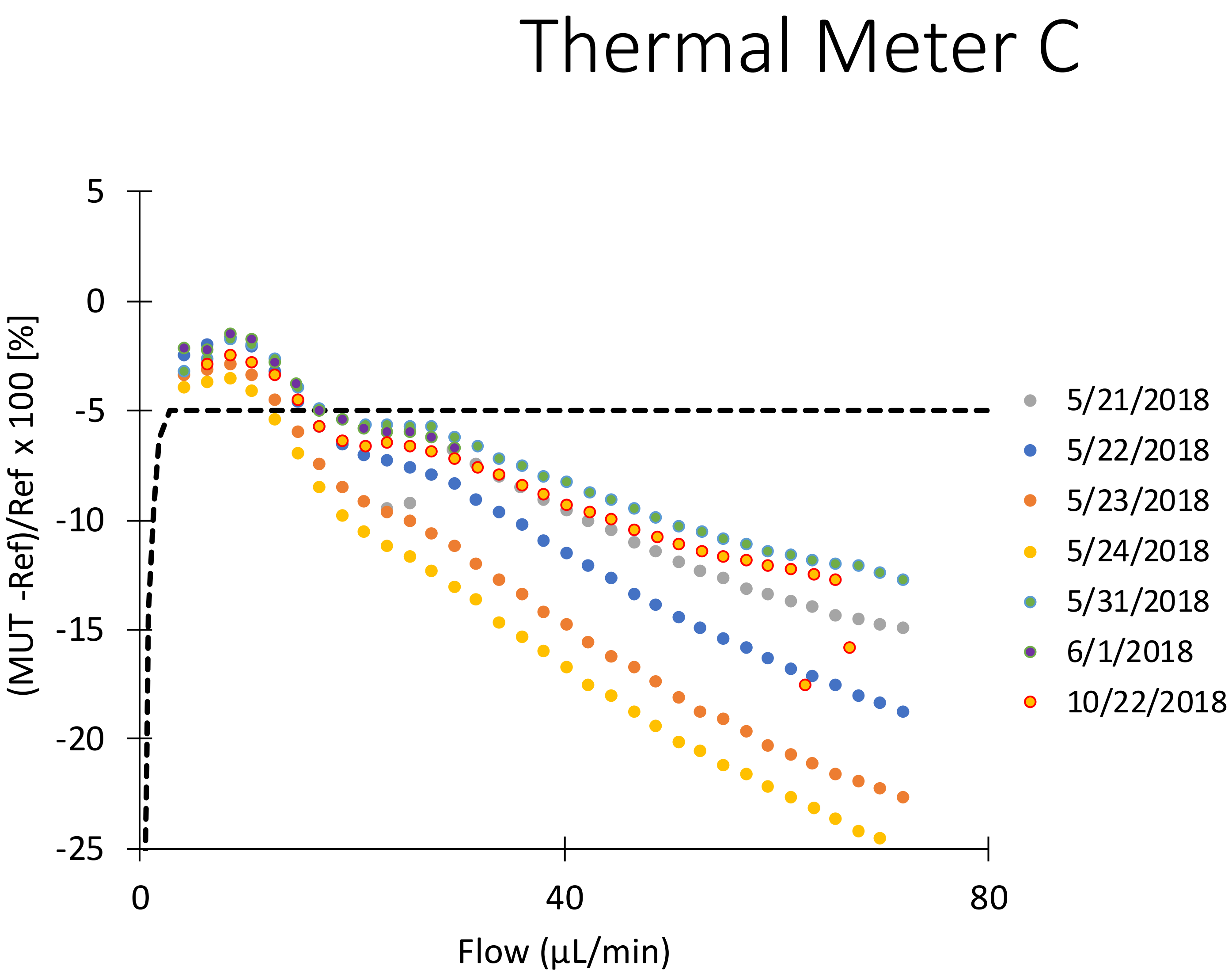
Thermal Meter A



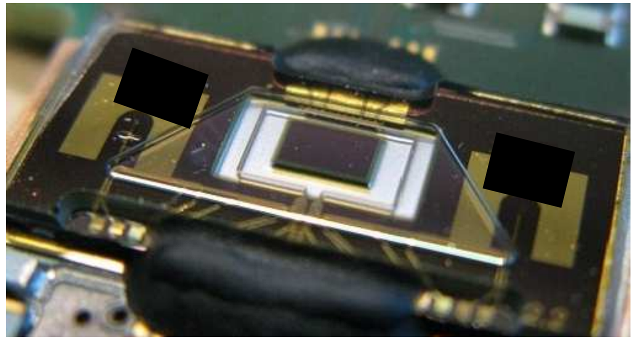


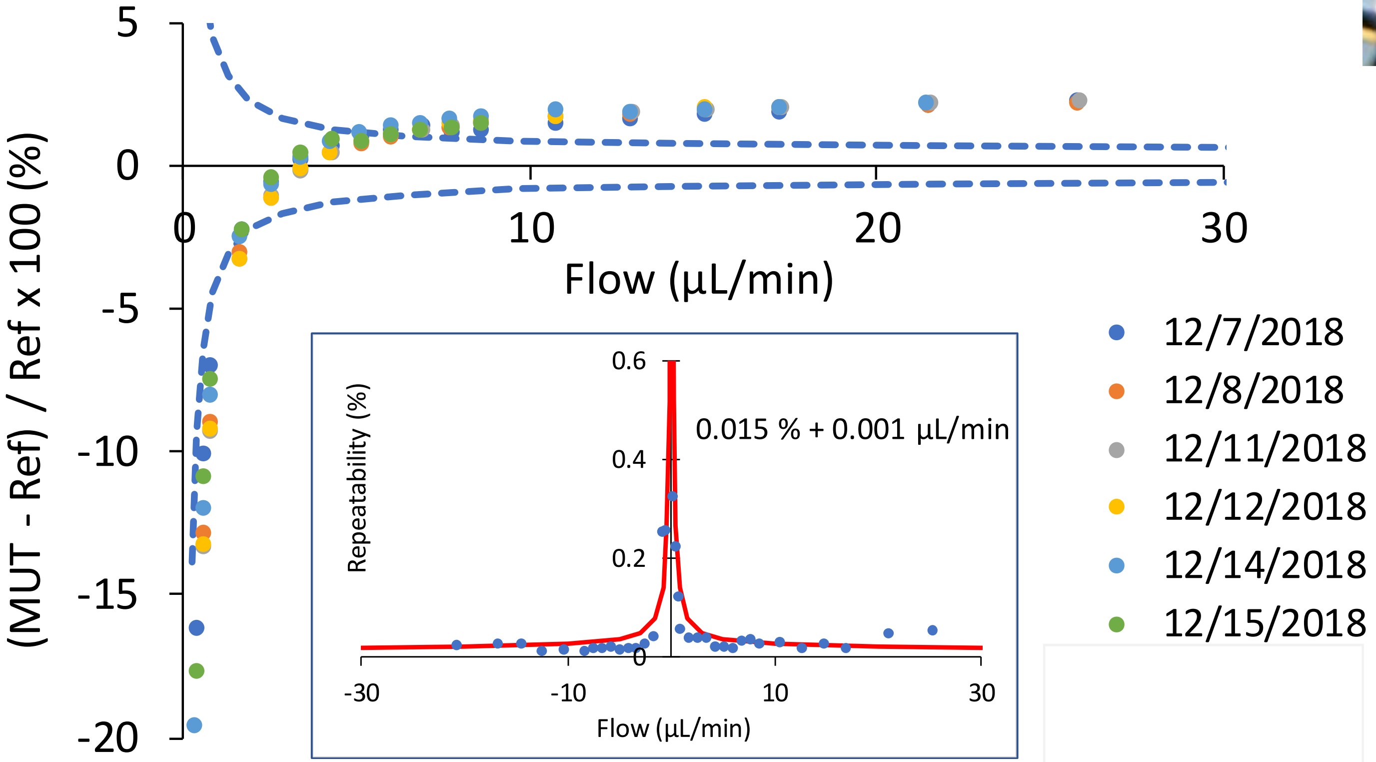
Thermal Meter B




Thermal Meter C
(MUT -Ref)/Ref x 100 [%]
5
0
-5
-10
-15
-20
-25
0
40
80
Flow (µL/min)
5/21/2018
5/22/2018
5/23/2018
5/24/2018
5/31/2018
6/1/2018
10/22/2018

Coriolis Meter D

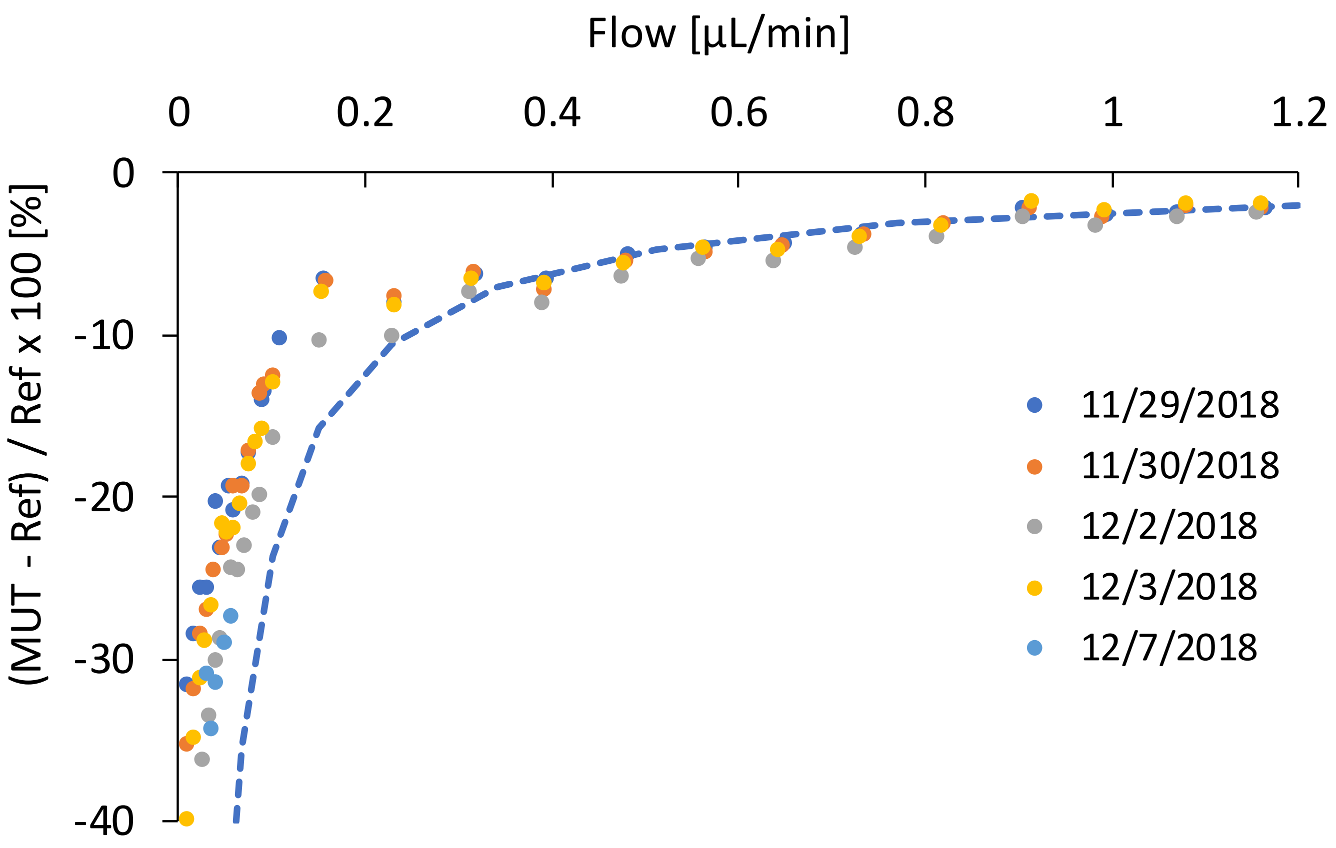


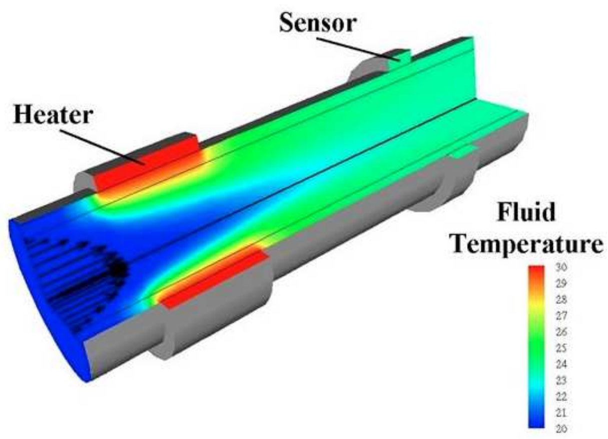


Standard deviation of 5 one-minute averages

NOT re-zeroed

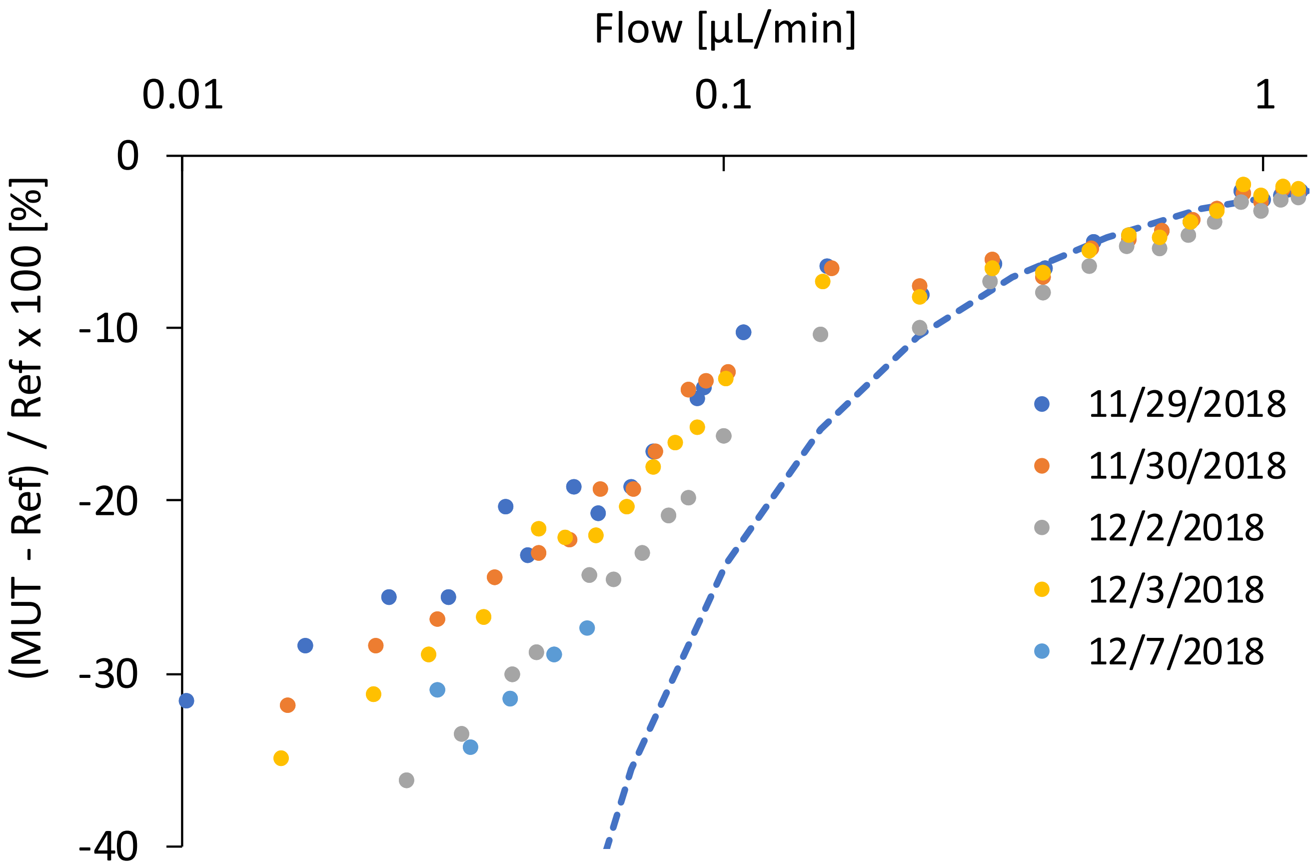
Thermal Meter E

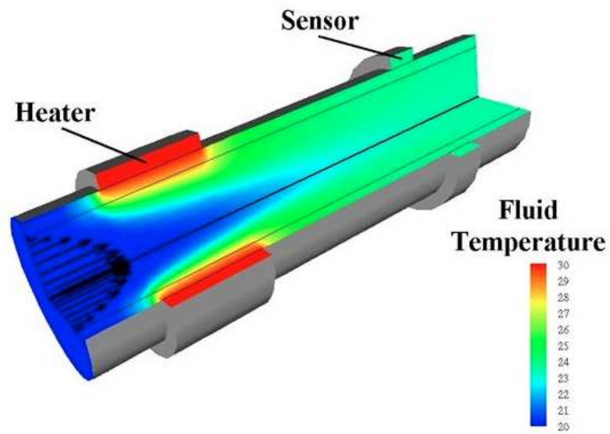




Summary and Conclusions

- Improvements: liquid bridge, evaporation trap, camera, pipette positioner
- Derived flow equations and presented uncertainty analysis
- At high flows: repeatability and hydrostatic corrections
- At low flows: evaporation corrections and repeatability
- Calibrations of commercial meters: stable within 1.5 % for many months
- Flow meter uncertainty in user's application can be significantly improved (3x) by calibration against a reference flow standard





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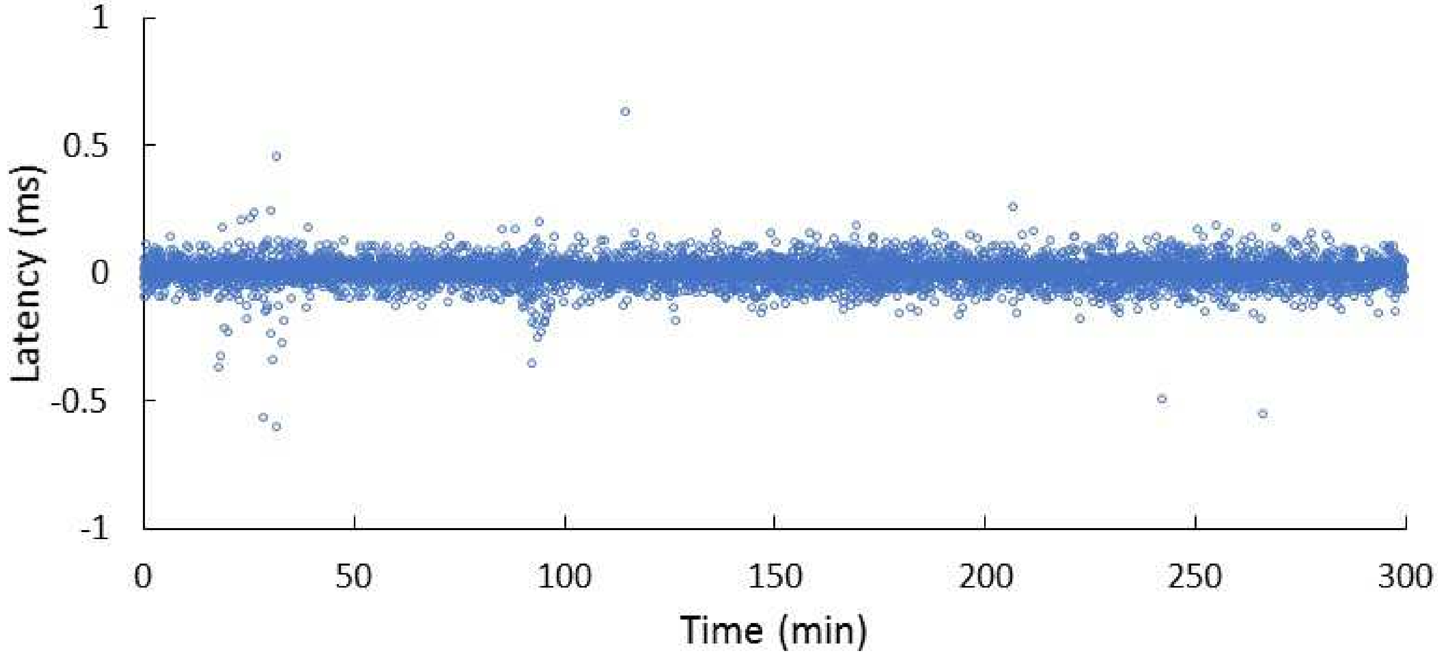
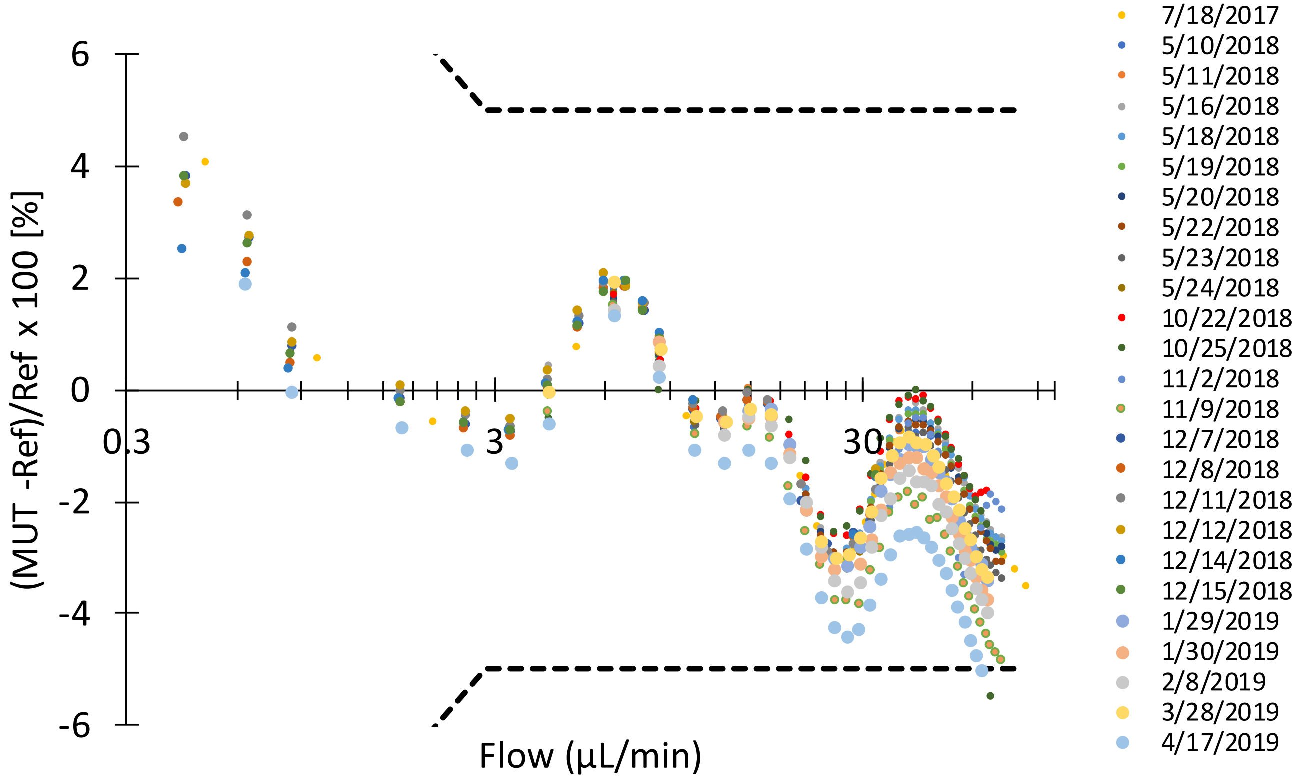


Log7262018.xlsx



6
4
2
0
-2
-4
-6
0.3
3
30
(MUT -Ref)/Ref x 100 [%]
Flow (µL/min)
7/18/2017
5/10/2018
5/11/2018
5/16/2018
5/18/2018
5/19/2018
5/20/2018
5/22/2018
5/23/2018
5/24/2018
10/22/2018
10/25/2018
11/2/2018
11/9/2018
12/7/2018
12/8/2018
12/11/2018
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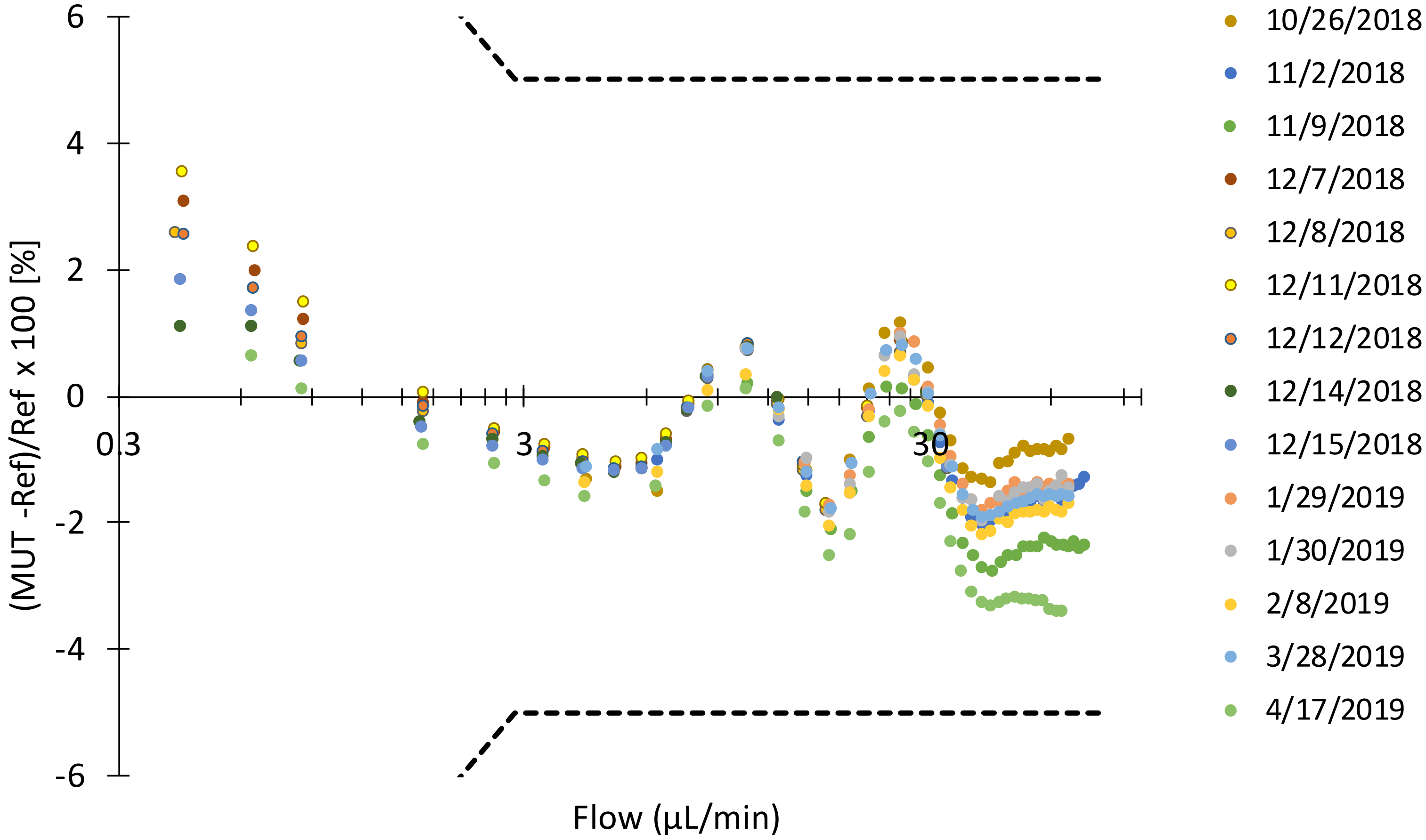
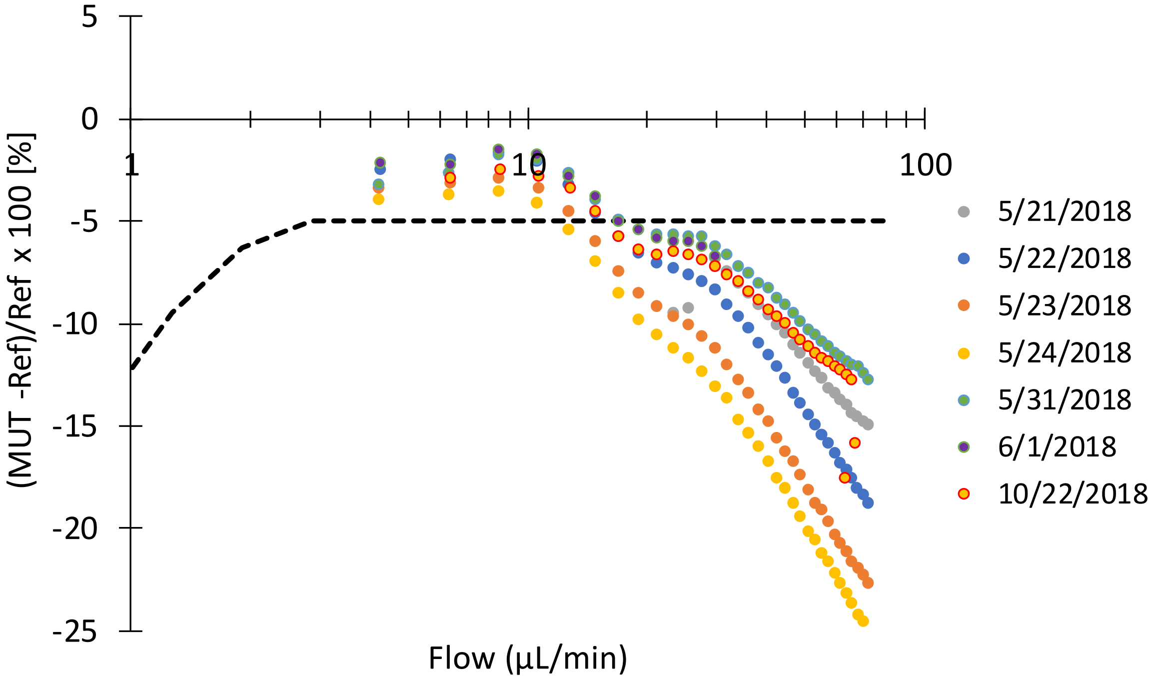
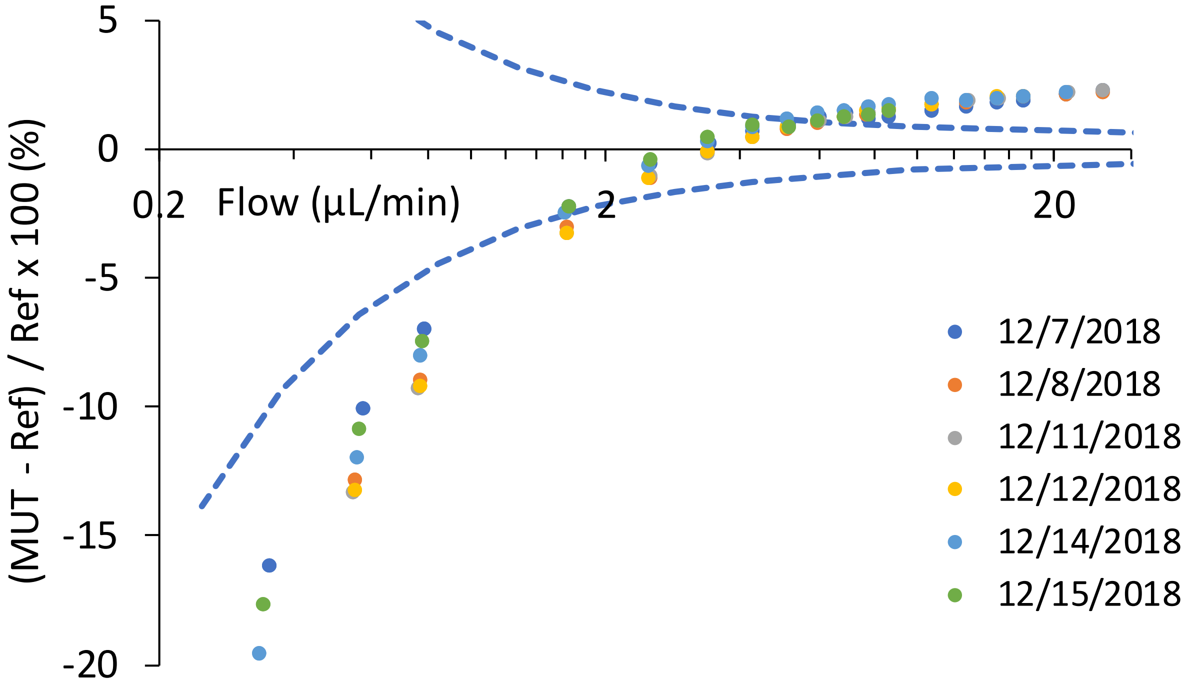
12/15/2018
1/29/2019
1/30/2019
2/8/2019
3/28/2019
4/17/2019


6
4
2
0
-2
-4
-6
0.3
3
30
(MUT -Ref)/Ref x 100 [%]
Flow (µL/min)
10/26/2018
11/2/2018
11/9/2018
12/7/2018
12/8/2018
12/11/2018
12/12/2018
12/14/2018
12/15/2018
1/29/2019
1/30/2019
2/8/2019
3/28/2019
4/17/2019



5
0
-5
-10
-15
-20
-25
1
10
100
(MUT -Ref)/Ref x 100 [%]
Flow (µL/min)
5/21/2018
5/22/2018
5/23/2018
5/24/2018
5/31/2018
6/1/2018
10/22/2018



5
0
-5
-10
-15
-20
(MUT - Ref) / Ref x 100 (%)
0.2
Flow (µL/min)
2
20
12/7/2018
12/8/2018
12/11/2018
12/12/2018
12/14/2018
12/15/2018