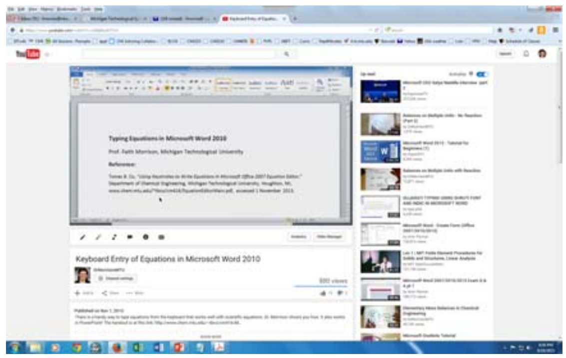
CM3215
Fundamentals of Chemical Engineering Laboratory

**Typing Equations in MS Word 2010**




https://www.youtube.com/watch?v=ceNp9meHTmY

***Professor Faith Morrison***
Department of Chemical Engineering
Michigan Technological University

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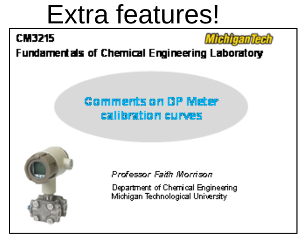
## CM3215
## Fundamentals of Chemical Engineering Laboratory

**Calibrate Rotameter and Orifice Meter and Explore Reynolds #**

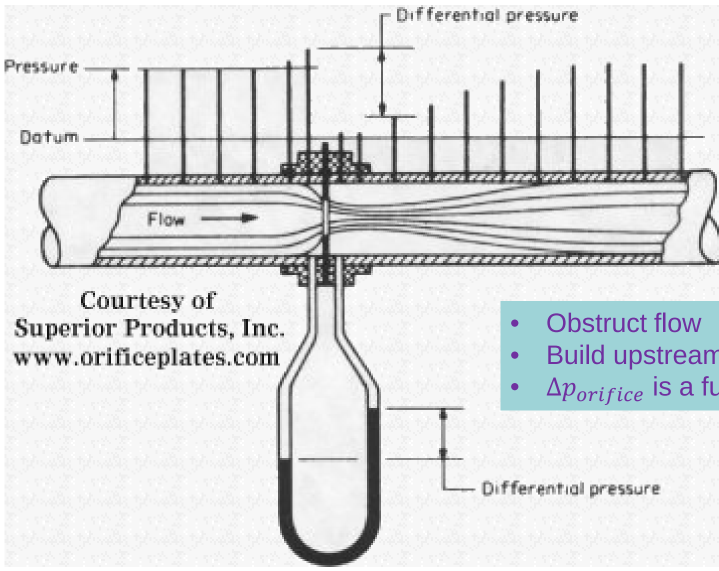
***Professor Faith Morrison***
Department of Chemical Engineering
Michigan Technological University

Extra features!




2

## What is an Orifice Flow Meter?




- Obstruct flow
- Build upstream pressure
- $\Delta p_{orifice}$ is a function of $Q$

Image source: www.cheresources.com/flowmeas.shtml

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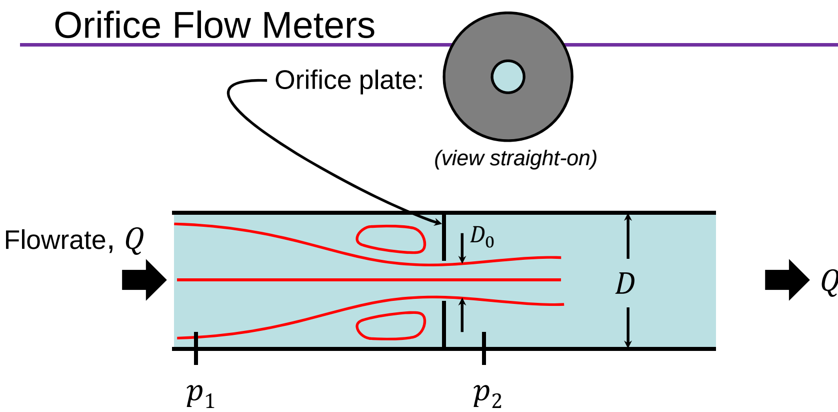
## Orifice Flow Meters




Pressure drop across the orifice $\Delta p_{orifice}$ is correlated with flow rate (mechanical energy balance)

*(SI-SO, steady, $\rho$ const., no rxn, no phase chg, $T$ const, no heat xfer)*

$$\frac{\Delta p}{\rho} + \frac{\Delta(\langle v \rangle^2)}{2} + g\Delta z + F = \frac{W_{s,on}}{\dot{m}}$$

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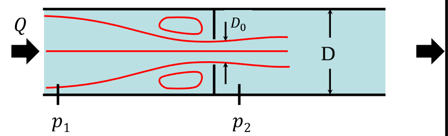
## Orifice Flow Meters

MEB: Apply MEB between upstream point (1) and a point in the *vena contracta* (2):




$$\frac{\Delta p}{\rho} + \frac{\Delta(\langle v\rangle^2)}{2} + g\Delta z + F = \frac{W_{s,on}}{\dot{m}}$$

$\Delta p_{orifice}$

$$\frac{p_2 - p_1}{\rho} + \frac{\langle v\rangle_2^2 - \langle v\rangle_1^2}{2} = 0$$

Macroscopic mass balance:

$$\frac{\langle v\rangle_1 \pi D^2}{4} = \frac{\langle v\rangle_2 \pi D_0^2}{4}$$

Combine and eliminate $\langle v\rangle_2$

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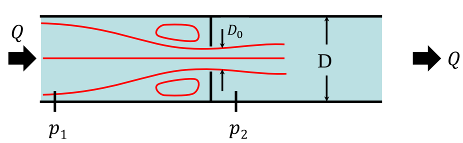
## Orifice Flow Meters

Apply MEB between upstream point and a point in the *vena contracta;* combine with mass balance:




$$Q = \frac{\pi D^2}{4}\sqrt{\frac{\frac{2(\Delta p_{orifice})}{\rho}}{\left(\frac{D^4}{D_0^4} - 1\right)}}$$

$$\Delta p_{orifice} \equiv p_1 - p_2$$

*Q: What should you plot versus what to get a straight-line correlation?*

*(give your answer in your prelab)*

*Reference: Morrison, An Introduction to Fluid Mechanics, Cambridge, 2013, page 837, problem 43.*

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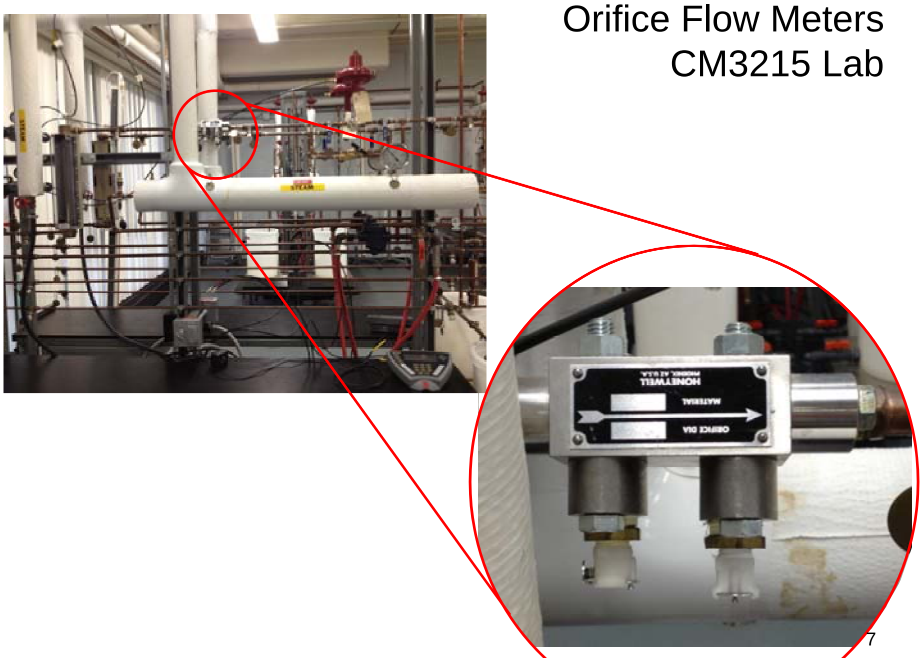
## Orifice Flow Meters
## CM3215 Lab



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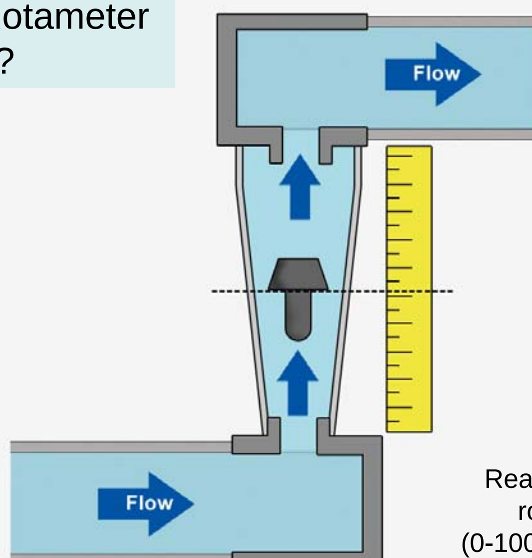
## What is a Rotameter Flow Meter?




Reading on the rotameter (0-100%) is linearly correlated with flow rate

www.alicatscientific.com/images/rotameter_big.gif

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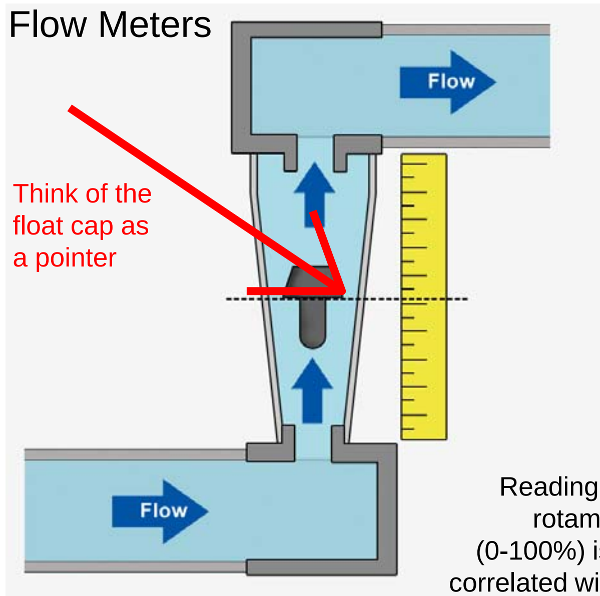
## Rotameter Flow Meters




Reading on the rotameter (0-100%) is linearly correlated with flow rate

www.alicatscientific.com/images/rotameter_big.gif

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## Reynolds Number

$$\mathrm{Re} \equiv \frac{\rho \langle v_z \rangle D}{\mu}$$

This combination of experimentally measureable variables is the key number that correlates with the flow regime that is observed. In a pipe:

- Laminar (Re < 2100)
- Transitional
- Turbulent (Re > 4000)

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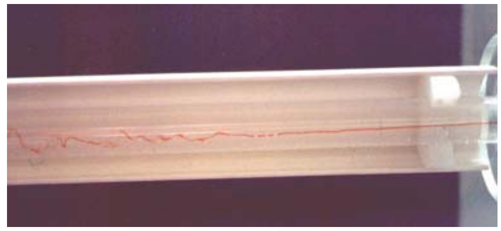
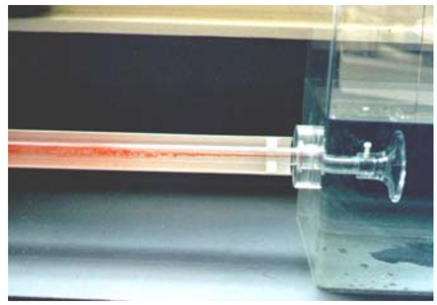
**O. Reynolds' Dye Experiment, 1883**



Transitional flow

$$\mathrm{Re} \equiv \frac{\rho \langle v_z \rangle D}{\mu}$$



Turbulent flow

Images: www.flometrics.com/reynolds_experiment.htm
accessed 4 Feb 2002

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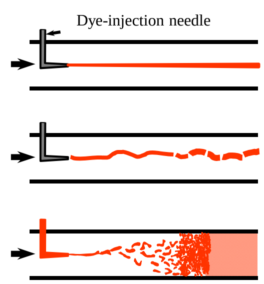
## Flow Regimes in a Pipe

$\mathrm{Re} < 2100$ Laminar
- smooth
- one direction only
- predictable

$2100 < \mathrm{Re} < 4000$ Transitional

$\mathrm{Re} > 4000$ Turbulent




- chaotic - fluctuations within fluid
- transverse motions
- unpredictable - deal with average motion
- most common

$$\mathrm{Re} \equiv \frac{\rho \langle v_z \rangle D}{\mu}$$

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Data may be organized in terms of two dimensionless parameters:

$\rho$ = density
$\langle v_z \rangle$ = average velocity
$D$ = true pipe inner diameter
$\mu$ = viscosity
$(p_0 - p_L)$ = pressure drop
$L$ = pipe length

Flow rate

**Reynolds Number**

$$\mathrm{Re} \equiv \frac{\rho \langle v_z \rangle D}{\mu}$$

*(This is a definition)*

Pressure Drop

**Fanning Friction Factor**

$$f = \frac{\frac{1}{4}\Delta p_{pipe}}{\frac{L}{D}\left(\frac{1}{2}\rho \langle v_z \rangle^2\right)}$$

*(This comes from applying the definition of friction factor **f** to pipe flow)*

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Flow rate

**Reynolds Number**

$$\mathrm{Re} \equiv \frac{\rho \langle v_z \rangle D}{\mu}$$

For now, we measure this

Pressure Drop

**Fanning Friction Factor**

$$f = \frac{\frac{1}{4}\Delta p_{pipe}}{\frac{L}{D}\left(\frac{1}{2}\rho \langle v_z \rangle^2\right)}$$

*(This comes from applying the definition of friction factor **f** to pipe flow)*

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$(p_0 - p_L)$ = pressure drop
$L$ = pipe length

Data may be organized in terms of two dimensionless parameters:

Flow rate

**Reynolds Number**

$$\mathrm{Re} \equiv \frac{\rho \langle v_z \rangle D}{\mu}$$

For now, we measure this

Pressure Drop

**Fanning Friction Factor**

$$f = \frac{\frac{1}{4}\Delta p_{pipe}}{\frac{L}{D}\left(\frac{1}{2}\rho \langle v_z \rangle^2\right)}$$

In a few weeks, we measure this as well

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## Experimental Notes

- Measure orifice pressure drop $\Delta p_{orifice}$ with Honewell DP meter (low pressure drops) or Bourdon gauges (high pressure drops)
- Determine **uncertainty** for all measurements (reading error, calibration error, error propagation)
- DP meter has valid output only from 4-20mA – above 20mA it is **over range (saturated)**
- What is lowest ***accurate*** $\Delta p$ that you can measure with the Honeywell DP meter? With the Bourdon gauges? Consider your uncertainties. (At what point will the *error* be 100% of your signal? What's your tolerance for %error?)
- True triplicates must include **all** sources of random error (All steps that it takes to move the system to the operating condition must be taken for each replicate. Thus, setting the flowrate with the needle valve and the rotameter must be done for each replicate.)
- Watch level of Tank-01 (there is no **overflow** protection)

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## Report Notes

- Design your graphs to communicate a point clearly (chart design); you may make multiple graphs with the same data if they are needed to make your point.
- The axes of your graphs must reflect the correct number of significant figures for your data.
- Calculate averages of triplicates (needed for replicate error)
- Do not use the averages in calibration-curve fitting (use unaveraged data and LINEST).
- Use LINEST to determine confidence intervals on slope and intercept
- True inner diameter of type L copper tubing may be found in the *Copper Tube Handbook* (see lab website). The sizes ¼, ½, and 3/8 are called *nominal pipe sizes*.

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**CM3215 Fundamentals of Chemical Engineering Laboratory**

Lab: Calibrate Rotameter and Explore Reynolds Number

- Pump water through pipes of various diameters
- Measure flow rate with pail-and-scale method
- Calibrate the rotameter
- Calibrate the orifice meter (measure $\Delta p_{orifice}(Q)$)
- Calculate Re for each run
- Determine if flow is laminar, turbulent, transitional
- Use appropriate error analysis, sig figs

**Calibrate Flowmeters and Explore Reynolds Number**

**Pre-laboratory Assignment**
Familiarize yourself with Reynolds number, rotameters, and orifice meters. Find an accurate calibration curve for the Honeywell DP meter at your lab station (your own calibration curve or one from the archive) and have the equation in your lab notebook. Prepare a safety section in your laboratory notebook detailing all safety issues associated with this laboratory. Prepare the data tables in your notebook you will use for data acquisition. All sheets of paper must be affixed on all four sides with clear tape before the start of lab.

*Answer these questions as part of your prelab (write the answer in the notebook):*

objectives as discussed in **Data Analysis** below.

**Experimental Procedures**

**Overall procedure:**
1. Prepare the work station for isothermal water flow (see Procedure A in the appendix).
2. Turn on Ohaus electronic scale (Model CD-33; WI-09) that is attached to the balance under Tank 1 by plugging in the AC/DC power converter (120 VAC -> 9VDC 500 mA) into the AC outlet. When the Ohaus scale is on it will show the following on its screen: "Weight 4.160 kg (for example)." Press "Tare" key. It will show "0.000 kg."
3. Ready the Honeywell DP meter (see

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## PreLab Assignment

- Familiarize yourself with Reynolds number, rotameters, and orifice meters.
- Find a good estimate of the calibration curve for the DP meter at your lab station (cycle 2) and have the equation and plot in your lab notebook.
- Prepare a safety section
- Prepare data acquisition tables
- Answer these questions in your lab notebook:

  1. *What should you plot (what versus what) to get a straight line correlation out of the orifice meter calibration data?*
  2. *In this experiment we calibrate the rotameter for flow directed through ½", 3/8", and ¼" pipes (nominal sizes); will the calibration curve be the same for these three cases, or different?*
  3. *What is "dead heading" the pump?*

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**CM3215**
**Fundamentals of Chemical Engineering Laboratory**

## Comments on DP Meter calibration curves

***Professor Faith Morrison***

Department of Chemical Engineering
Michigan Technological University

www.honeywellprocess.com/
ST 3000 Smart Pressure Transmitter Models Specifications 34-ST-03-65

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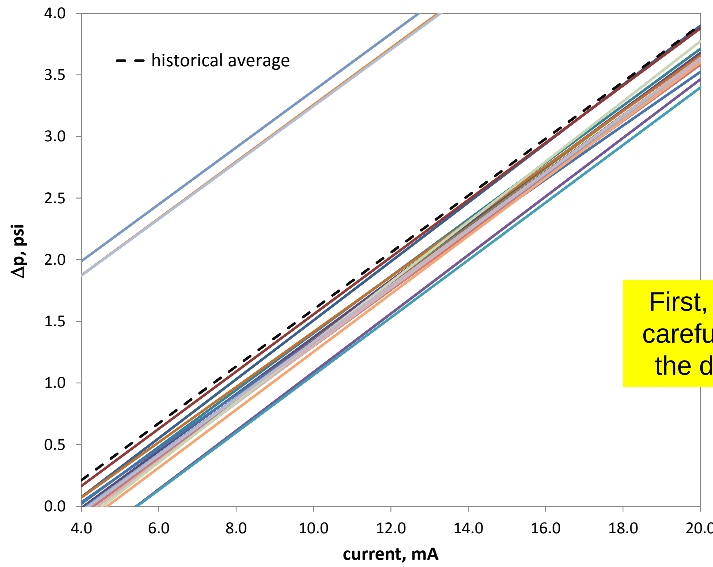
## Station 1 Archive (uncorrected)




First, look carefully at the data.

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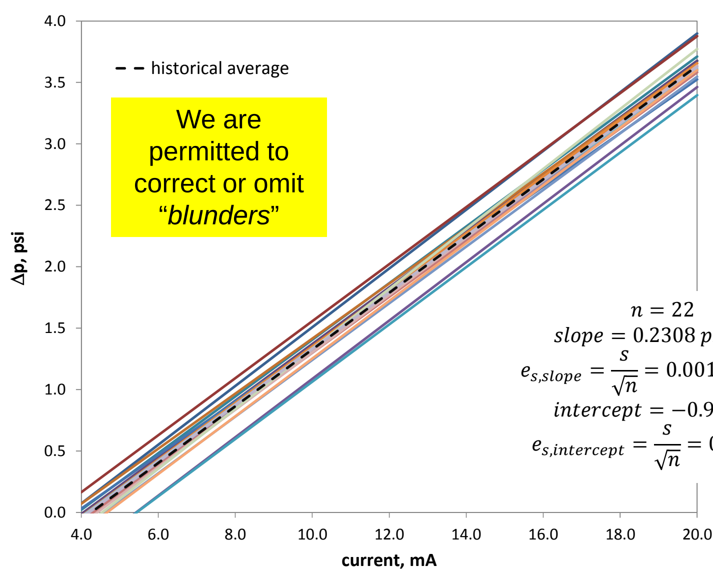
## Station 1 Archive (corrected for obvious errors)




We are permitted to correct or omit "*blunders*"

$$n = 22$$
$$slope = 0.2308\ psi/mA$$
$$e_{s,slope} = \frac{s}{\sqrt{n}} = 0.0011\ psi/mA$$
$$intercept = -0.982\ psi$$
$$e_{s,intercept} = \frac{s}{\sqrt{n}} = 0.027\ psi$$

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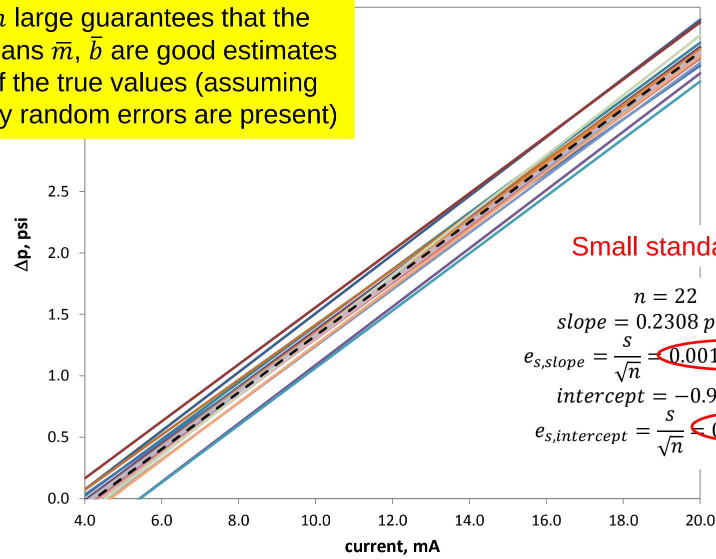
## Station 1 Archive (corrected for obvious errors)

$n$ large guarantees that the means $\bar{m}$, $\bar{b}$ are good estimates of the true values (assuming only random errors are present)




Small standard errors

$$n = 22$$
$$slope = 0.2308\ psi/mA$$
$$e_{s,slope} = \frac{s}{\sqrt{n}} = 0.0011\ psi/mA$$
$$intercept = -0.982\ psi$$
$$e_{s,intercept} = \frac{s}{\sqrt{n}} = 0.027\ psi$$

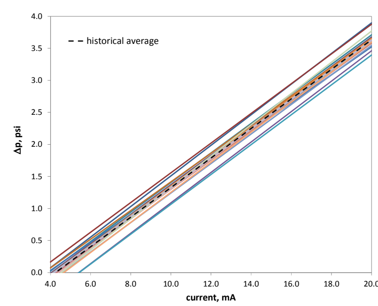




## Station 1 Archive (corrected for obvious errors)

Historical, 95% CI:

$$\bar{m} = 0.2308 \pm 0.0022\ psi/mA$$
$$\bar{b} = -0.98 \pm 0.05\ psi$$



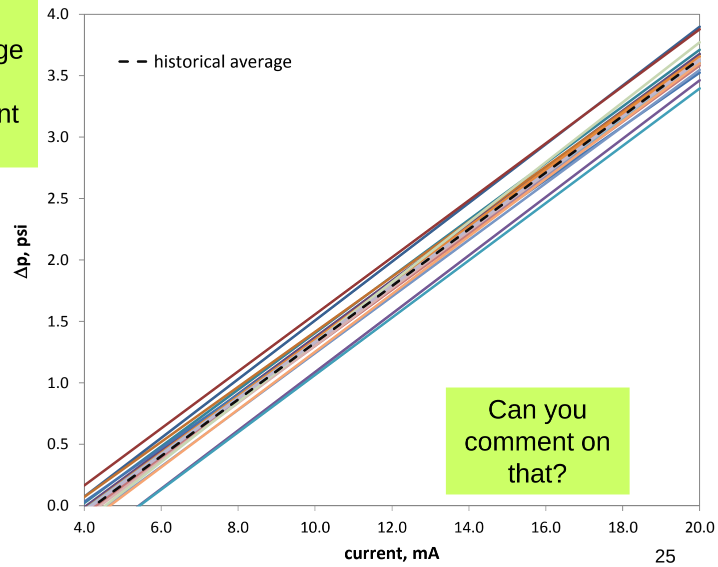

We are 95% confident that the true values of the slope and intercept are within these intervals.

(if only random error is present)

## Station 1 Archive

Historical, 95% CI:
$\bar{m} = 0.2308 \pm 0.0022\ psi/mA$
$\bar{b} = -0.98 \pm 0.05\ psi$

Note that the historical average almost goes through the point $(I, \Delta p) = (4{,}0)$




Can you comment on that?

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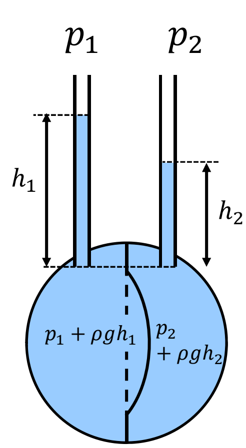
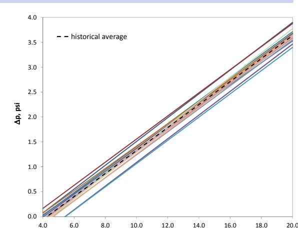
## Honeywell DP Meter

Historical, 95% CI:
$\bar{m} = 0.2308 \pm 0.0022\ psi/mA$
$\bar{b} = -0.98 \pm 0.05\ psi$

www.honeywellprocess.com/
ST 3000 Smart Pressure Transmitter
Models Specifications 34-ST-03-65




$p_1 > p_2$




The presence of residual water may cause a **systematic upward deviation** in the $\Delta p = p_1 - p_2$ measurement.

$$\Delta p = p_1 + \rho g h_1 - (p_2 + \rho g h_2)$$
$$= p_1 - p_2 + \rho g (h_1 - h_2)$$

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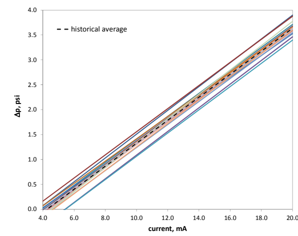
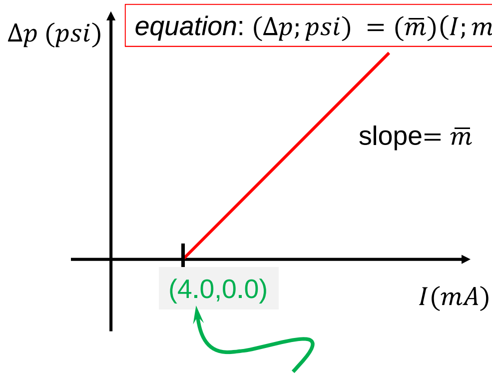
## Station 1 Archive

Historical, 95% CI:
$\bar{m} = 0.2308 \pm 0.0022\ psi/mA$
$\bar{b} = -0.98 \pm 0.05\ psi$




(identify a systematic error; correct the calibration curve)

*equation*: $(\Delta p; psi) = (\bar{m})(I; mA) + b$




If we know **this point** is on our correlation line, we can solve for a value of $b$, independent of the systematic offset in the data.

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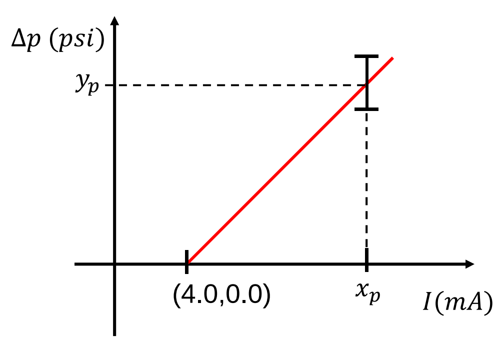
## Another Error-Related question:

$(\Delta p; psi) = (\bar{m})(I; mA) + b$

What's the **lowest** accurate $\Delta p$?

Can we measure
$\Delta p = 10 psi$?
$1 psi$?
$0.1 psi$?
$0.01 psi$?
$0.001 psi$?
$0.0001 psi$?




When will the **value** be indistinguishable from the **noise** (error)?

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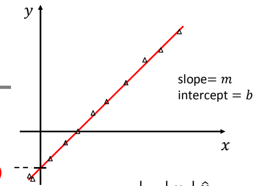
From *Error Analysis Lecture 5* on LINEST:

**Ordinary, *Least Squares*, Linear Regression**

What are the error limits on a value of $y$ obtained from the equation $y = \hat{m}x + \hat{b}$?




| $i$ | $x_i$ | $y_i$ | $\hat{y}_i$ |
|---|---|---|---|
| 1 | $x_1$ | $y_1$ | $\hat{y}_1$ |
| 2 | $x_2$ | $y_2$ | $\hat{y}_2$ |
| ⋮ | ⋮ | ⋮ | ⋮ |
| $n$ | $x_n$ | $y_n$ | $\hat{y}_n$ |

*Answer:*

at $x_p$, $y_p = \left(\hat{m}x_p + \hat{b}\right) \pm 2s_{y_p}$

$$s_{y_p}^2 = s_{y,x}^2\left(\frac{1}{n} + \frac{\left(x_p - \bar{x}\right)^2}{SS_{xx}}\right)$$

(This is the final result of the algebra indicated on previous slide see Appendix B of the handout.)

for $n - 2 \leq 6$, replace "2" with $t_{0.025,n-2}$

Use this for error limits on the fit.

In Excel:
- $s_{y,x}$ = STEYX(y-range,x-range)
- $SS_{xx}$ = DEVSQ(x-range)
- $\bar{x}$ = AVERAGE(x-range)

The error limits on a $\Delta p$ obtained from the line:

$$\Delta p = \Delta p_{\substack{predicted \\ from \\ calibration \\ curve}} \pm 2s_{y_p}$$

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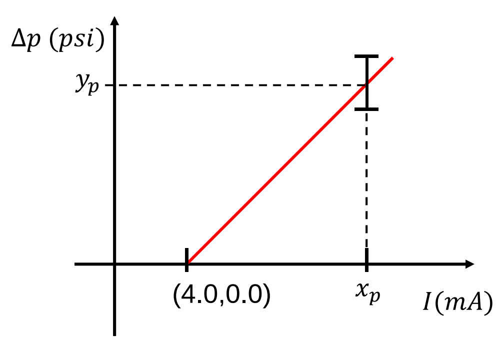
Another Error-Related question:

$$(\Delta p; psi) = (\bar{m})(I; mA) + b$$

What's the **lowest** accurate $\Delta p$?




$$\Delta p = \Delta p_{\substack{predicted \\ from \\ calibration \\ curve}} \pm 2s_{y_p}$$

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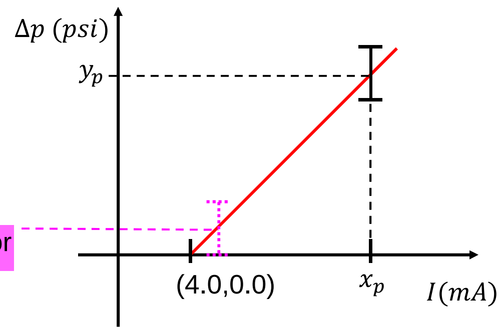
## Another Error-Related question:

$$(\Delta p; psi) = (\overline{m})(I; mA) + b$$

What's the **lowest** accurate $\Delta p$?

$2s_{y_p} = y_p \quad \Rightarrow$ 100% error




$$\Delta p = \Delta p_{\substack{predicted\\ from\\ calibration\\ curve}} \pm 2s_{y_p}$$

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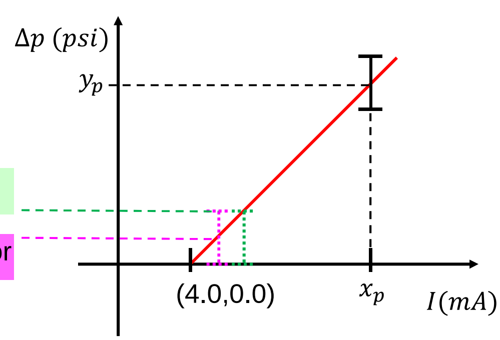
## Another Error-Related question:

$$(\Delta p; psi) = (\overline{m})(I; mA) + b$$

What's the **lowest** accurate $\Delta p$?

$4s_{y_p} = y_p \quad \Rightarrow$ 50% error

$2s_{y_p} = y_p \quad \Rightarrow$ 100% error




$$\Delta p = \Delta p_{\substack{predicted\\ from\\ calibration\\ curve}} \pm 2s_{y_p}$$

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## Another Error-Related question:

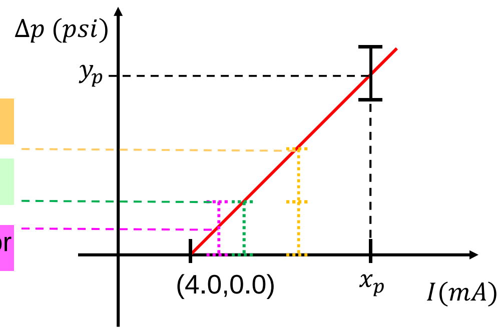
$(\Delta p; psi) = (\overline{m})(I; mA) + b$

What's the **lowest** accurate $\Delta p$?

$8s_{y_p} = y_p \Rightarrow$ 25% error

$4s_{y_p} = y_p \Rightarrow$ 50% error

$2s_{y_p} = y_p \Rightarrow$ 100% error




$$\Delta p = \Delta p_{\substack{predicted\\ from\\ calibration\\ curve}} \pm 2s_{y_p}$$

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## Another Error-Related question:

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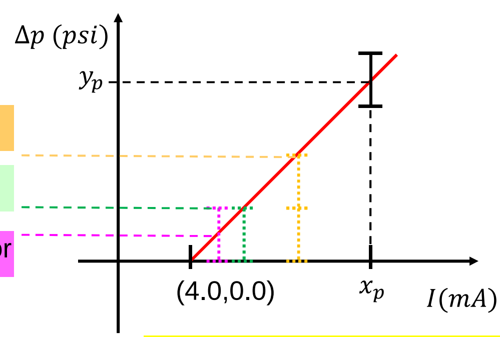
$2s_{y_p} = y_p \Rightarrow$ 100% error




$$\Delta p = \Delta p_{\substack{predicted\\ from\\ calibration\\ curve}} \pm 2s_{y_p}$$

The choice is up to you.

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## Summary

- We can omit "blunders" from data sets
- We are always looking for possible sources of systematic error
- When a systematic error is identified (leftover water in unequal amounts on the two sides of the DP meter), we are justified in making adjustments to our correlations
- Note that the units of $\Delta p$ are $psi$ not $psig$. You've subtracted two numbers:

$$\boldsymbol{\Delta p = p_1 - p_2}$$

For example:

$$p_1 = 5psig = 6psia$$
$$p_2 = 0psig = 1psia$$
$$\boldsymbol{\Delta p = 5psi \quad = 5psi}$$

- The lowest number you can accurately report depends on your tolerance for uncertainty (25% max relative error is a good rule of thumb $\Rightarrow \Delta p_{min} \approx 8s_{y_p}$)

35



## Summary

- We can omit "blunders" from data sets
- We are always looking for possible sources of systematic error
- When a s… …equal amounts … …ed in making ad…
- Note that … …ted two numb…

Pay attention to pressures, and $\Delta p$'s: we measure many different pressures and $\Delta p$'s and **often there is confusion**

- The lowest number you can accurately report depends on your tolerance for uncertainty (25% max relative error is a good rule of thumb $\Rightarrow \Delta p_{min} \approx 8s_{y_p}$)

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