Webinars

Meeting the Challenges of CO2 Measurement with a new kind of Orifice Meter

Phil Stockton, Accord Energy Solutions Ltd

20th March 2023

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Webinars

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66 Compressible

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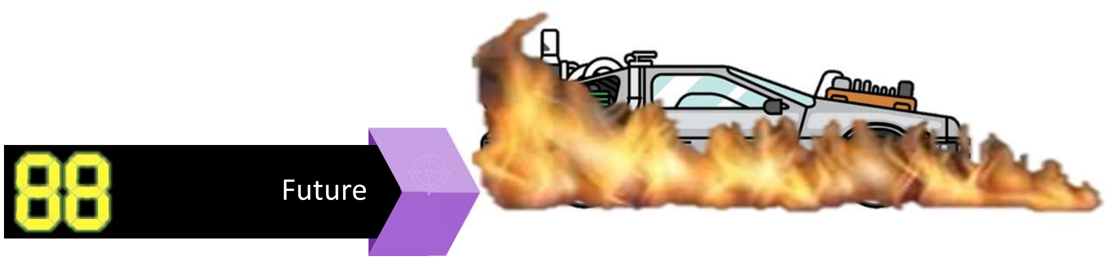

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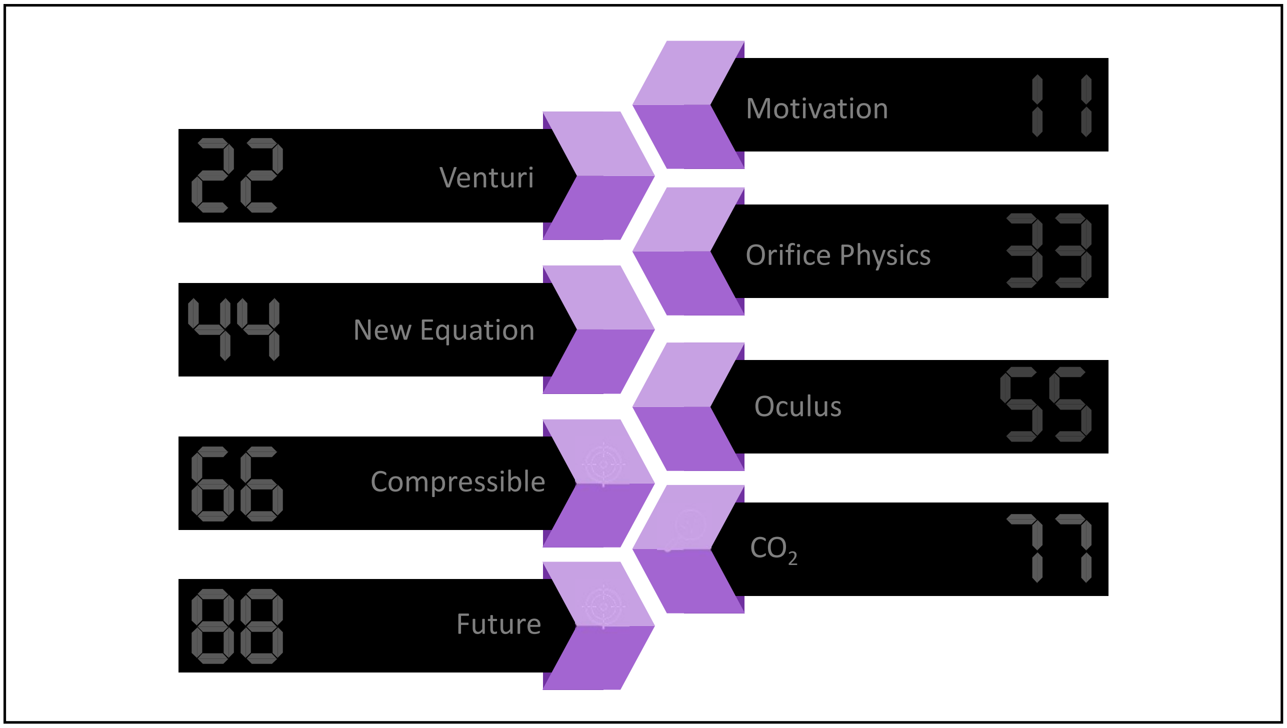

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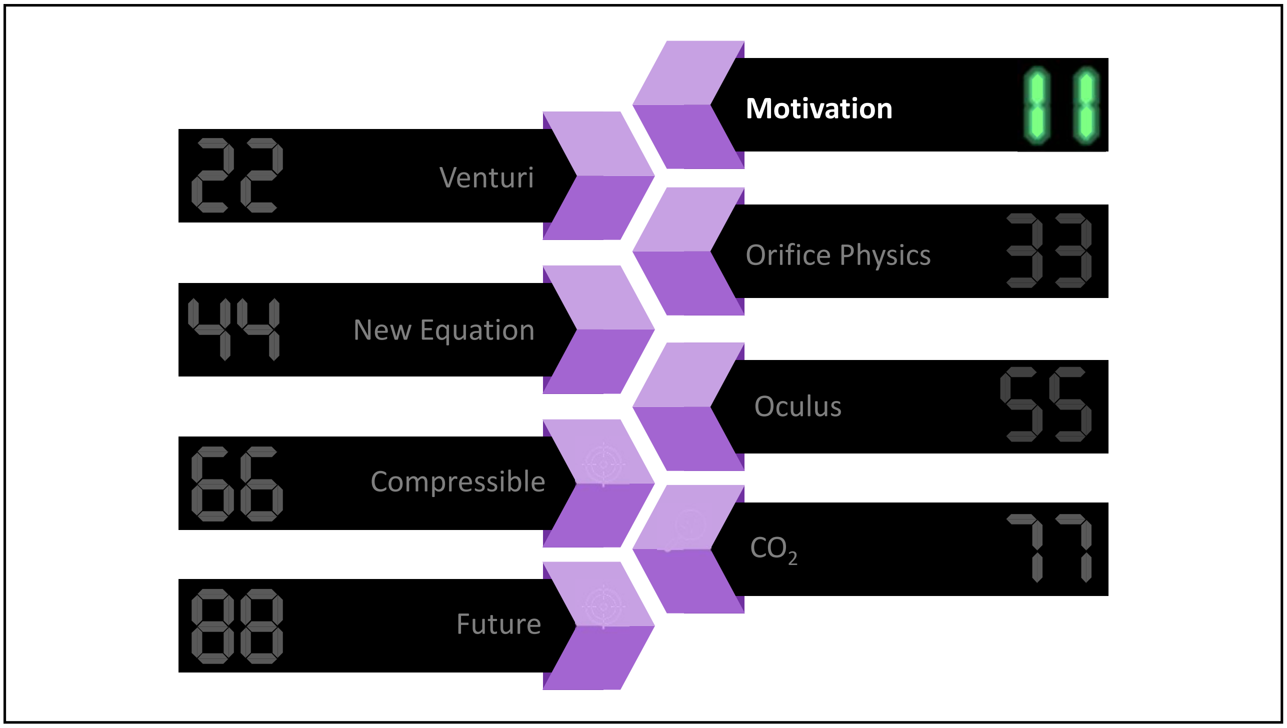
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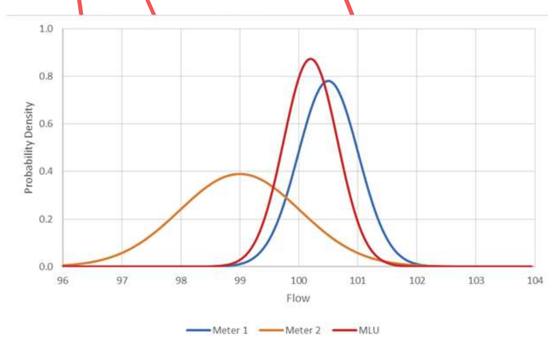
Motivation


Probability Density
1.0
0.8
0.6
0.4
0.2
0.0
96
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100
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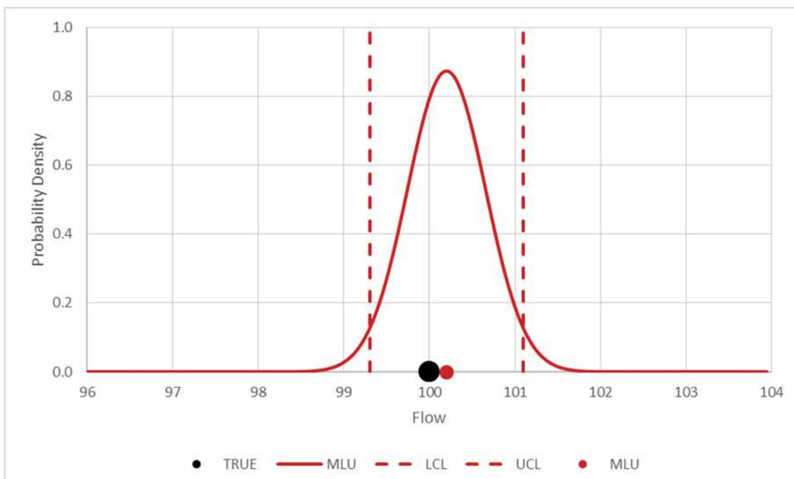
Flow
Meter 1
Meter 2
MLU

Motivation



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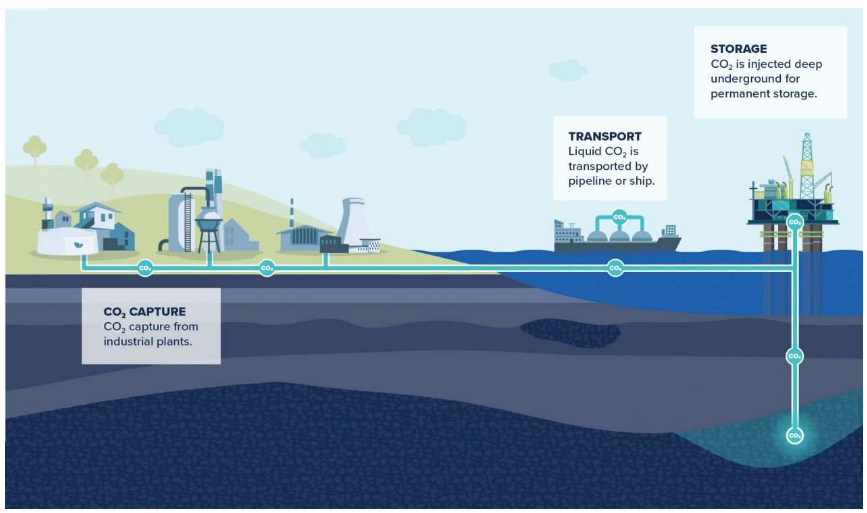
Motivation Carbon Capture and Sequestration



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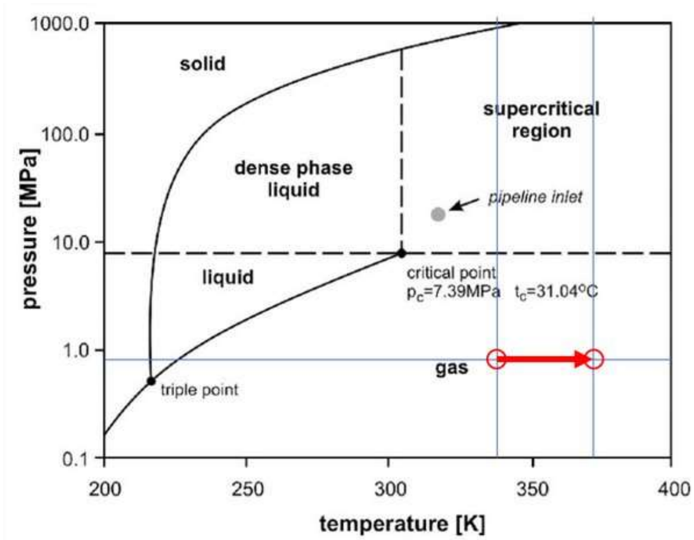
Motivation CO$_2$ Properties



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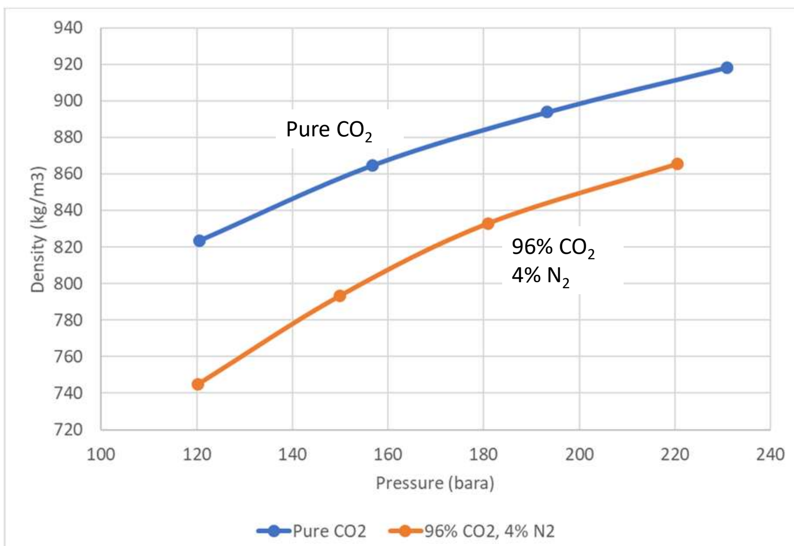
CO_2 Density as a Function of Pressure



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Motivation

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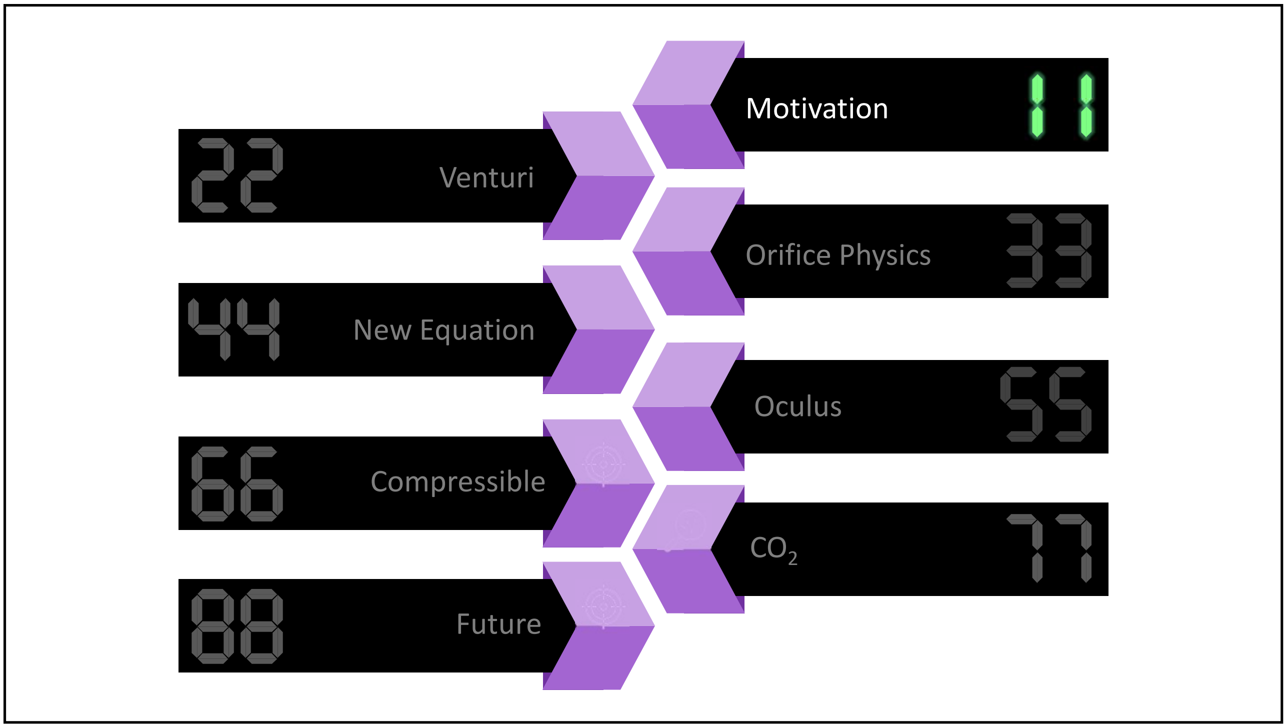
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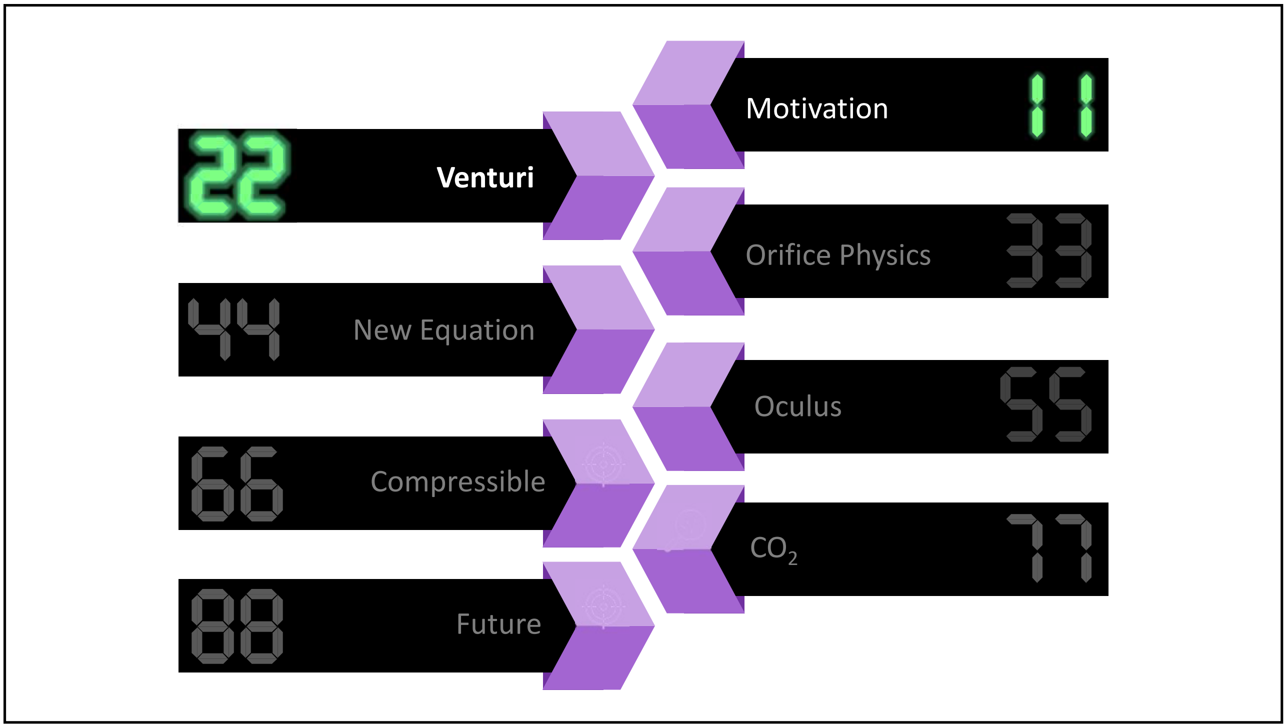

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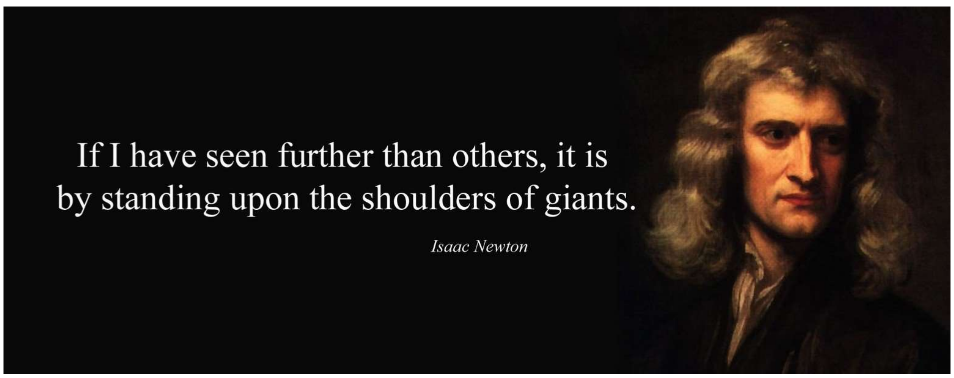
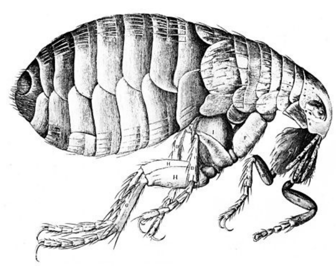



Robert Hooke



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Venturi Meter

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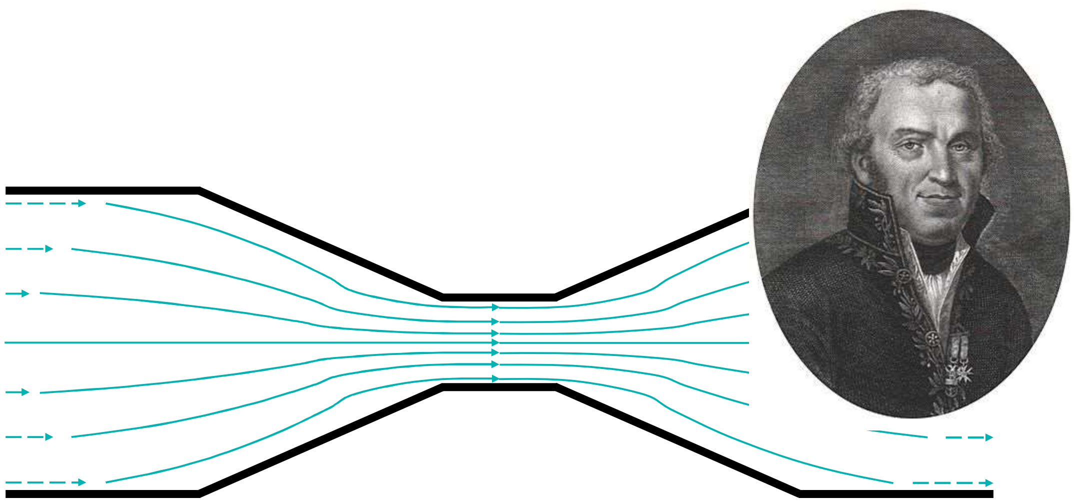
Venturi



Giovanni Battista Venturi (1797)

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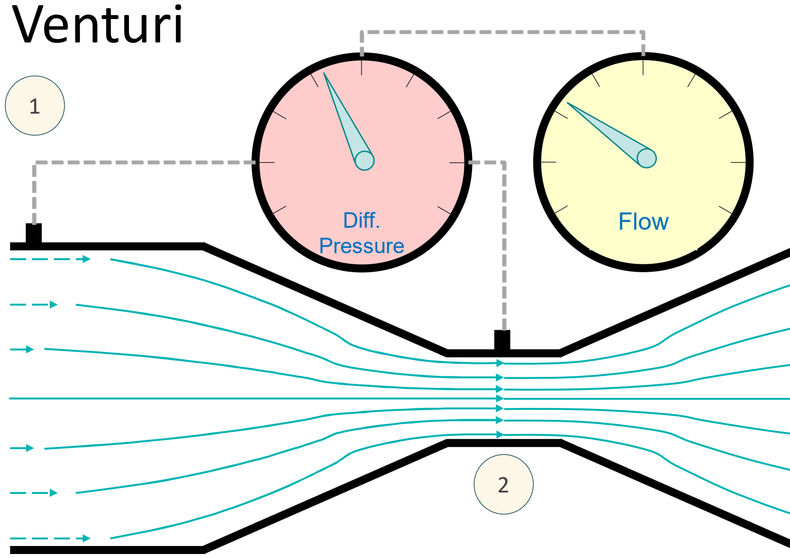
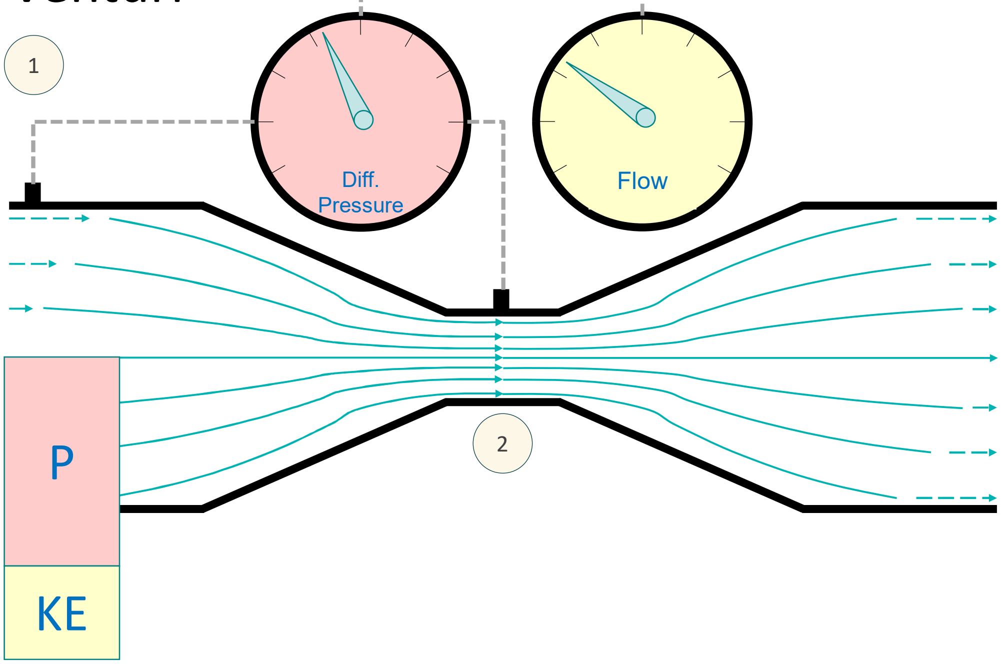
Venturi



$$P_1 + \frac{\rho V_1^2}{2} = P_2 + \frac{\rho V_2^2}{2}$$

Daniel Bernoulli (1738)

Venturi



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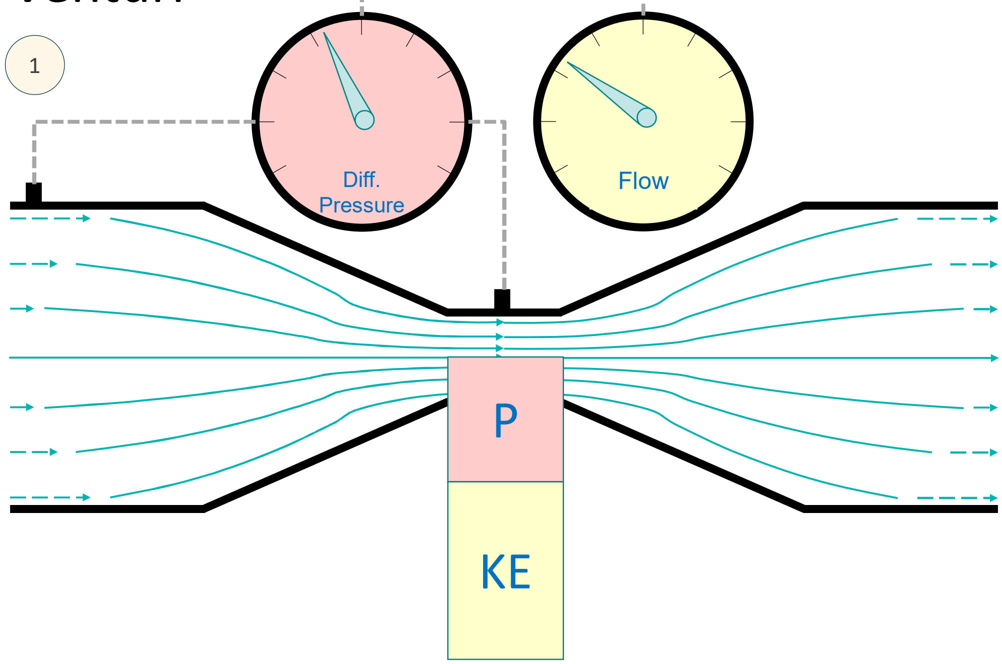
Venturi



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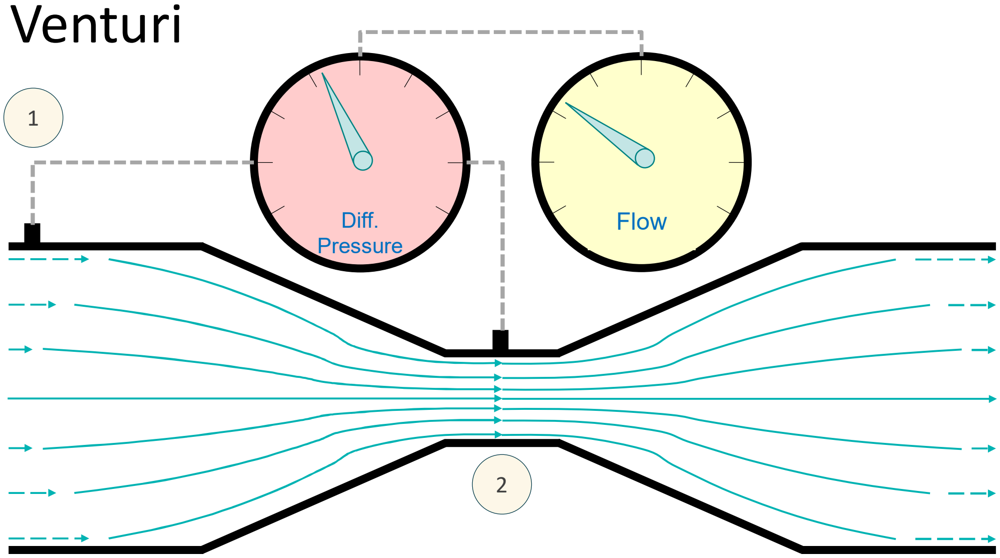
Venturi



"Energy" Conservation

Mass Conservation

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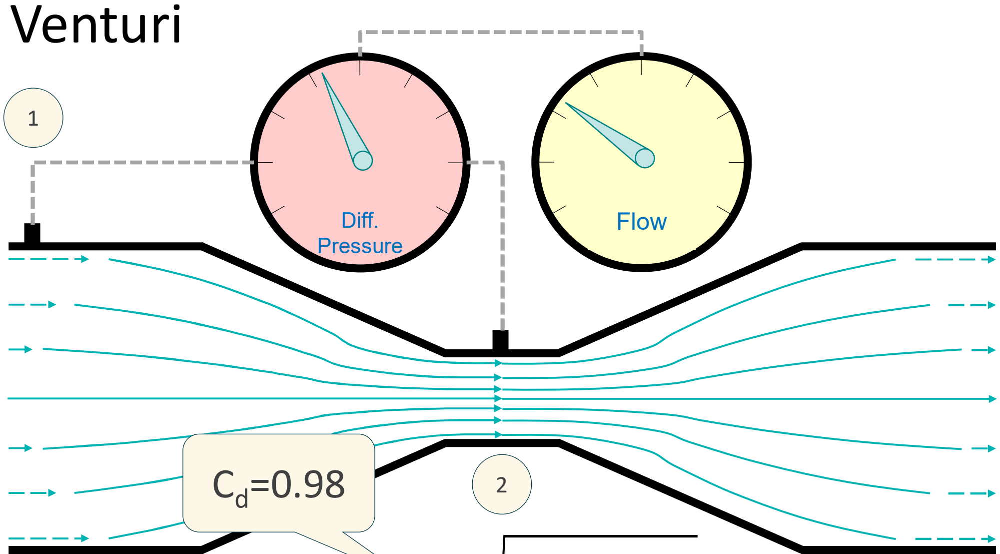
Venturi



$$m = A_2 \sqrt{\frac{2\rho(P_1 - P_2)}{1 - \left(\frac{A_2}{A_1}\right)^2}}$$

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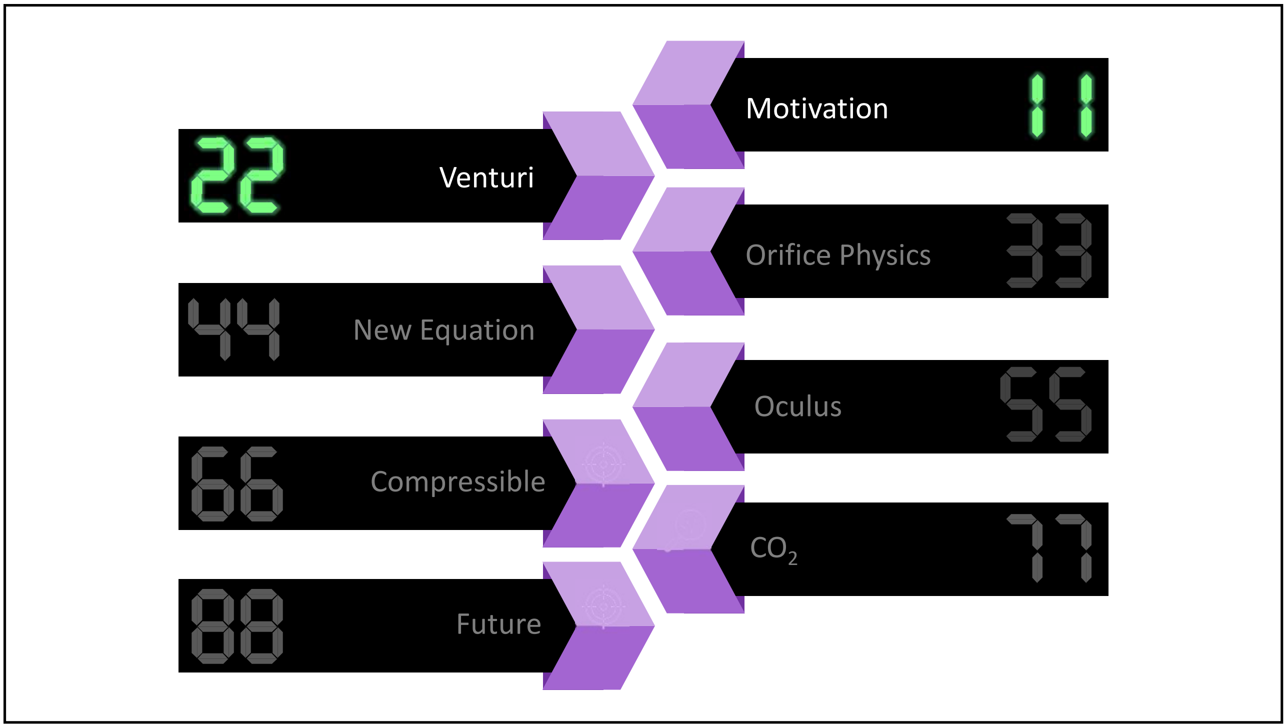

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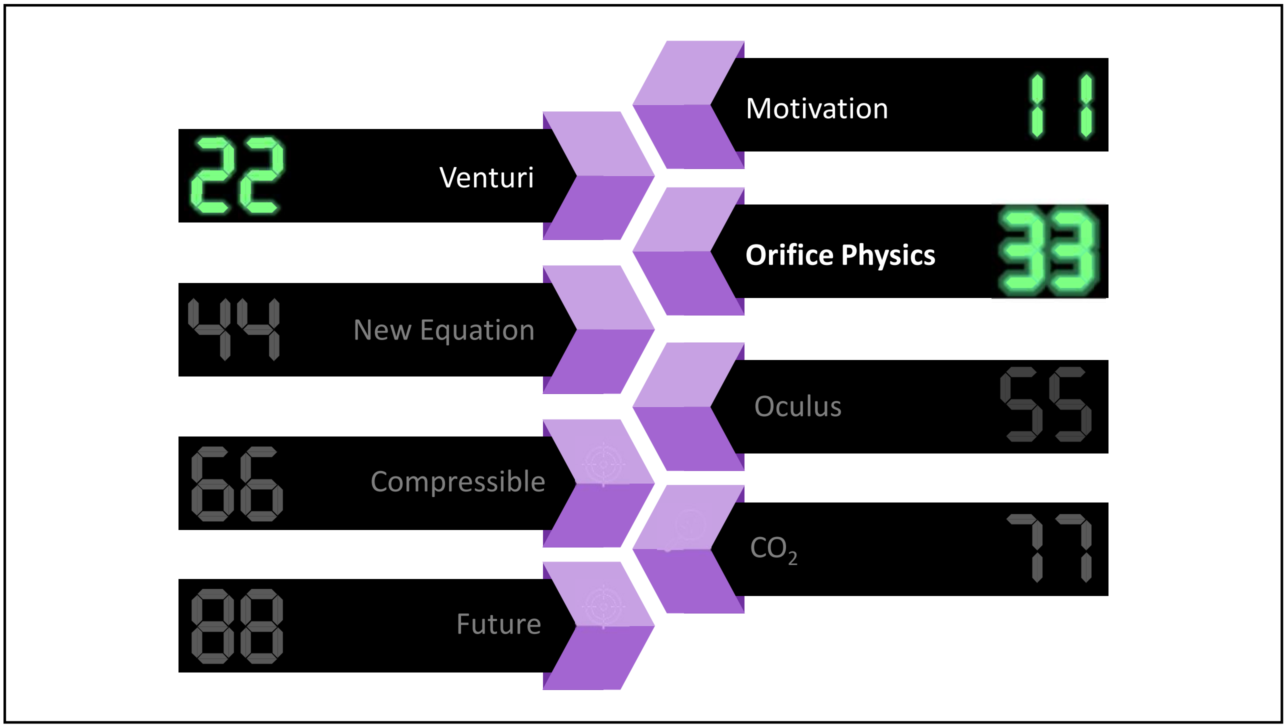
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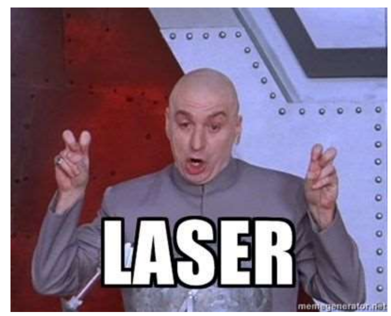
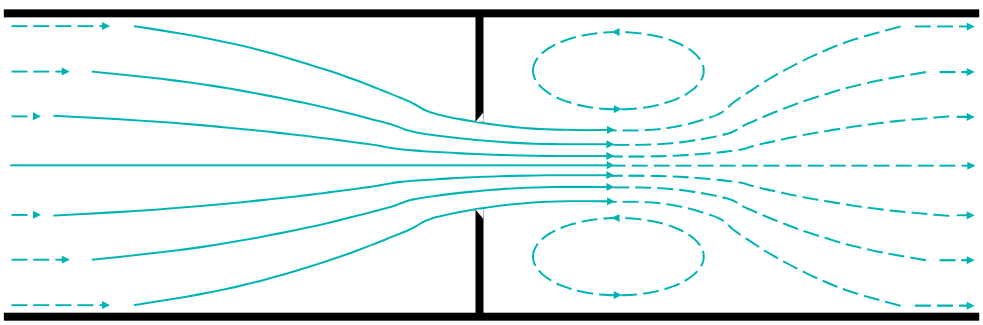
Orifice Meter

Orifice

C_d=0.6

$$m_{trad} = C_D \frac{\pi d_o^2}{4} \sqrt{\frac{2\rho \Delta P_t}{1-\beta^4}}$$





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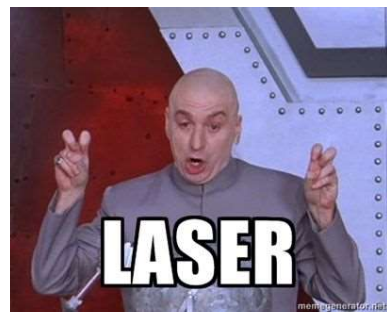
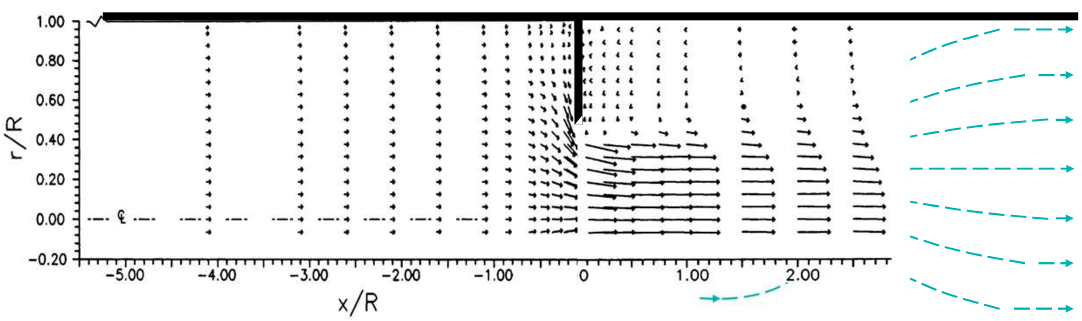
Orifice

C_d=0.6

$$m_{trad} = C_D \frac{\pi d_o^2}{4} \sqrt{\frac{2\rho \Delta P_t}{1 - \beta^4}}$$





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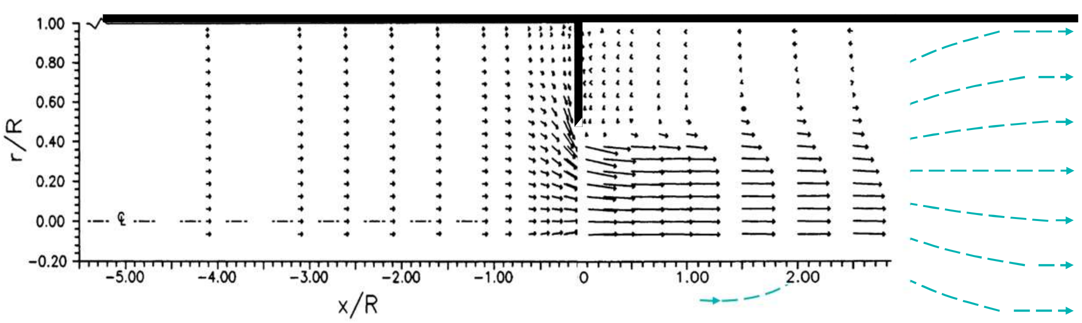
Orifice



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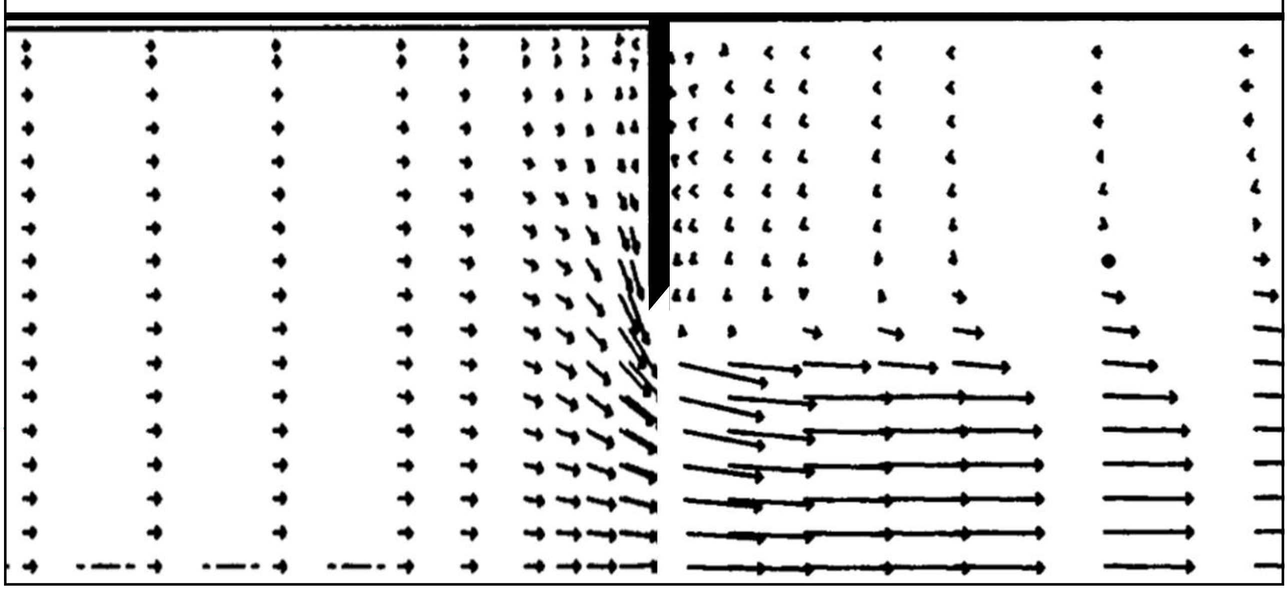
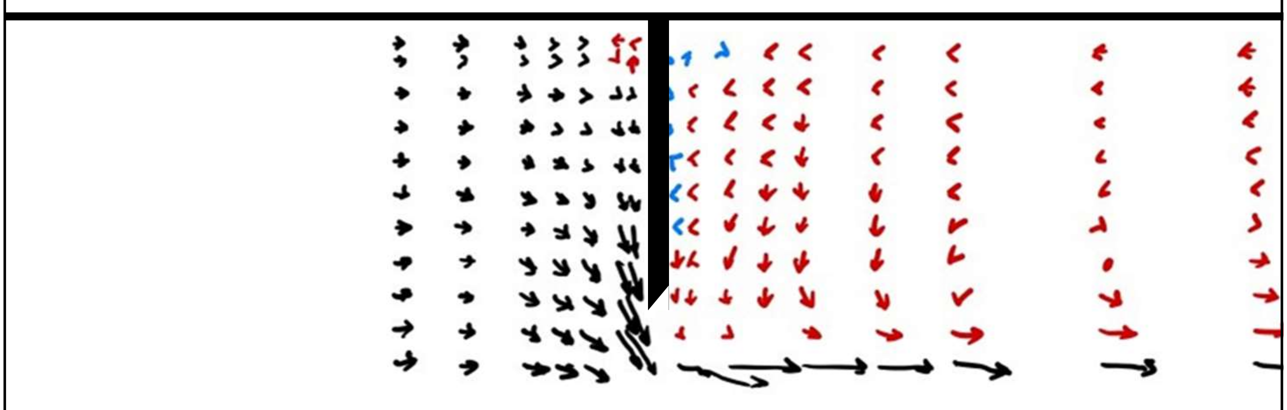
Orifice



Orifice



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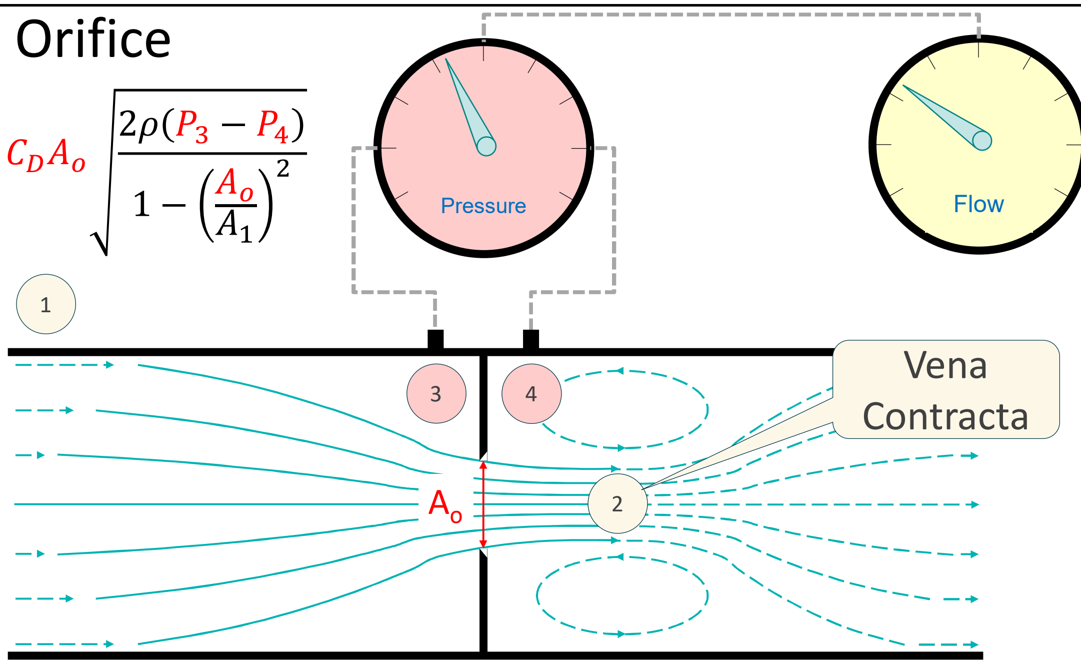
Orifice

$$m = C_D A_o \sqrt{\frac{2\rho(P_3 - P_4)}{1 - \left(\frac{A_o}{A_1}\right)^2}}$$



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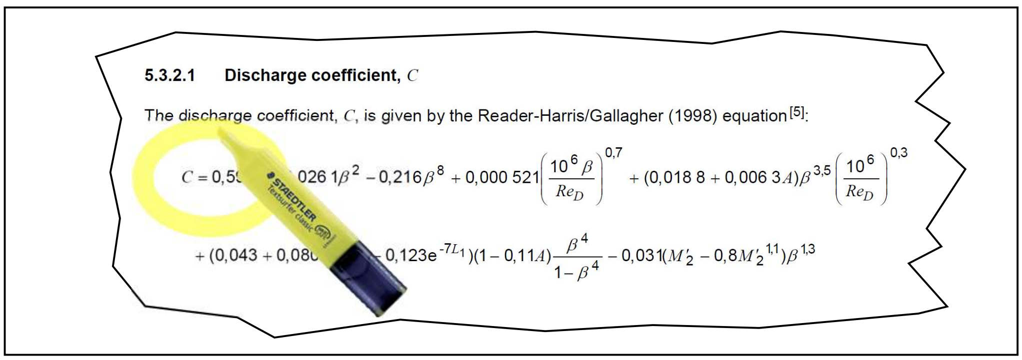
Orifice

$$m = C_D A_o \sqrt{\frac{2\rho(P_3 - P_4)}{1 - \left(\frac{A_o}{A_1}\right)^2}}$$

- C_D = 0.6, uncertainty ± 0.5%
- Uncertainty in mass flow (m) = ± 0.5 to 1%



5.3.2.1 Discharge coefficient, C

The discharge coefficient, C, is given by the Reader-Harris/Gallagher (1998) equation[5]:

$$C = 0{,}59 \ldots 026\,1\beta^2 - 0{,}216\beta^8 + 0{,}000\,521\left(\frac{10^6\beta}{Re_D}\right)^{0{,}7} + (0{,}018\,8 + 0{,}006\,3A)\beta^{3{,}5}\left(\frac{10^6}{Re_D}\right)^{0{,}3}$$

$$+ (0{,}043 + 0{,}080 \ldots 0{,}123e^{-7L_1})(1 - 0{,}11A)\frac{\beta^4}{1-\beta^4} - 0{,}031(M'_2 - 0{,}8M'^{1{,}1}_2)\beta^{1{,}3}$$

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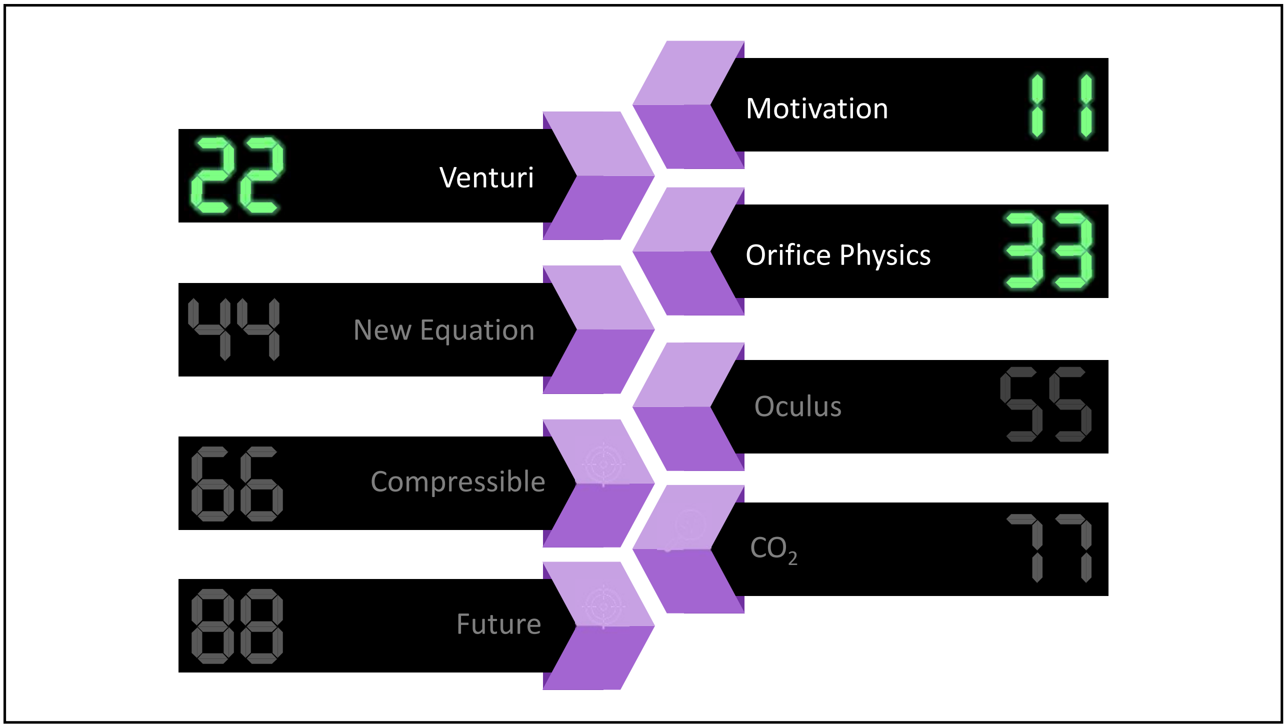

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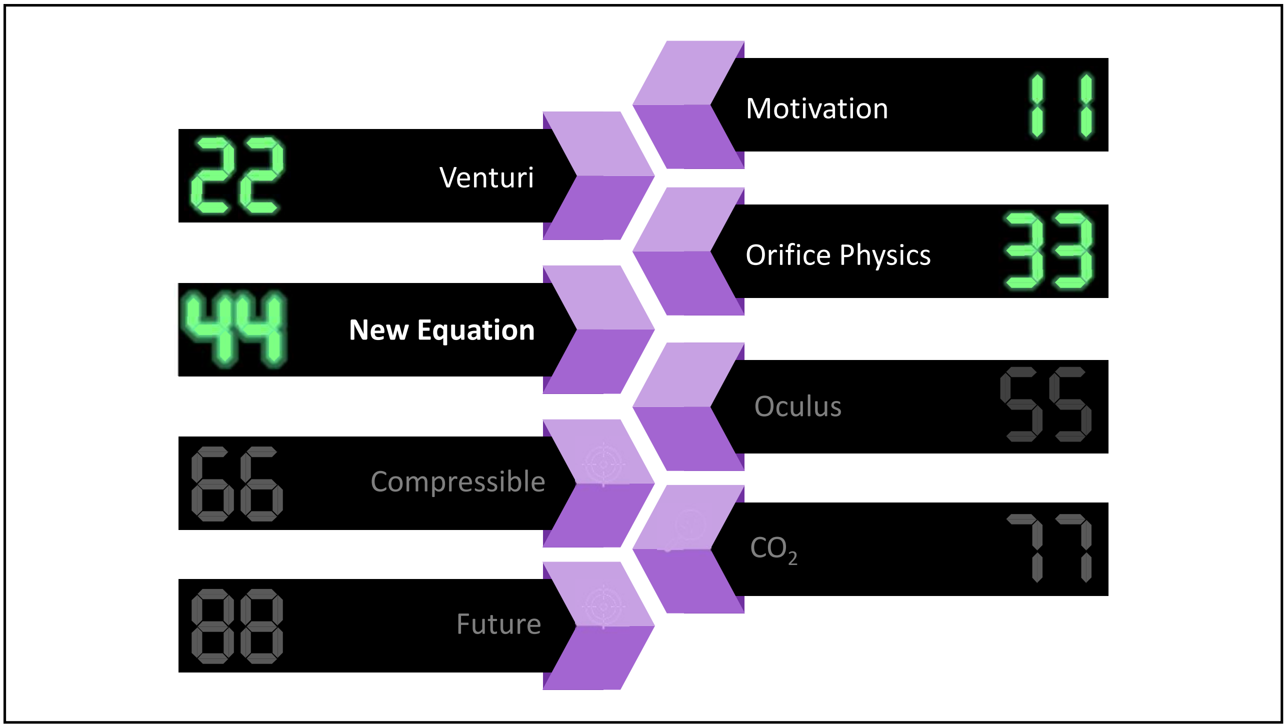
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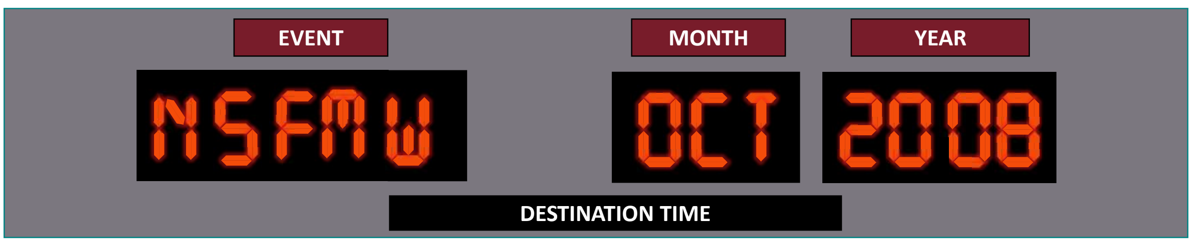
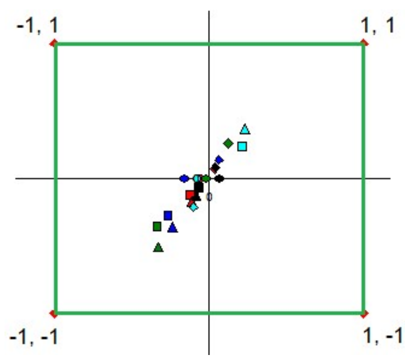
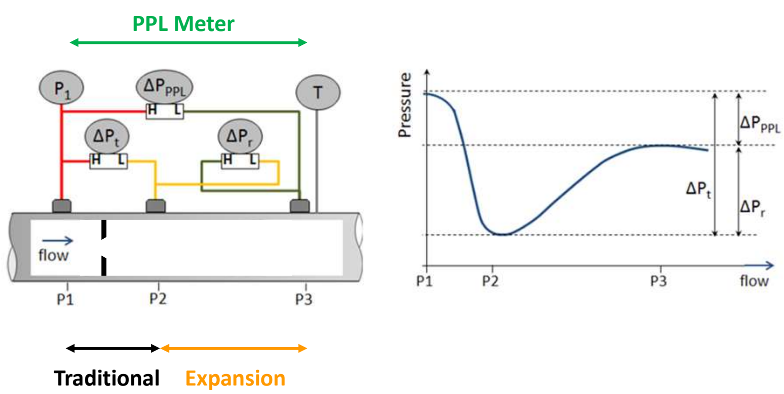
Three ΔPs





DP Diagnostics



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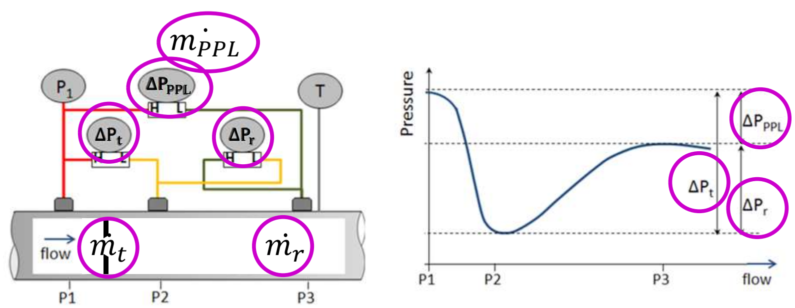
Three DP Meters



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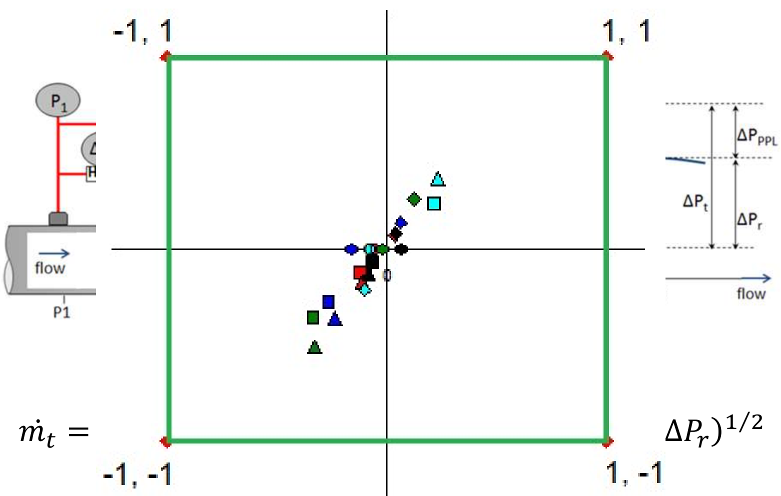
Three DP Meters



$\dot{m}_t =$ $\Delta P_r)^{1/2}$

$\dot{m}_{PPL} = AK_{PPL}(2\rho\Delta P_{PPL})^{1/2}$

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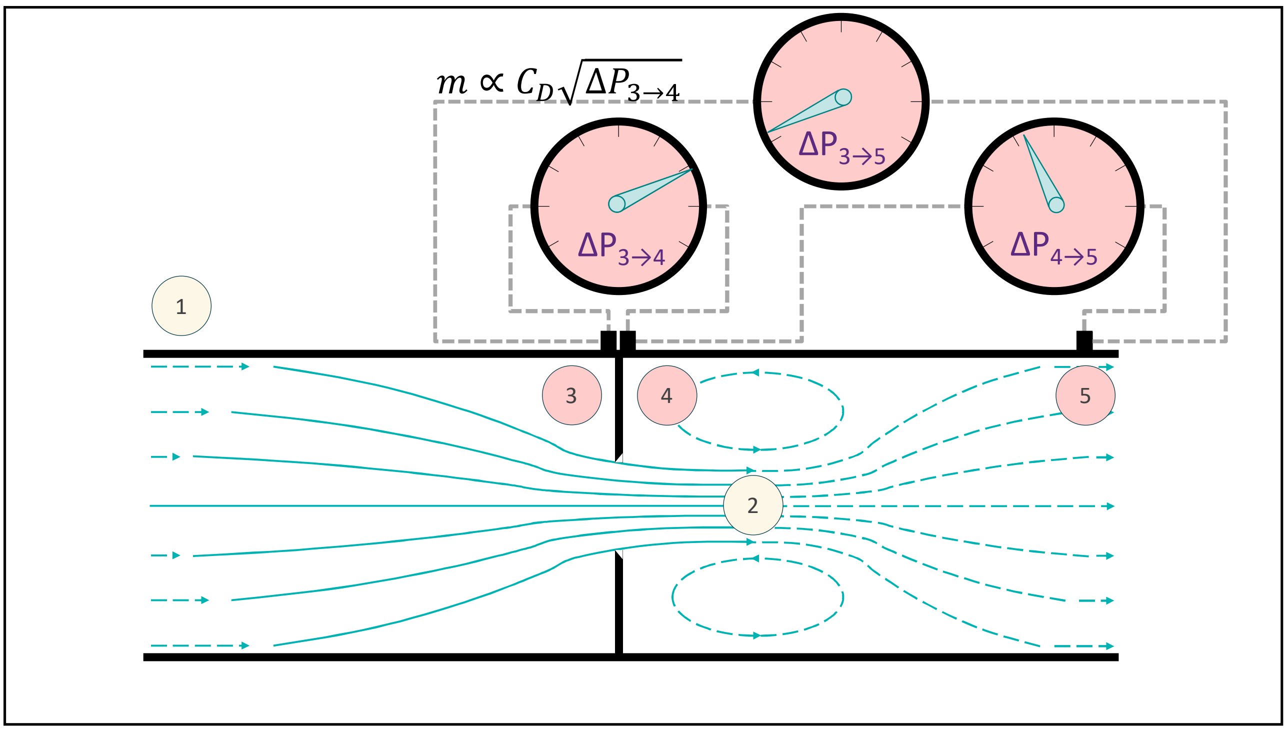

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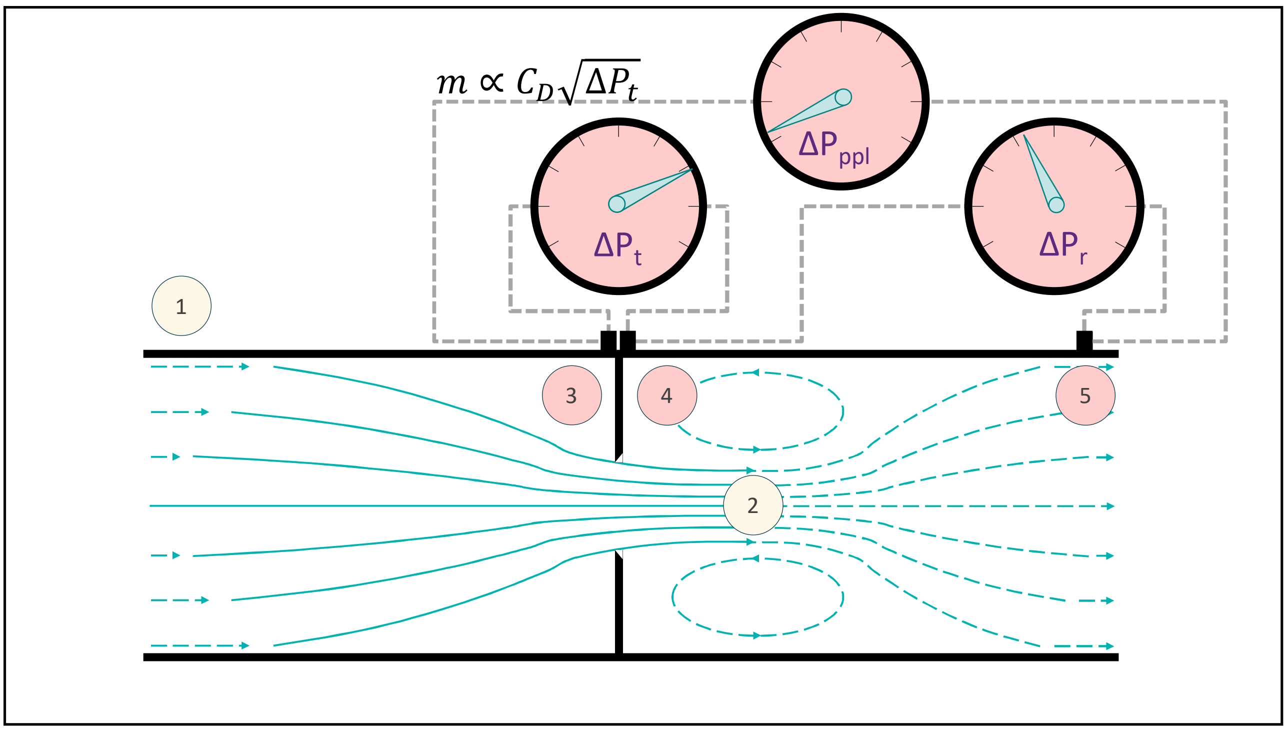

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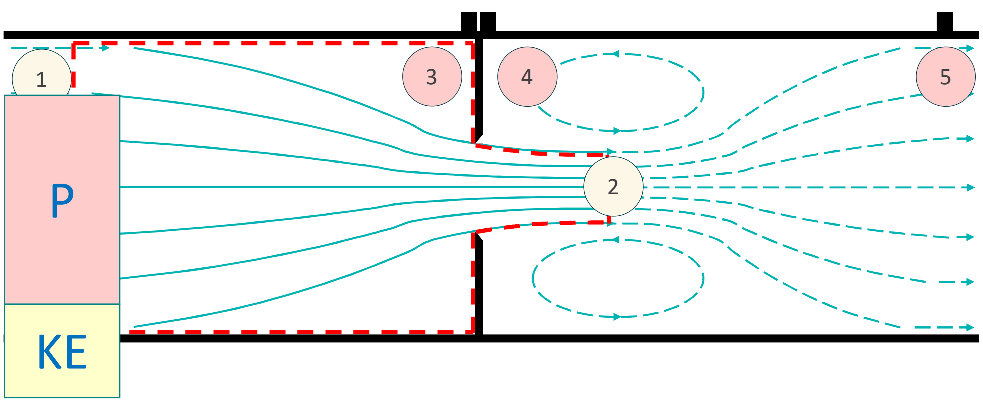
“Energy” Conservation (1→2)



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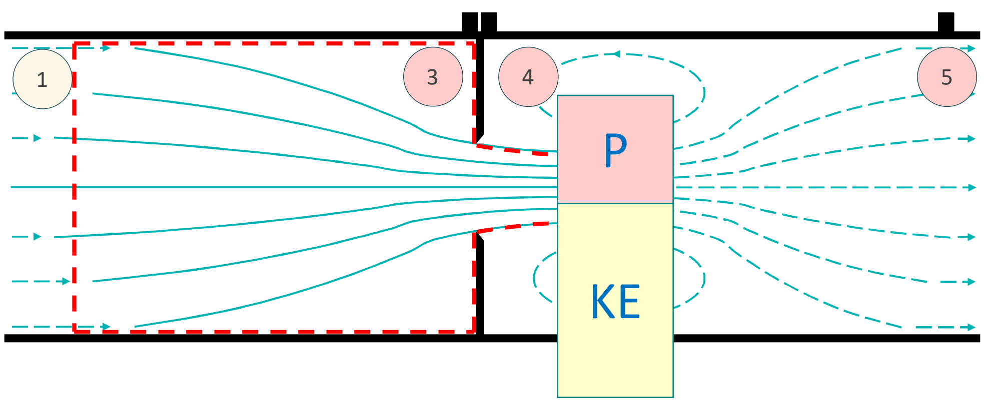
“Energy” Conservation
(1→2)



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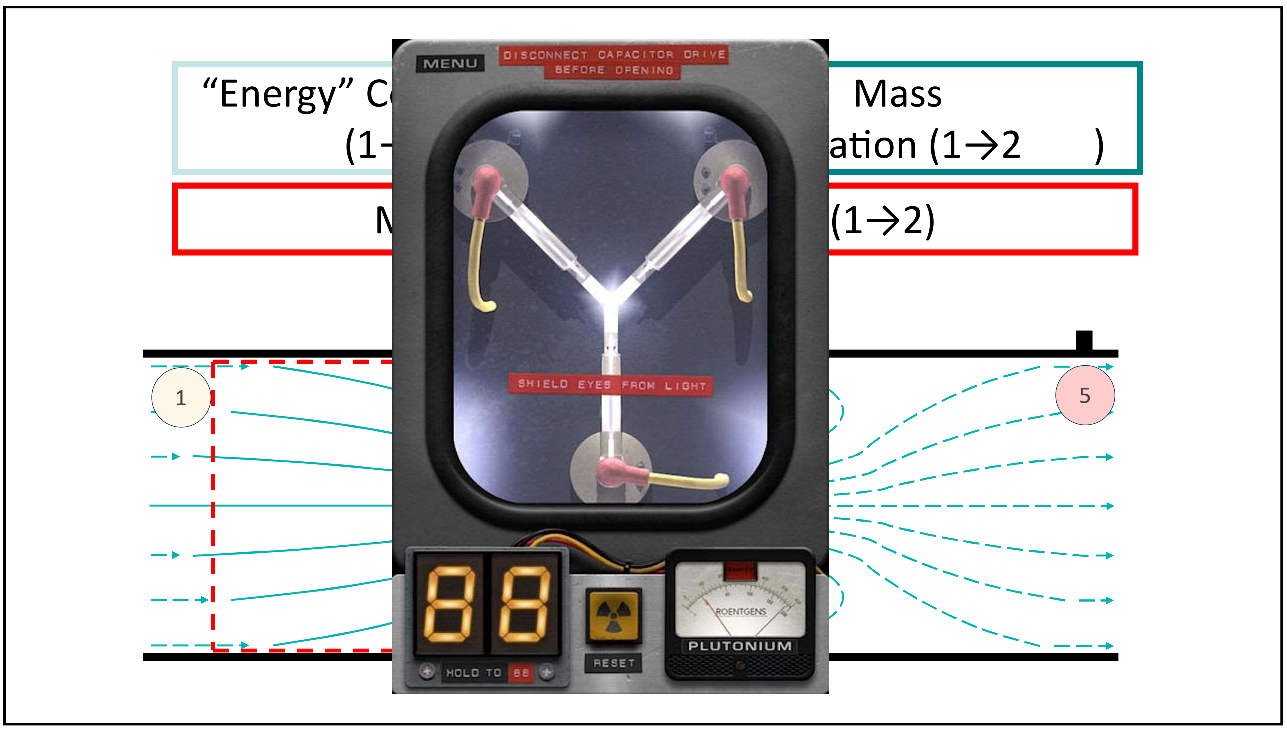
“Energy” C
Mass
ation (1→2)
(1→2)
1
5
MENU
DISCONNECT CAPACITOR DRIVE
BEFORE OPENING
SHIELD EYES FROM LIGHT
88
HOLD TO 88
RESET
ROENTGENS
PLUTONIUM

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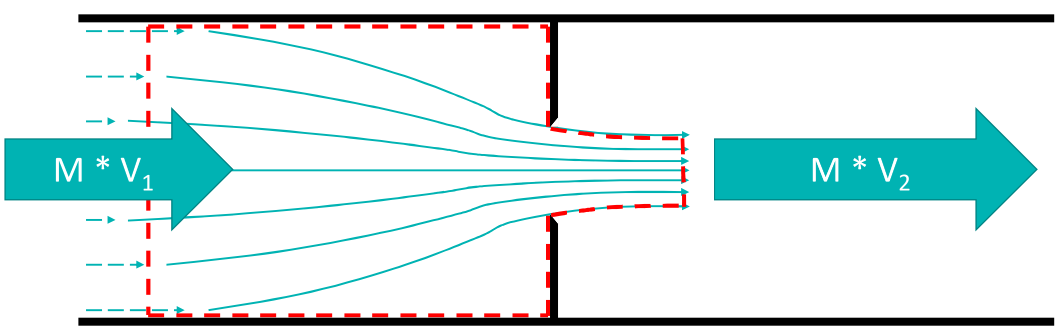

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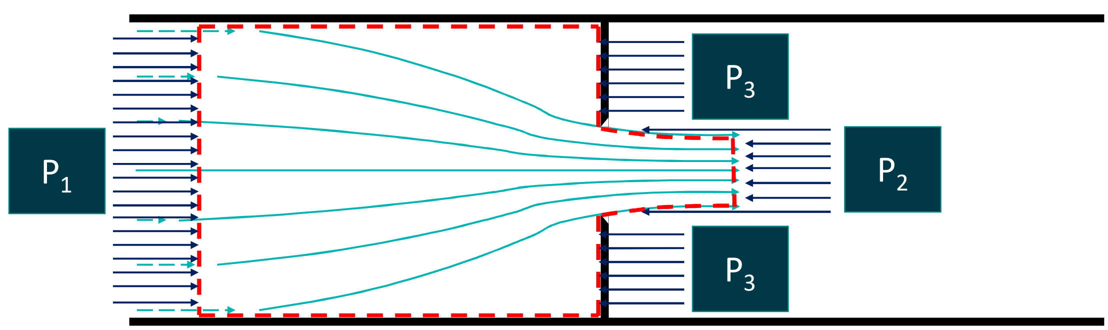

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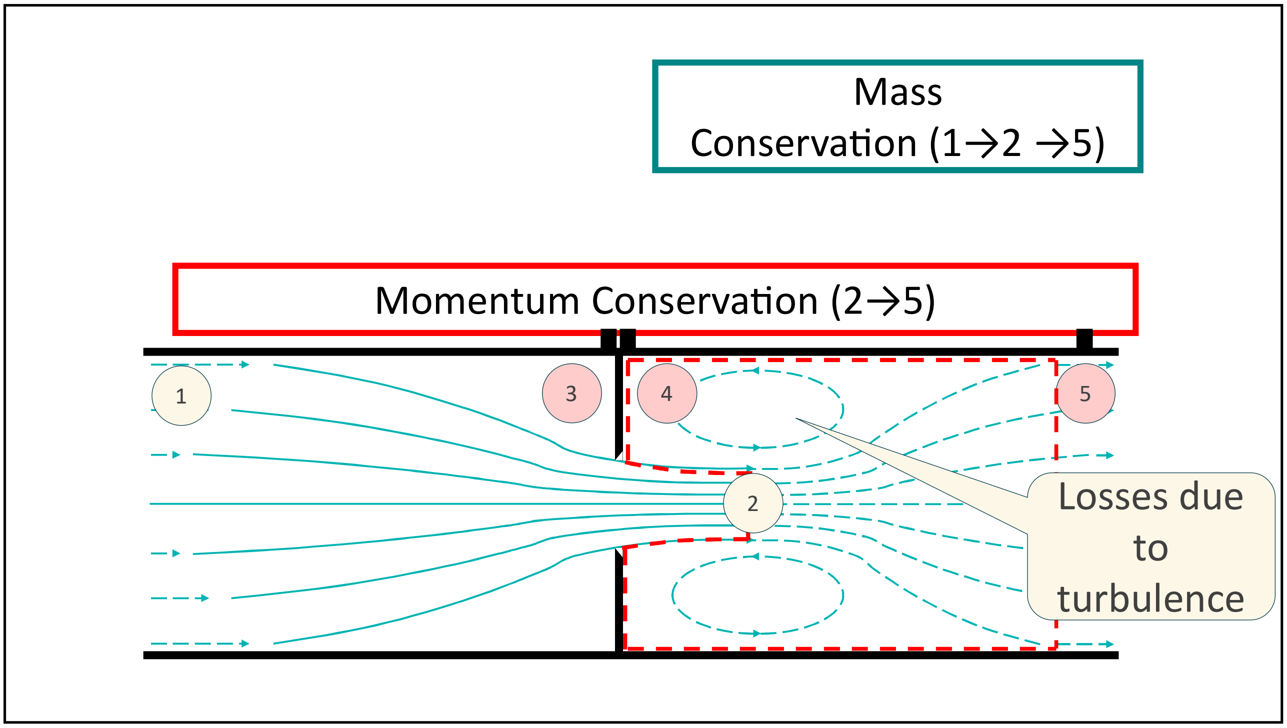
Mass
Conservation (1→2 →5)
Momentum Conservation (2→5)
1
3
4
5
2
Losses due
to
turbulence

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New Equation

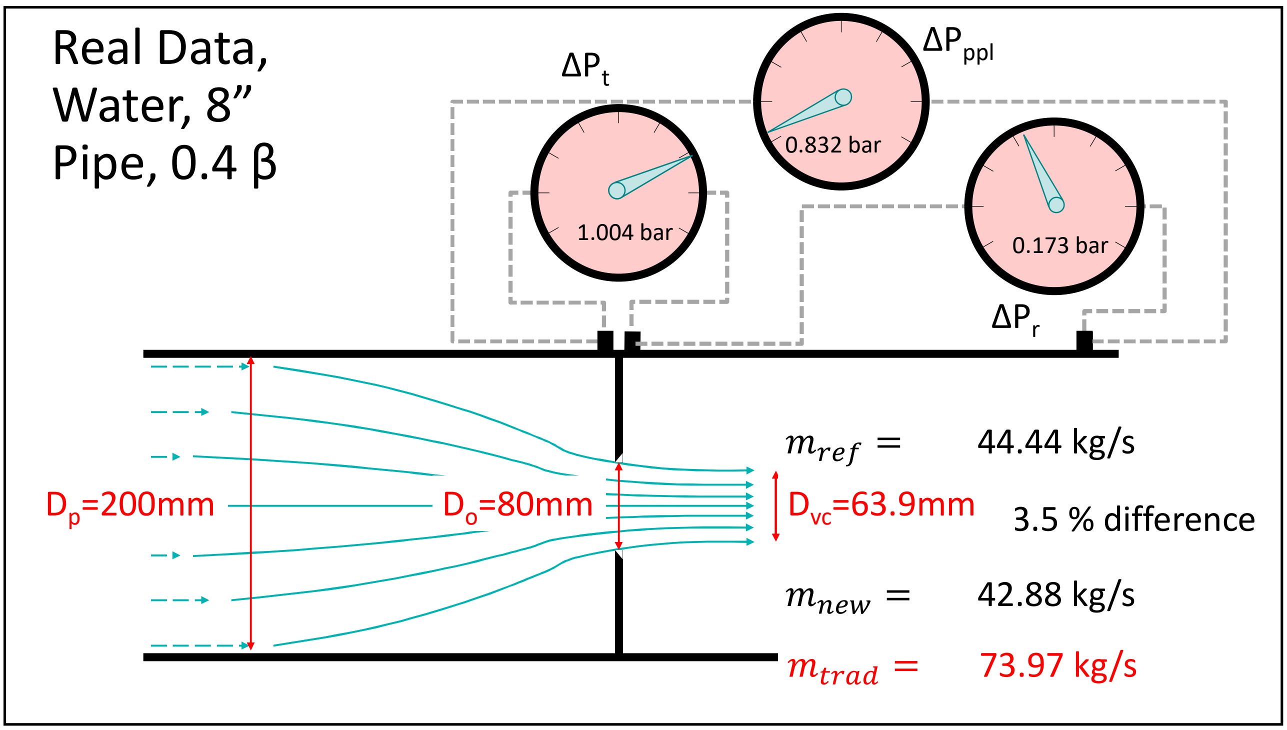
$$m_{new} = \frac{\pi d_o \Delta P_r^2 \sqrt{\rho}}{4\beta^2 \sqrt{2(1-\beta^2)(\Delta P_r + \Delta P_{ppl})}}$$

New Equation

$$m_{new} = \frac{\pi d_o^2}{4\beta^2} \frac{\Delta P_r \sqrt{\rho}}{\sqrt{2(1-\beta^2)\left(\Delta P_r + \Delta P_{ppl}\right)}}$$

ISO-5167-2

$$m_{trad} = C_D \frac{\pi d_o^2}{4} \sqrt{\frac{2\rho \Delta P_t}{1-\beta^4}}$$



Real Data, Water, 8” Pipe, 0.4 β
ΔP_t
ΔP_ppl
1.004 bar
0.832 bar
0.173 bar
ΔP_r
m_{ref} = 44.44 kg/s
D_p=200mm
D_o=80mm
D_{vc}=63.9mm
3.5 % difference
m_{new} = 42.88 kg/s
m_{trad} = 73.97 kg/s

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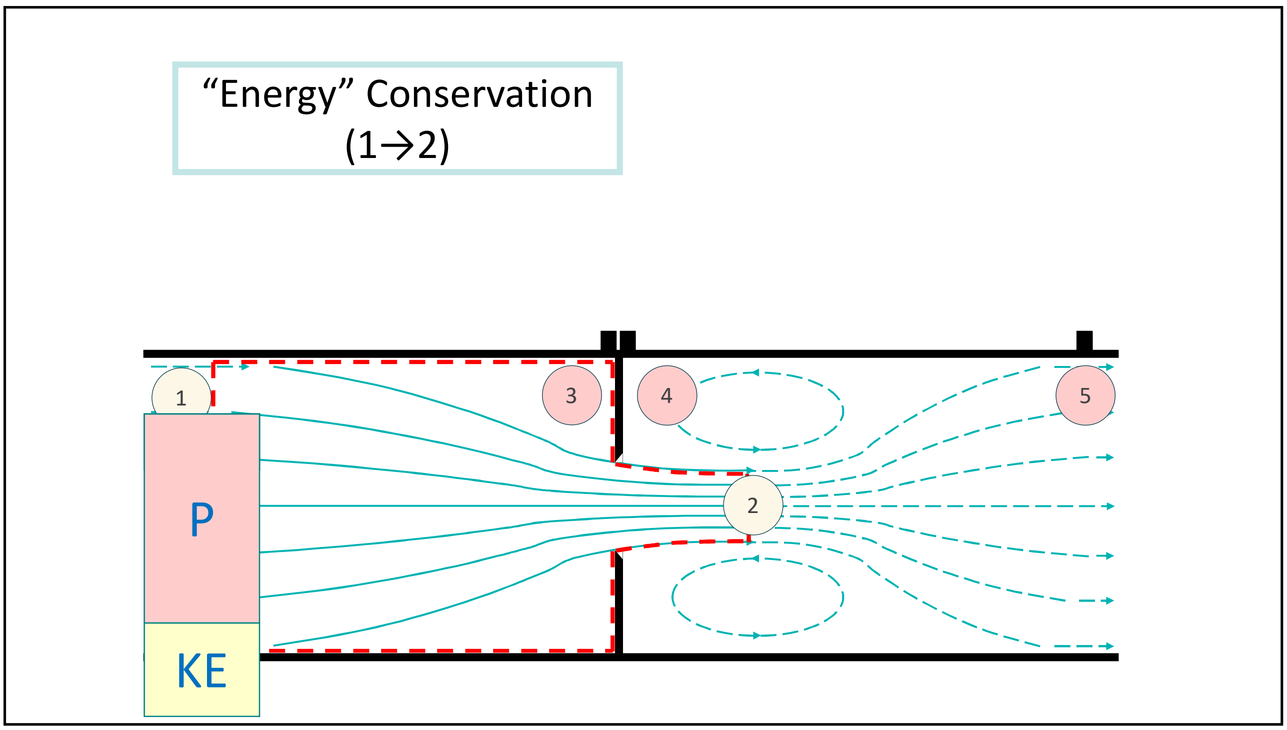

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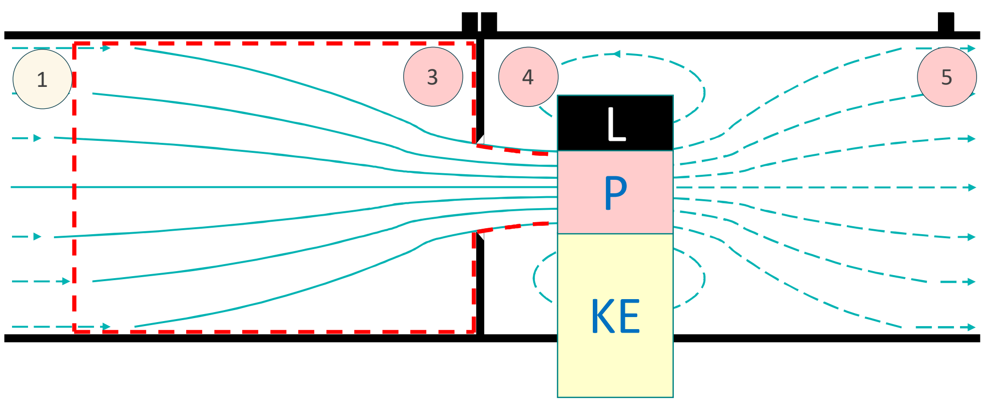
"Energy" Conservation
(1→2)



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New Equation (with Losses)

$$P_1 + \frac{\rho V_1^2}{2} = P_2 + \frac{\rho V_2^2}{2} + N\frac{\rho V_1^2}{2}$$

$$m_{new} = \rho\frac{\pi d_o^2}{4\beta^2}\sqrt{\frac{(1-\beta^2)\left(\Delta P_r + \Delta P_{ppl}\right) - \sqrt{\left((1-\beta^2)\left(\Delta P_r + \Delta P_{ppl}\right)\right)^2 - \boldsymbol{N}\Delta P_r^2}}{\rho\boldsymbol{N}}}$$

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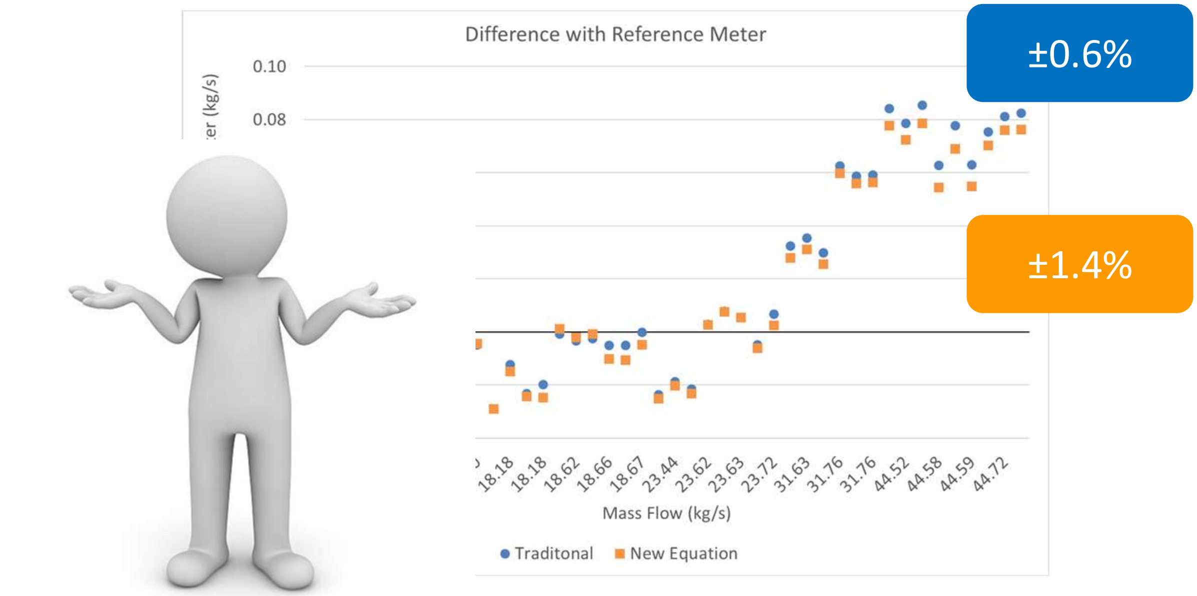
Real Data, Water, 8” Pipe, 0.4 β



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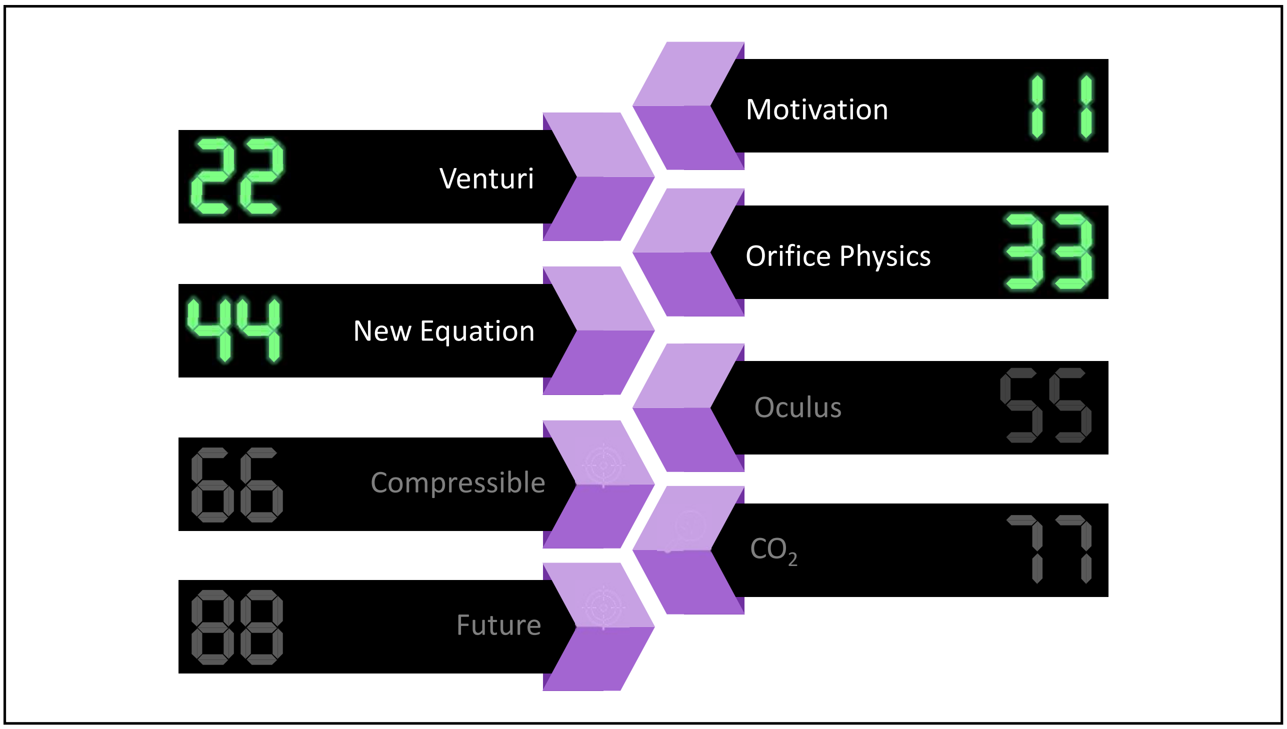
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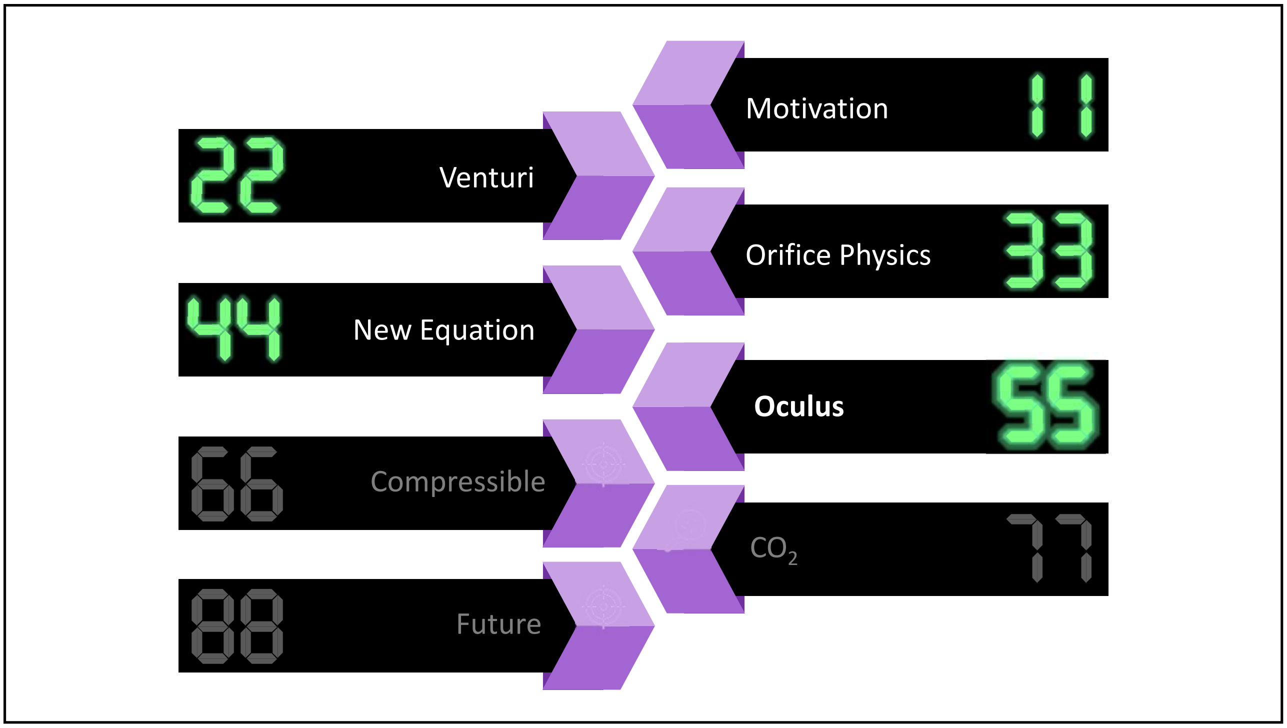
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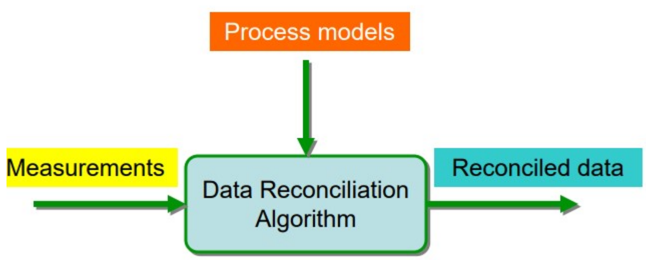
Data Reconciliation



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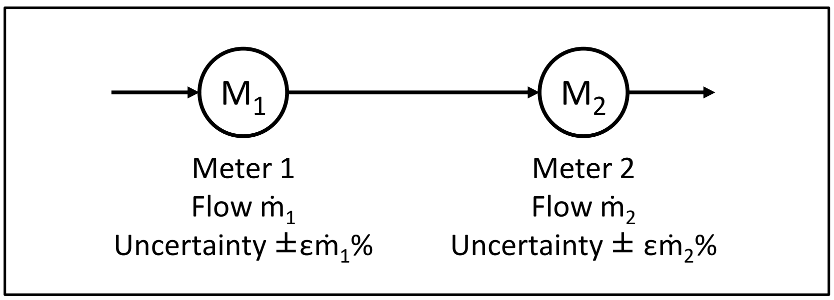
Two Independent Meters in Series



Meters will report different flow rates
Which one is closest to the true flow?
Uncertainty (±1%, ±2%,…)

100% certainty – both meters are measuring the same flow rate

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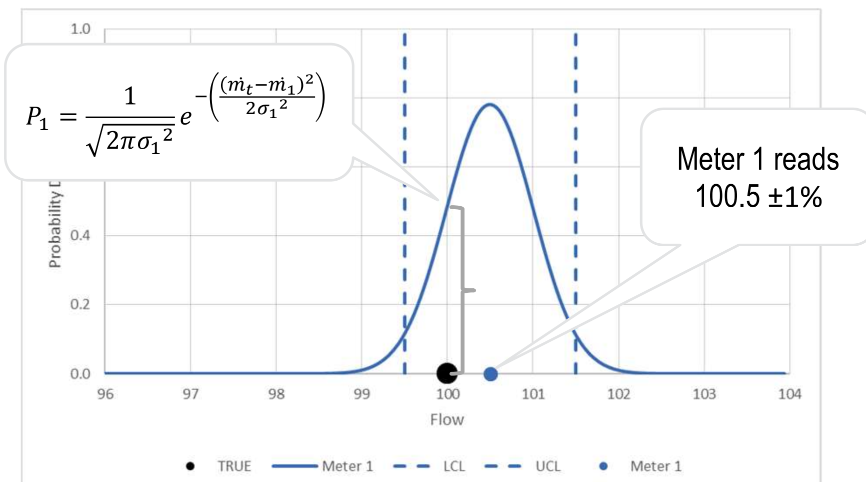
Two Independent Meters in Series



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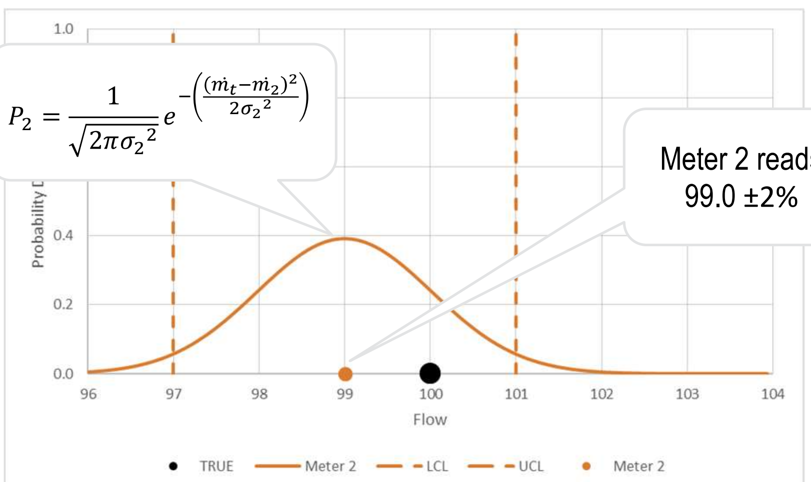
Two Independent Meters in Series



$$P_2 = \frac{1}{\sqrt{2\pi\sigma_2{}^2}} e^{-\left(\frac{(\dot{m}_t - \dot{m}_2)^2}{2\sigma_2{}^2}\right)}$$

Meter 2 reads
99.0 ±2%

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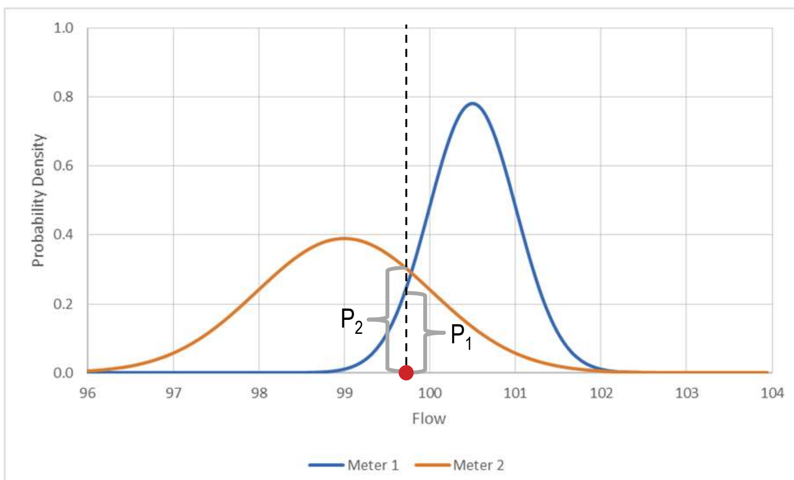
Two Independent Meters in Series



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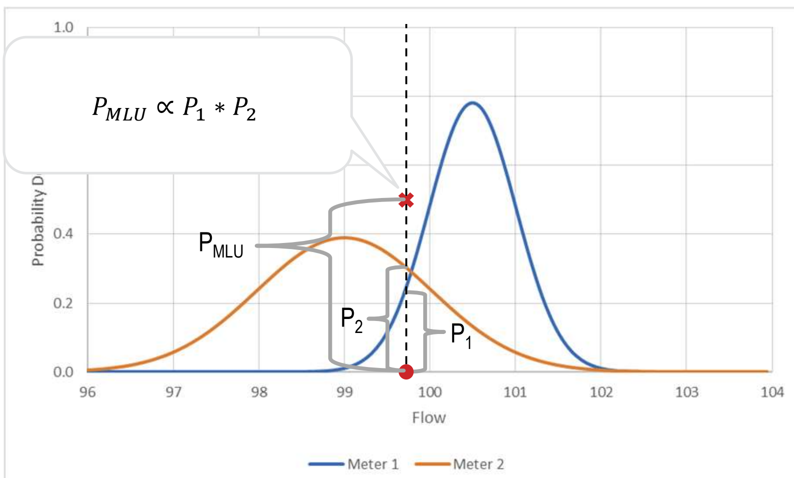
Two Independent Meters in Series



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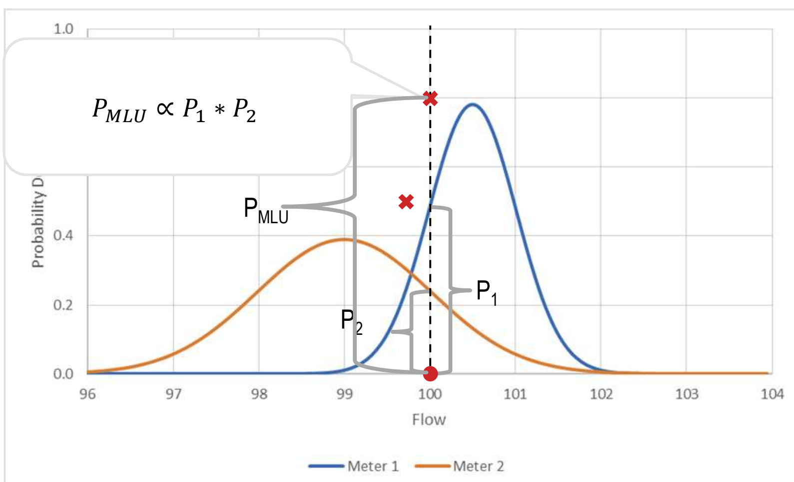
Two Independent Meters in Series



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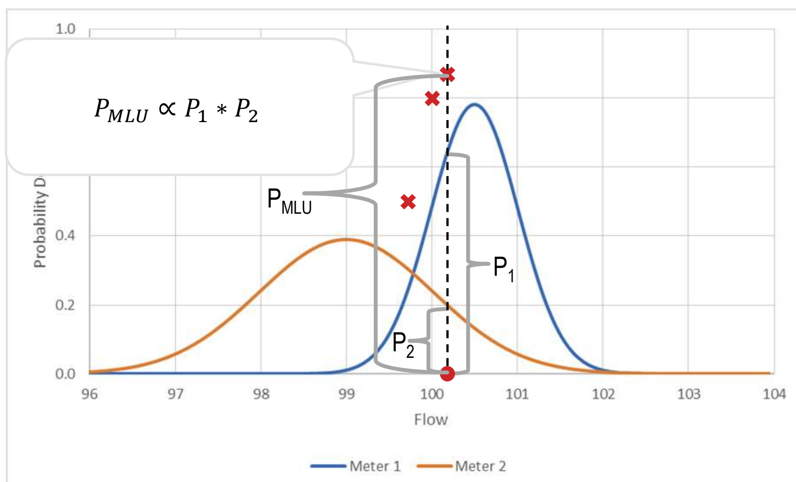
Two Independent Meters in Series



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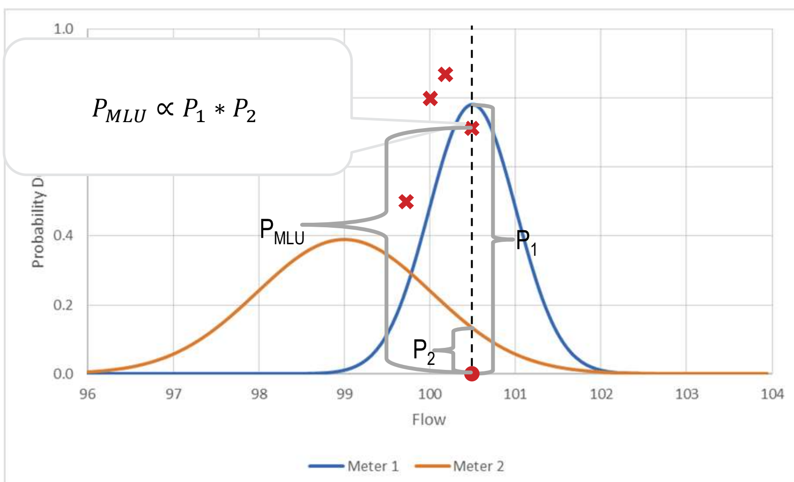
Two Independent Meters in Series



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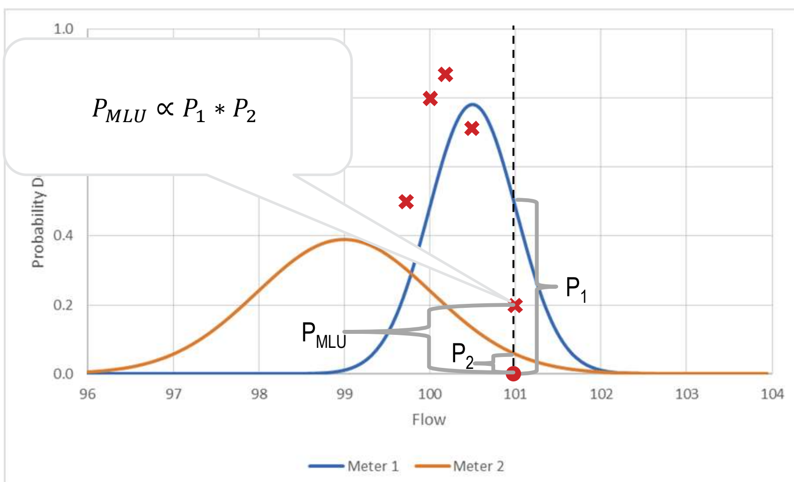
Two Independent Meters in Series



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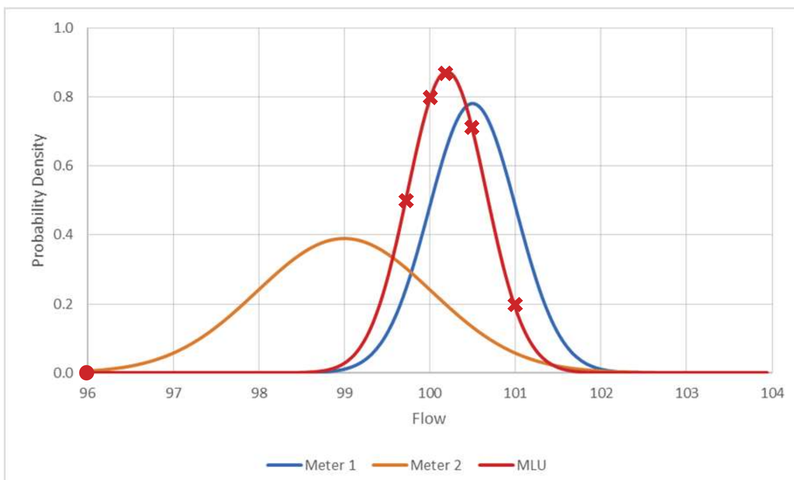
Two Independent Meters in Series



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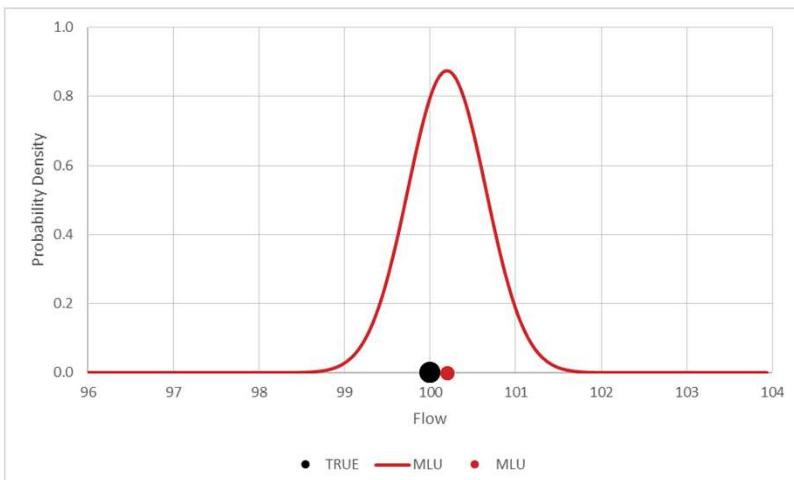
Maximum Likelihood Estimate (MLU)



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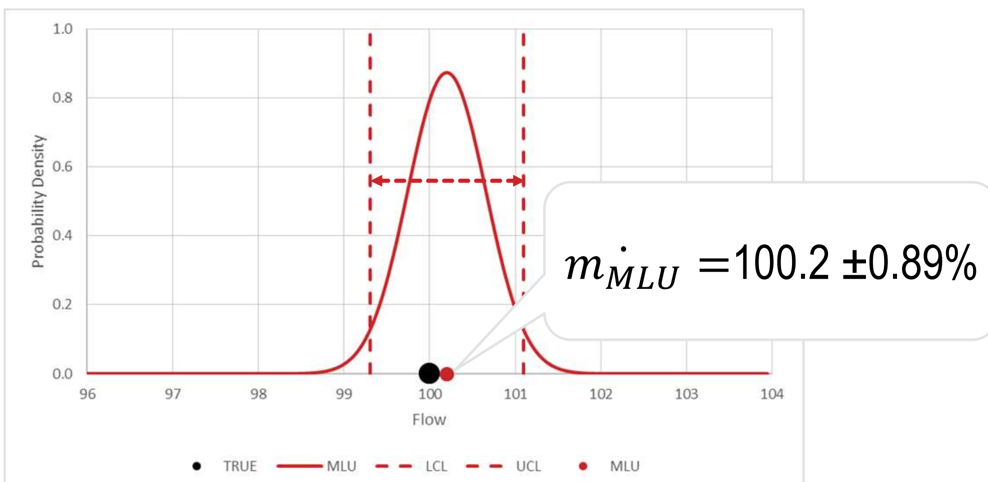
Maximum Likelihood Estimate (MLU)



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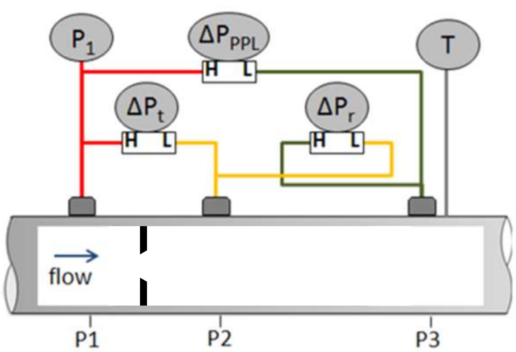
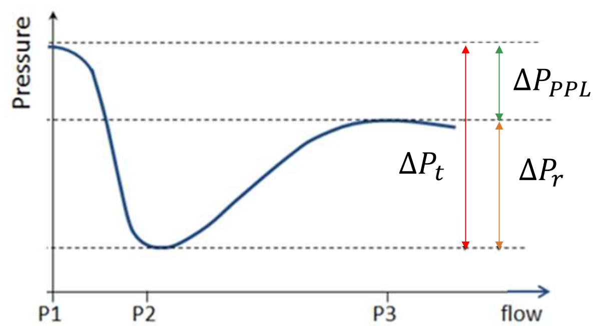
Three DP Measurements





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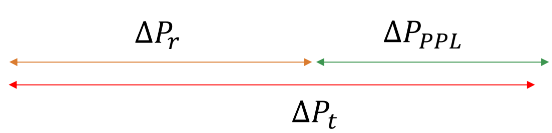
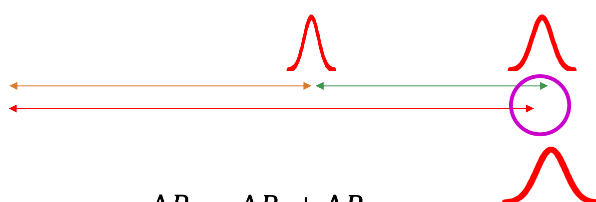
Pressure Drop Constraint

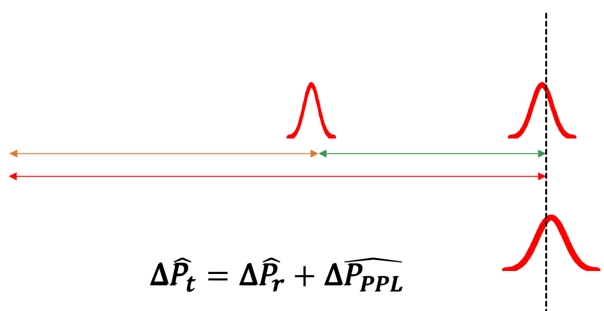


Pressure Drop Constraint



$$\Delta P_t = \Delta P_r + \Delta P_{PPL}$$

Pressure Drop Constraint



$$\Delta\widehat{P}_t = \Delta\widehat{P}_r + \Delta\widehat{P_{PPL}}$$

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Kalman Filter

EVENT

APOLLO

YEAR

1960s

DESTINATION TIME

Rudolf E. Kálmán

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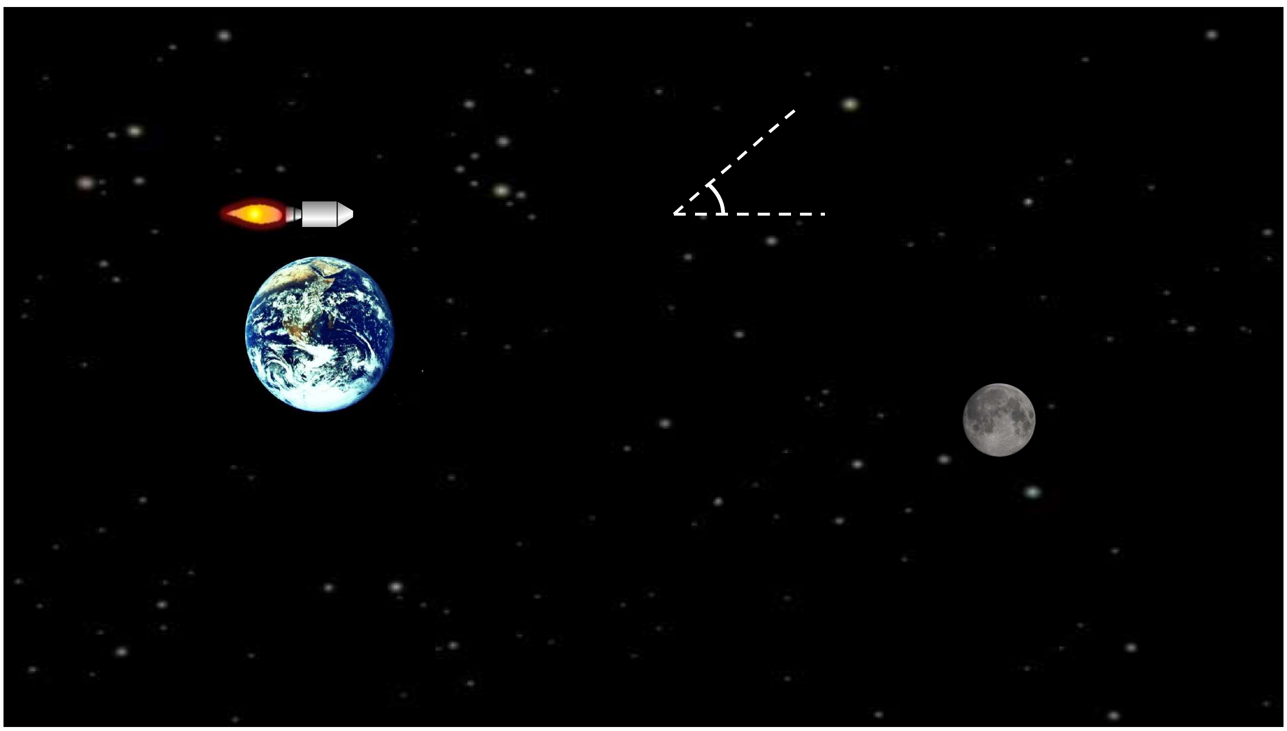

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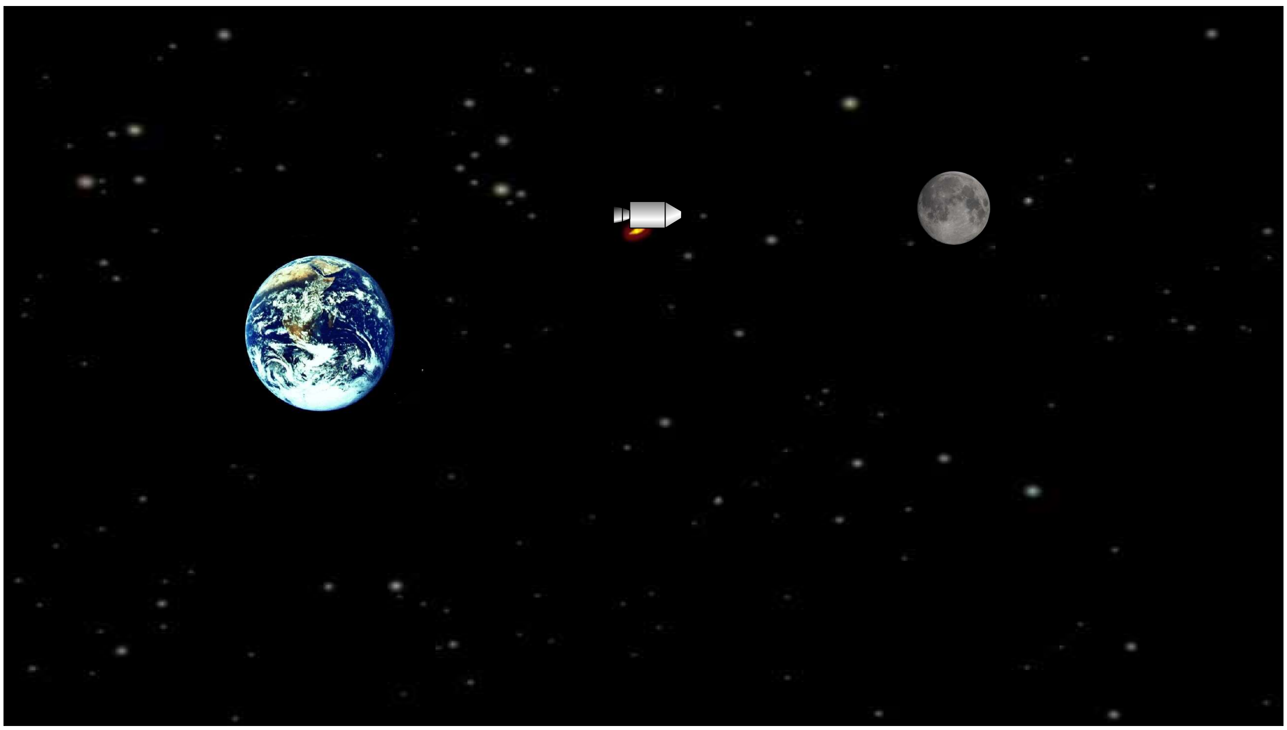

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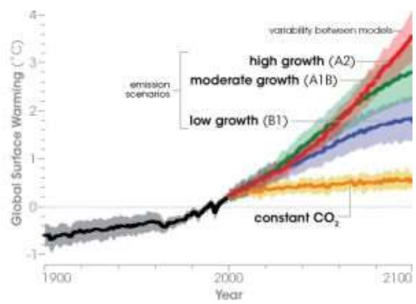
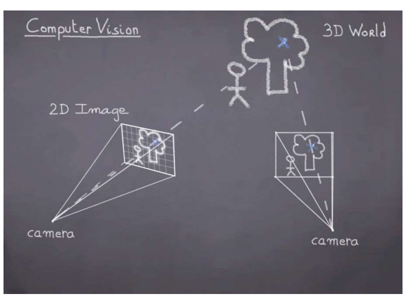
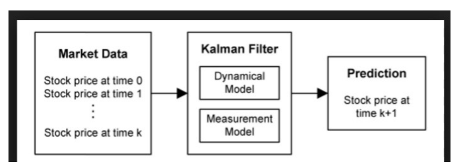
Kalman Filter Applications







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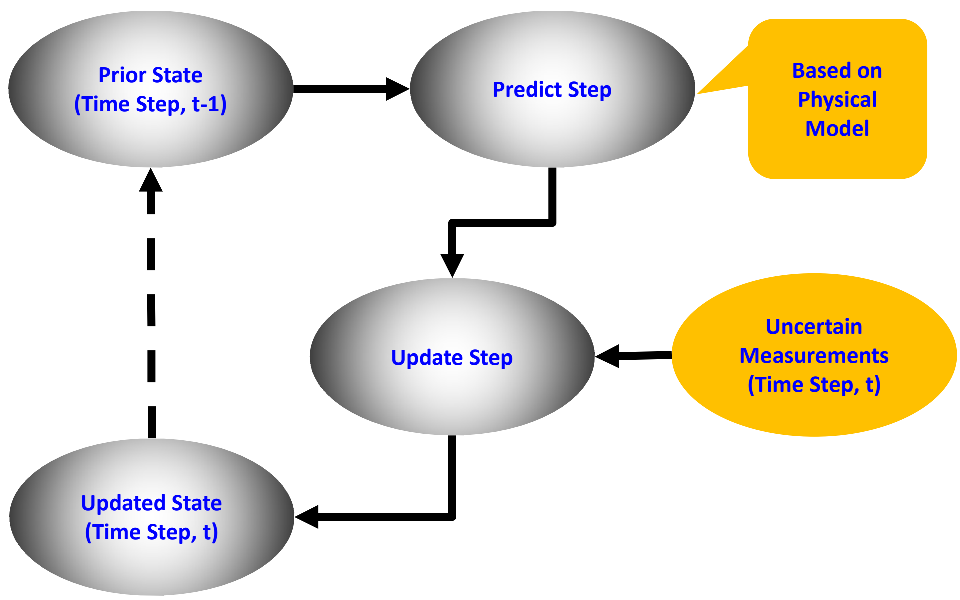
Kalman Filter Algorithm



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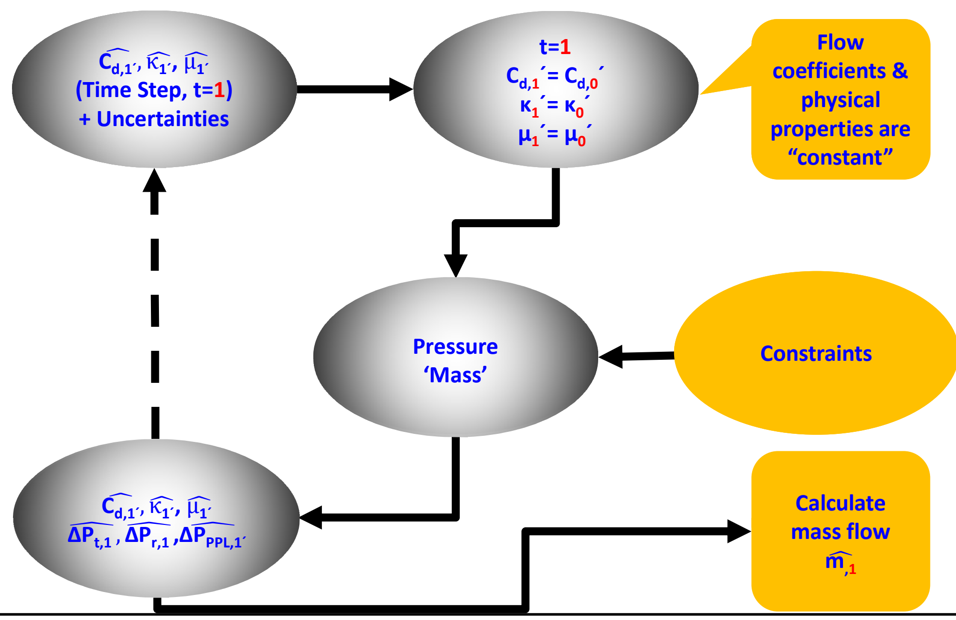
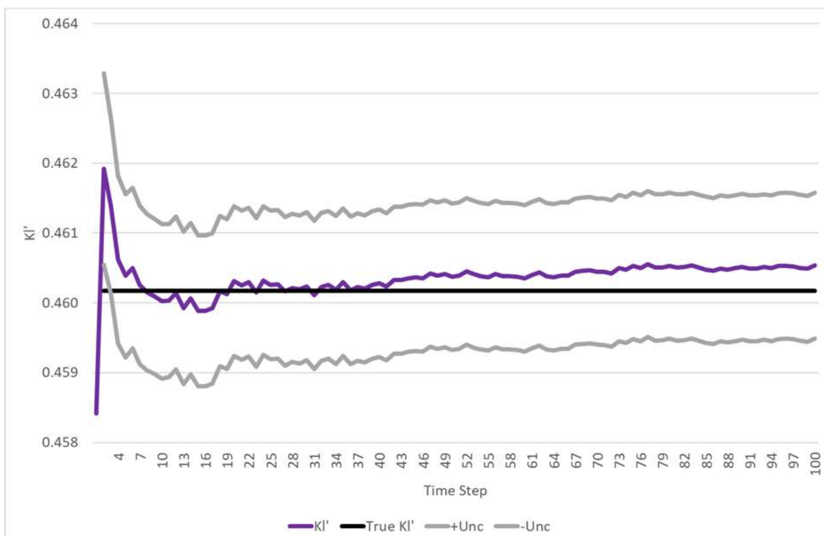
Kalman Filter Algorithm - MLU



Hypothetical Example – K_{PPL}' Evolution



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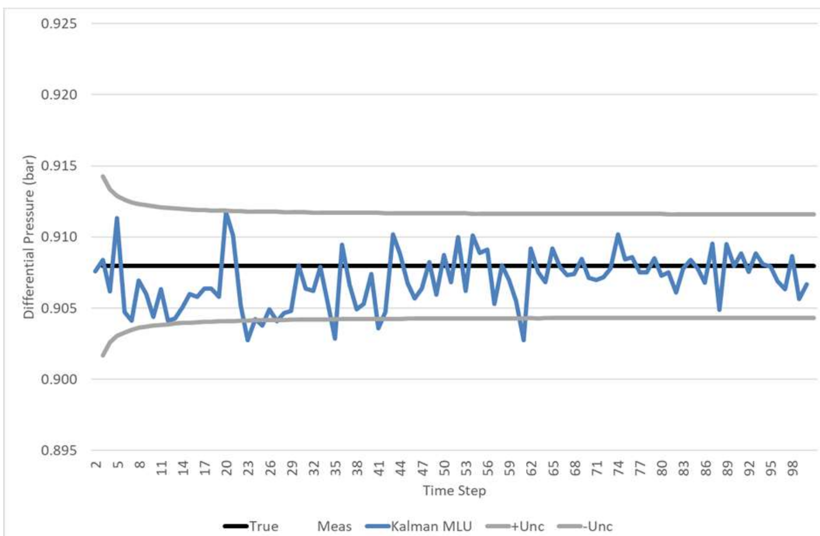
Hypothetical Example – ΔP_t Evolution



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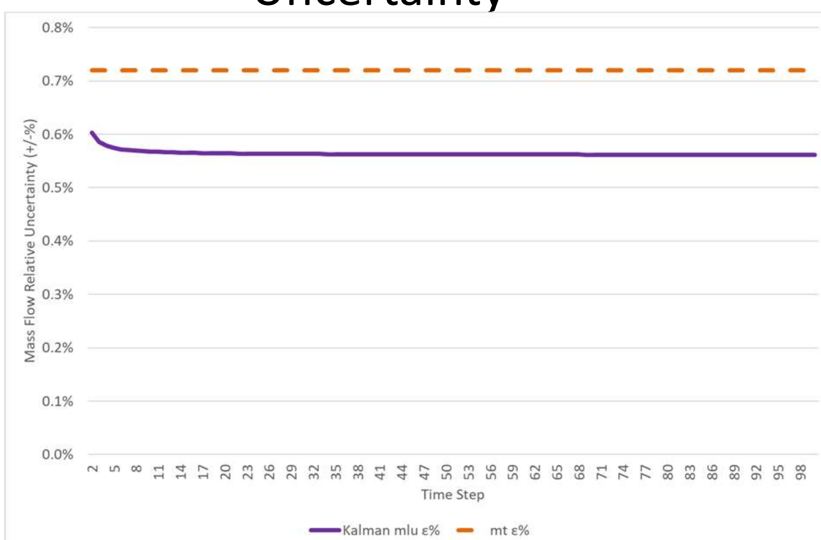
Hypothetical Example – Mass Flow Rate Uncertainty



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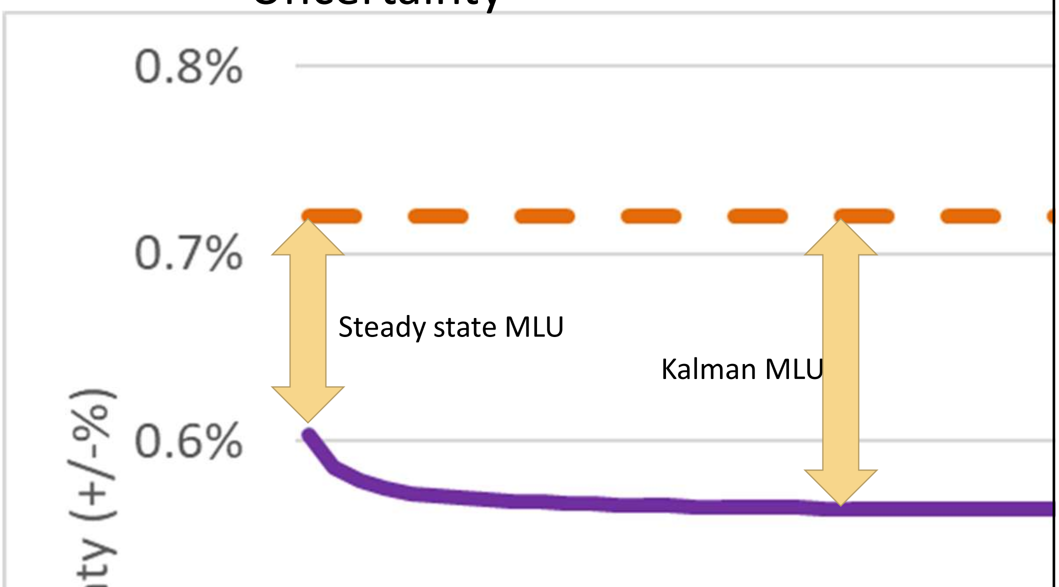
Hypothetical Example – Mass Flow Rate Uncertainty



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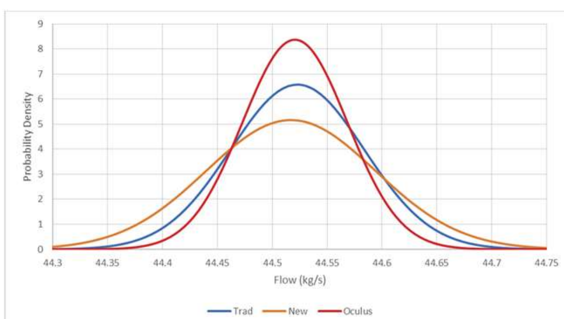
Oculus

EVENT | MONTH | YEAR
NSFMW | OCT | 2021

DESTINATION TIME



Oculus™

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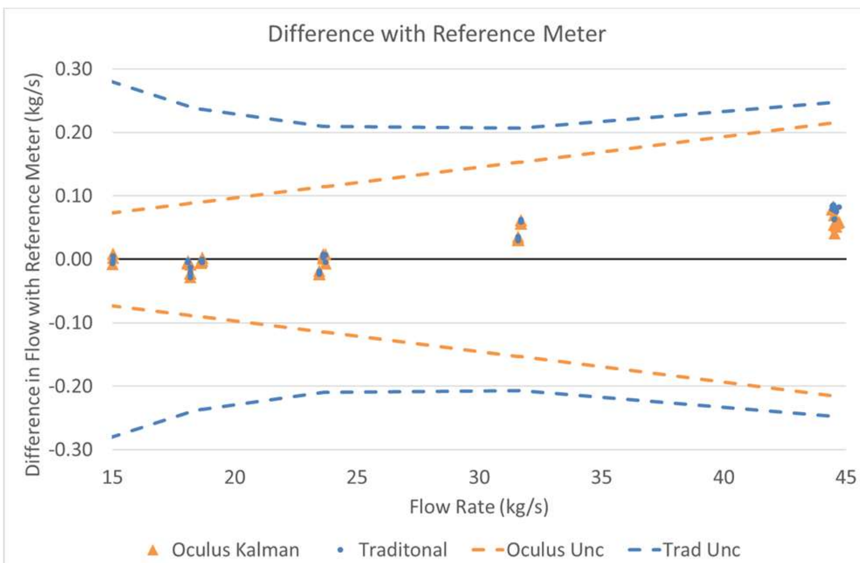
Real Data, Water, 8” Pipe, 0.4 β



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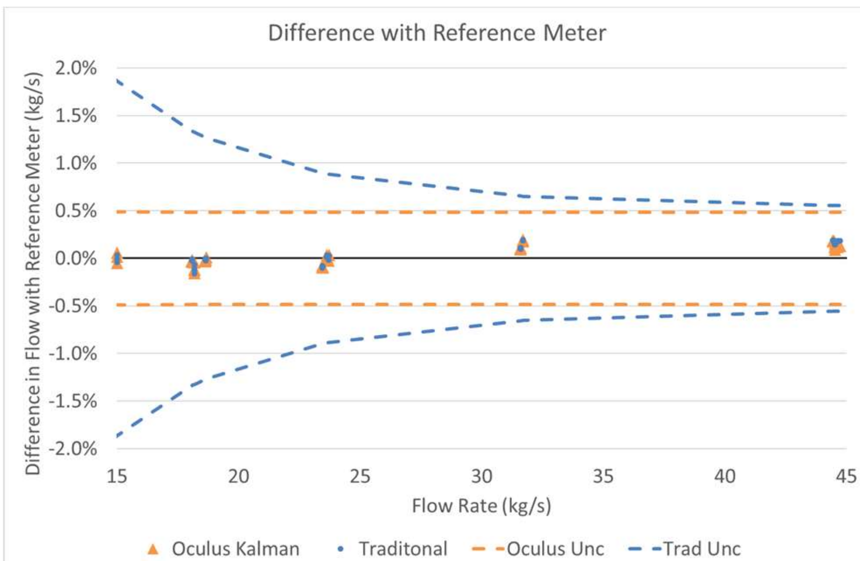
Real Data, Water, 8” Pipe, 0.4 β



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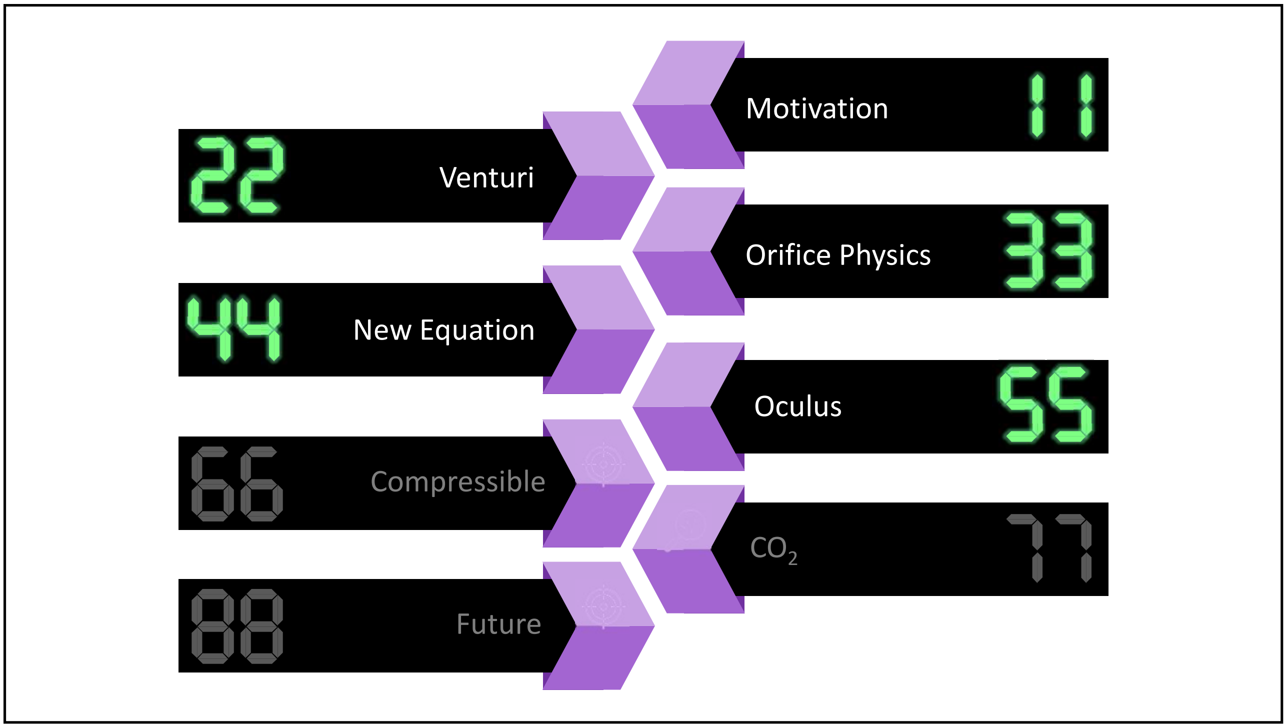

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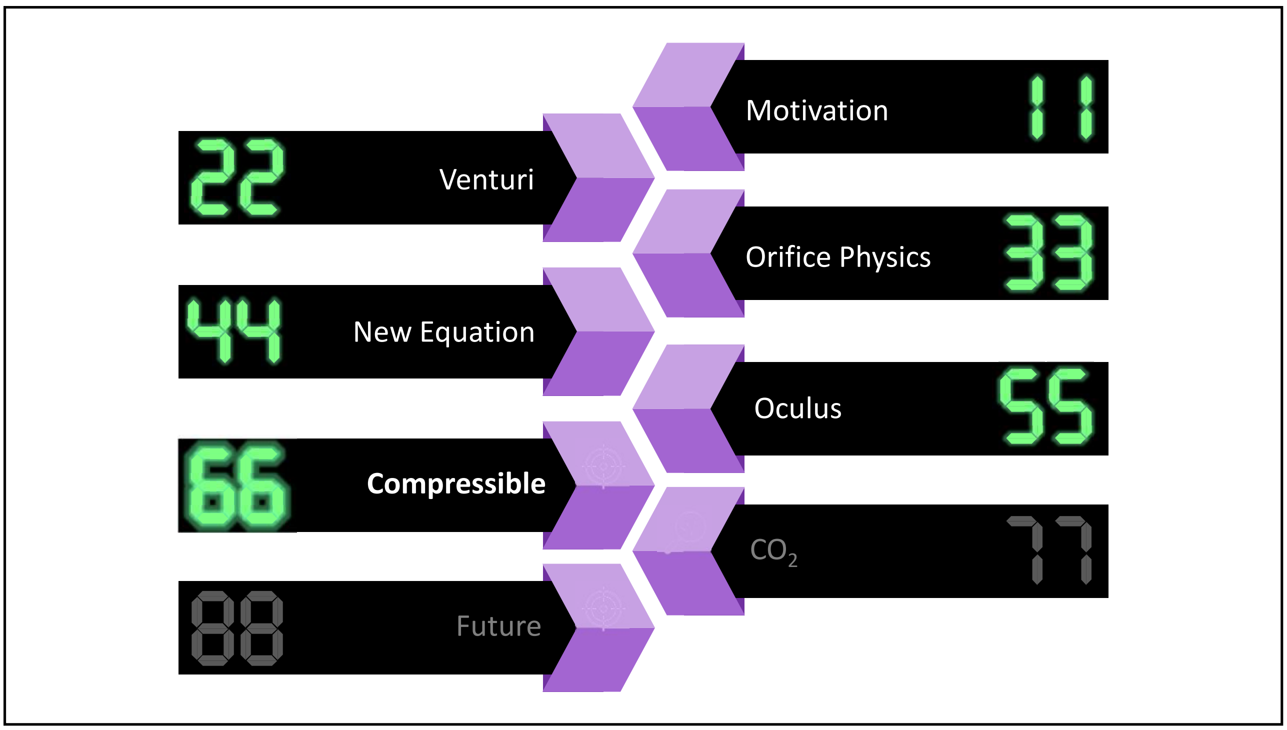
Motivation
22
Venturi
33
Orifice Physics
44
New Equation
55
Oculus
66
Compressible
77
CO_2
88
Future

89



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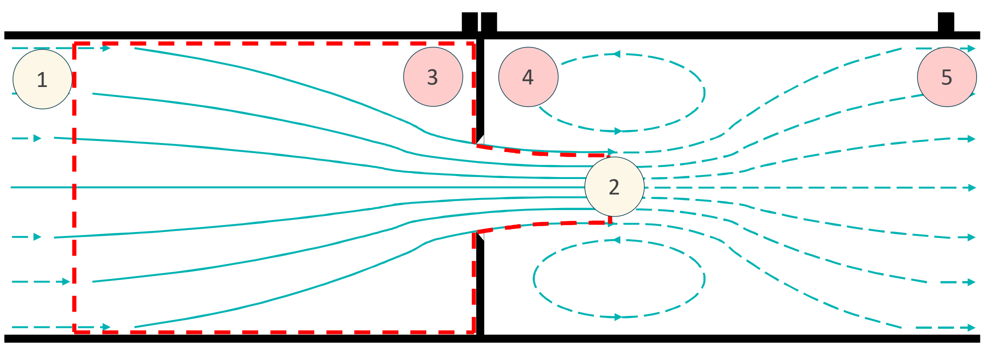
Gases: Compressible Flow

Mass
Conservation (1→2 →5)



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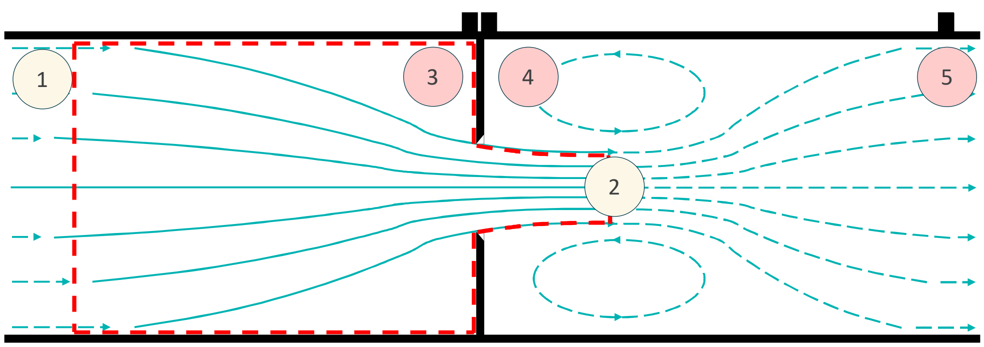
Gases: Compressible Flow

$$m_{trad} = \boldsymbol{\varepsilon} C_D \frac{\pi d_o^2}{4} \sqrt{\frac{2\rho \Delta P_t}{1-\beta^4}}$$



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Gases: Compressible Flow: ISO 5167-2

$$m_{trad} = \boldsymbol{\varepsilon} C_D \frac{\pi d_o^2}{4} \sqrt{\frac{2\rho \Delta P_t}{1-\beta^4}}$$

5.3.2.2 Expansibility [expansion] factor, ε

For the three types of tapping arrangement, the empirical formula[6]
[expansion] factor, ε, is as follows:

$$\varepsilon = 1-\left(0{,}351+0{,}256\beta^4+0{,}93\beta^8\right)\left[1-\left(\frac{p_2}{p_1}\right)^{1/\kappa}\right]$$

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Gases: Compressible Flow: ISO 5167-**3**

$$m_{vent} = \boldsymbol{\varepsilon} C \frac{\pi d_o^2}{4} \sqrt{\frac{2\rho \Delta P_t}{1-\beta^4}}$$

5.1.6.3 Expansibility [expansion] factor, ε

The expansibility [expansion] factor, ε, is calculated by m

$$\varepsilon = \sqrt{\left(\frac{\kappa\tau^{2/\kappa}}{\kappa-1}\right)\left(\frac{1-\beta^4}{1-\beta^4\tau^{2/\kappa}}\right)\left(\frac{1-\tau^{(\kappa-1)/\kappa}}{1-\tau}\right)}$$

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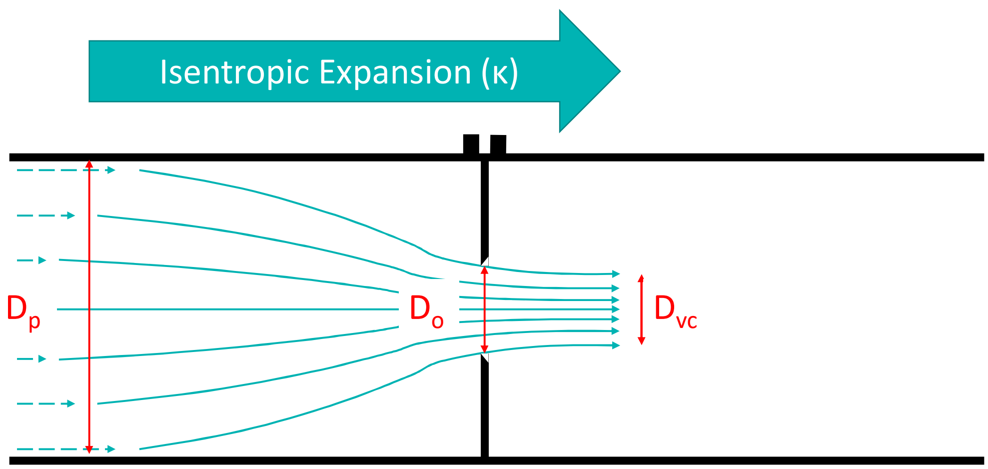

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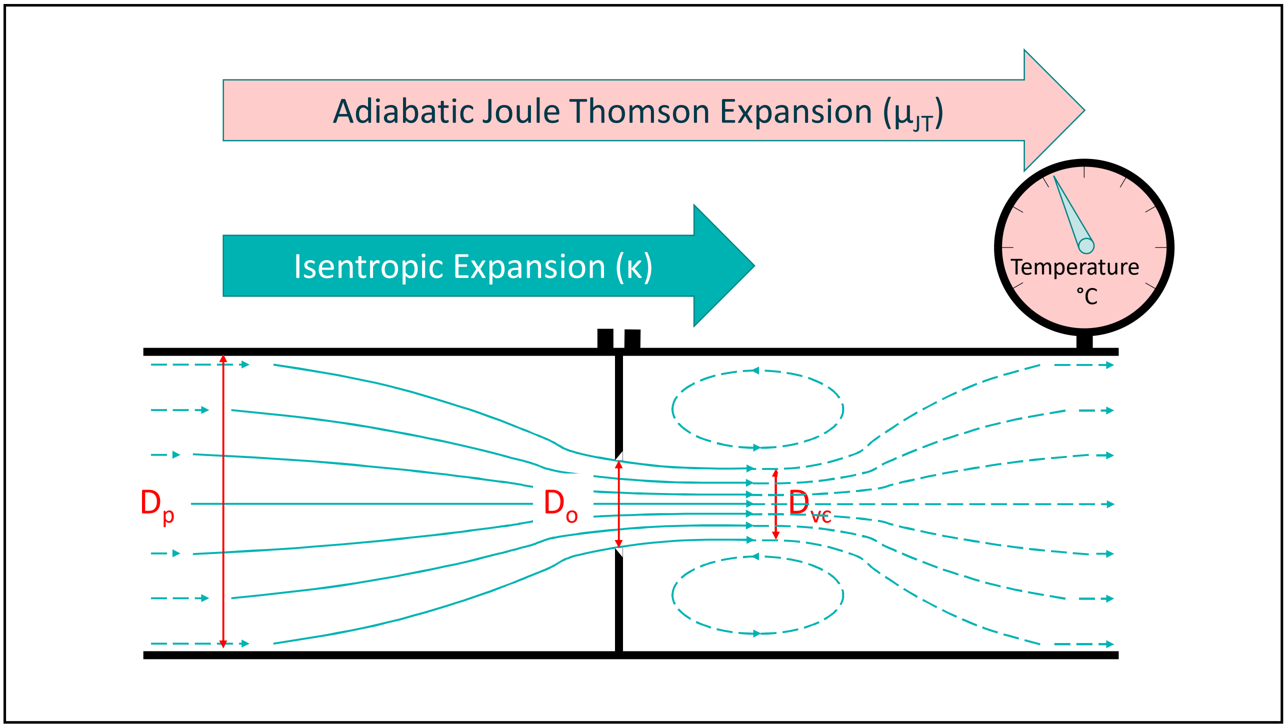
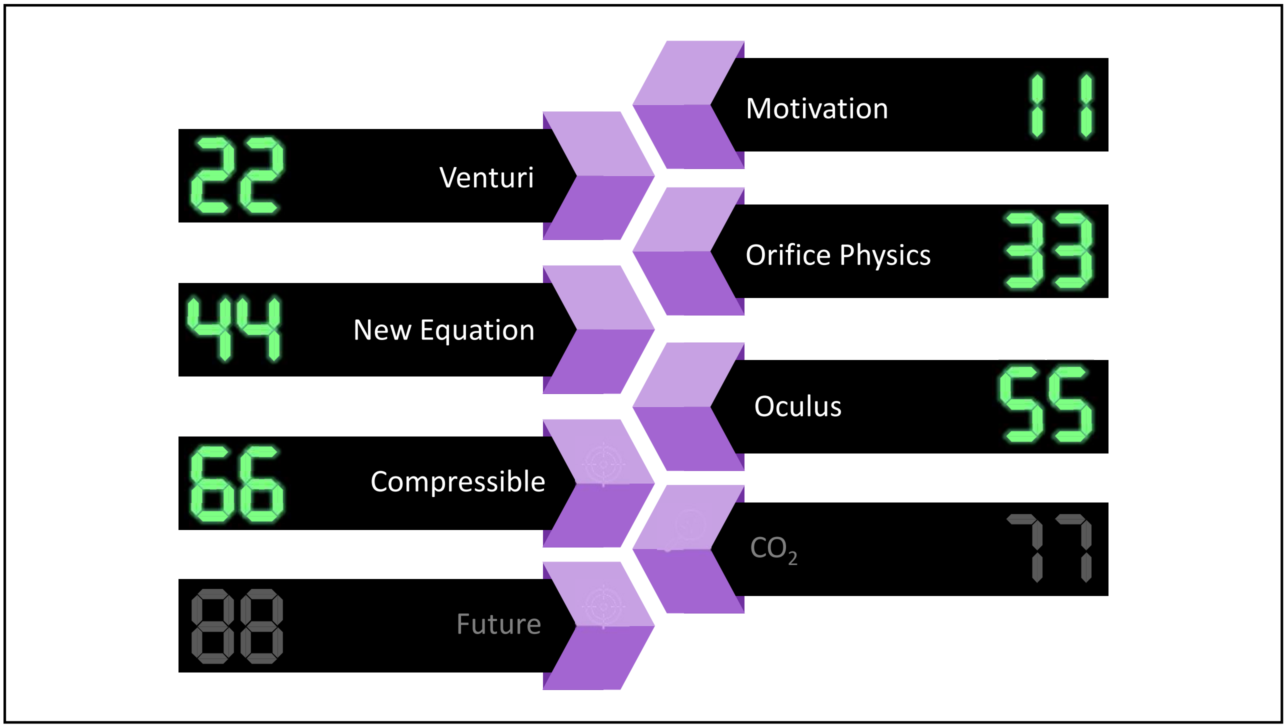

Adiabatic Joule Thomson Expansion (μ_{JT})
Isentropic Expansion (κ)
Temperature
°C
D_p
D_o
D_{vc}

96


Motivation 11
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88 Future

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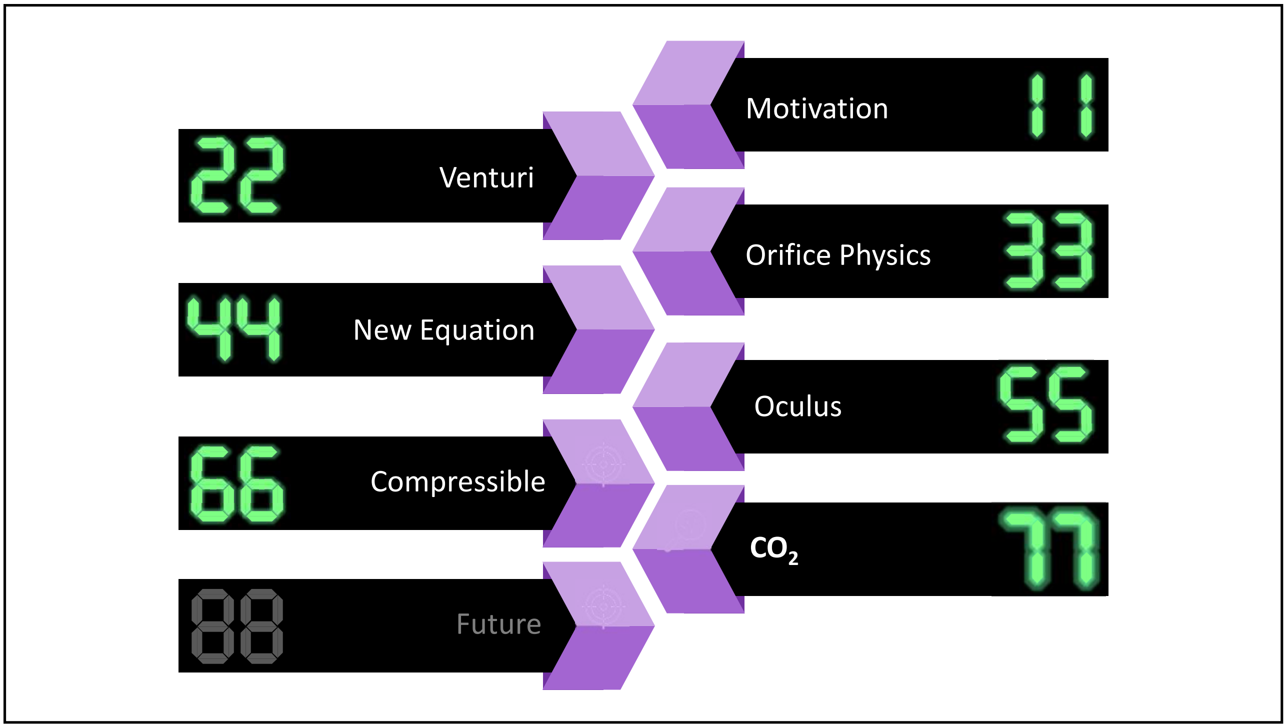
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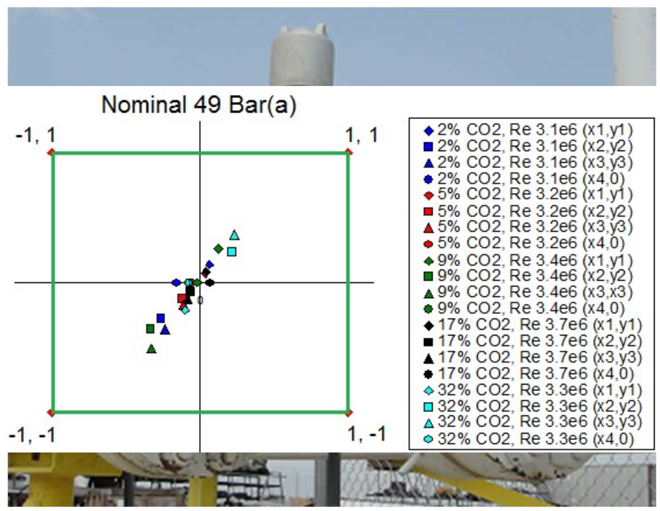
Real Data, Natural Gas / $CO_{2,}$ 8” Pipe, 0.56 β



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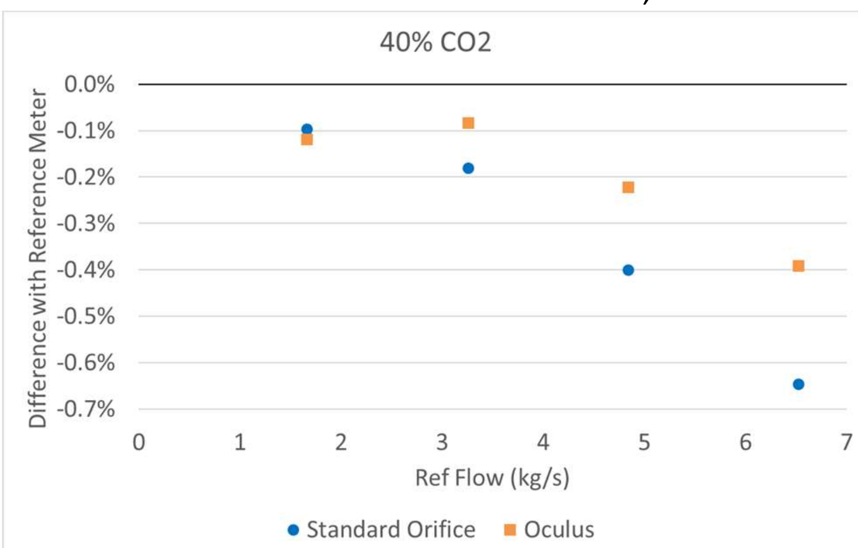
Real Data, Natural Gas / $CO_{2,}$ 8" Pipe, 0.56 β



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Real Data, Natural Gas / $CO_{2,}$ 8” Pipe, 0.56 β

Meter Type	Mean Absolute Deviation (%)
8” 0.56 Beta Orifice Traditional	**0.67%**
8” 0.56 Beta Orifice with Oculus	**0.51%**

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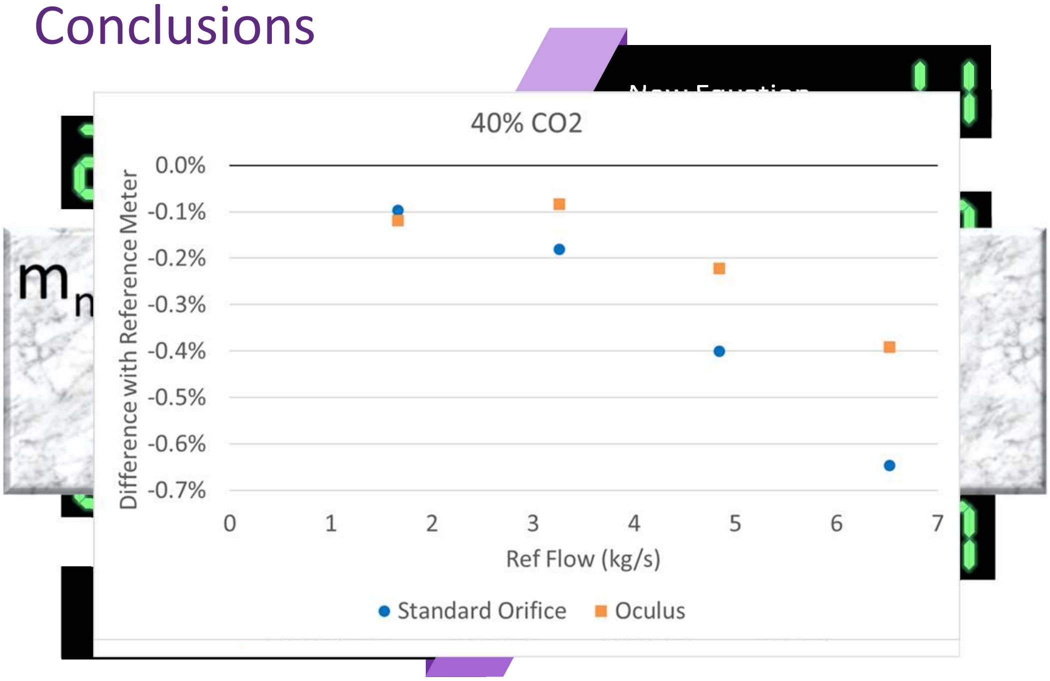
Conclusions



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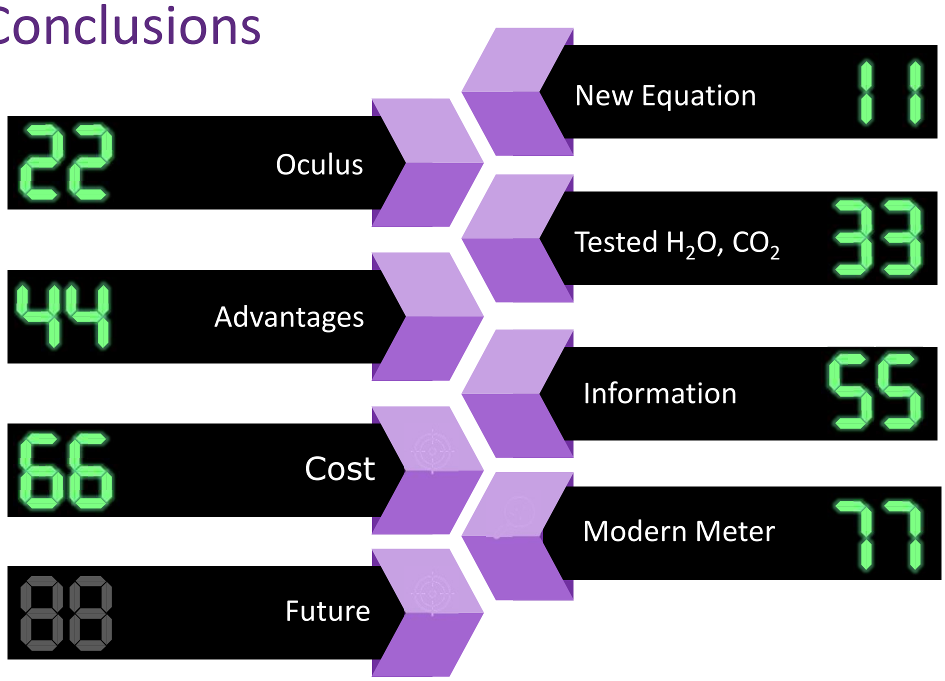
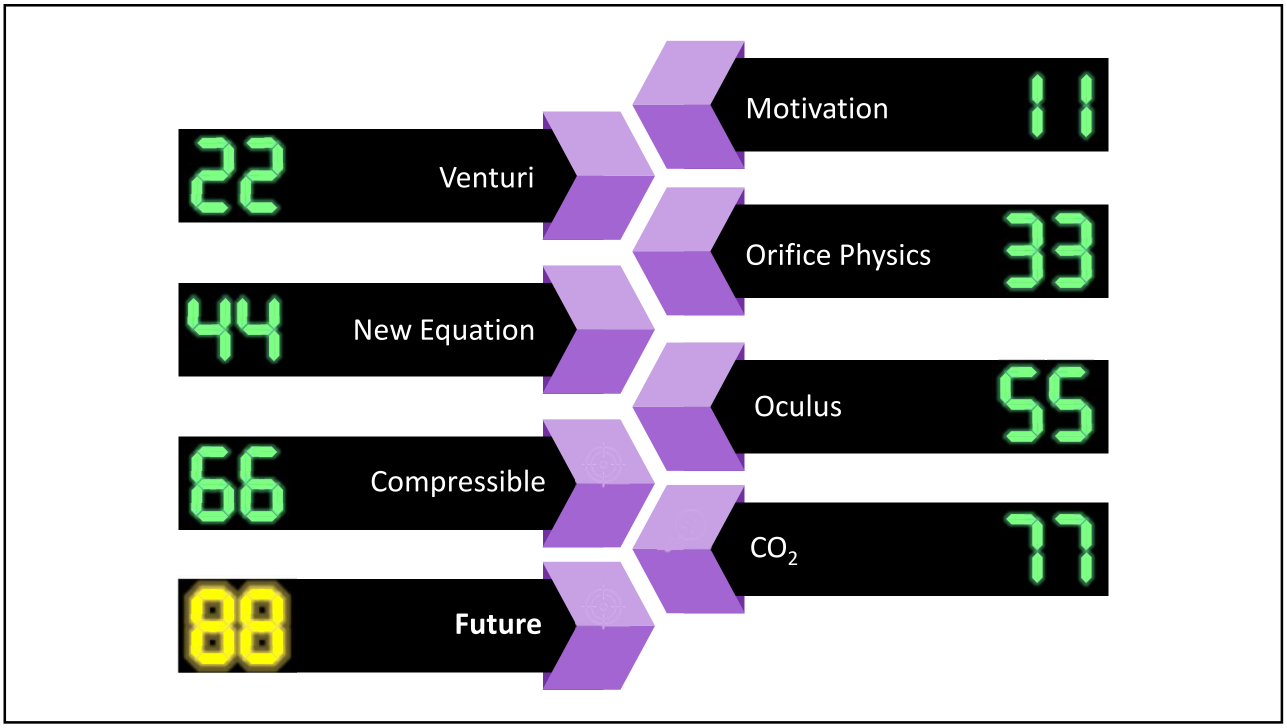
Conclusions





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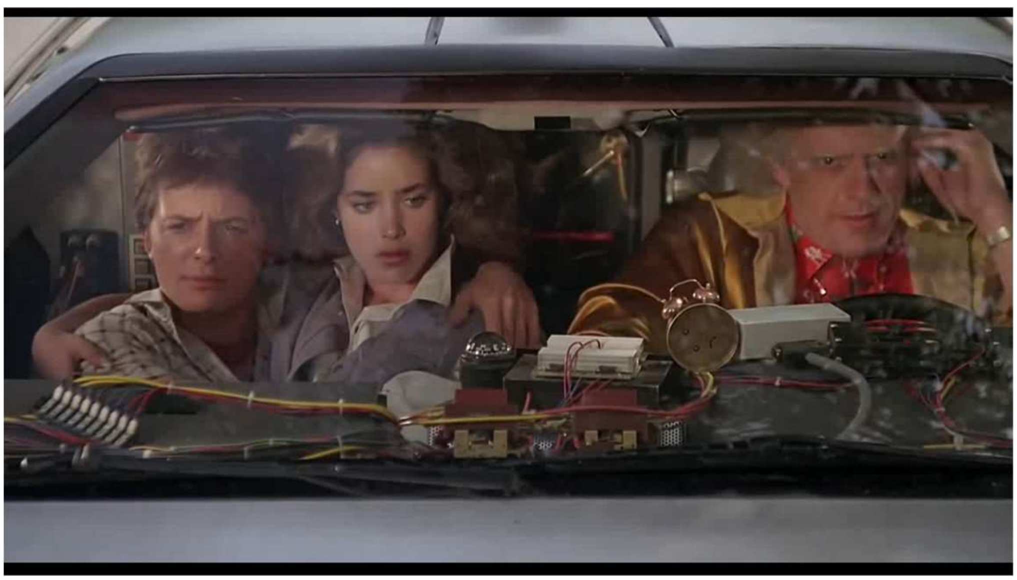

Calibration, where we're going, we don't need calibration.

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