Flow measurement: some problems to solve and some surprises

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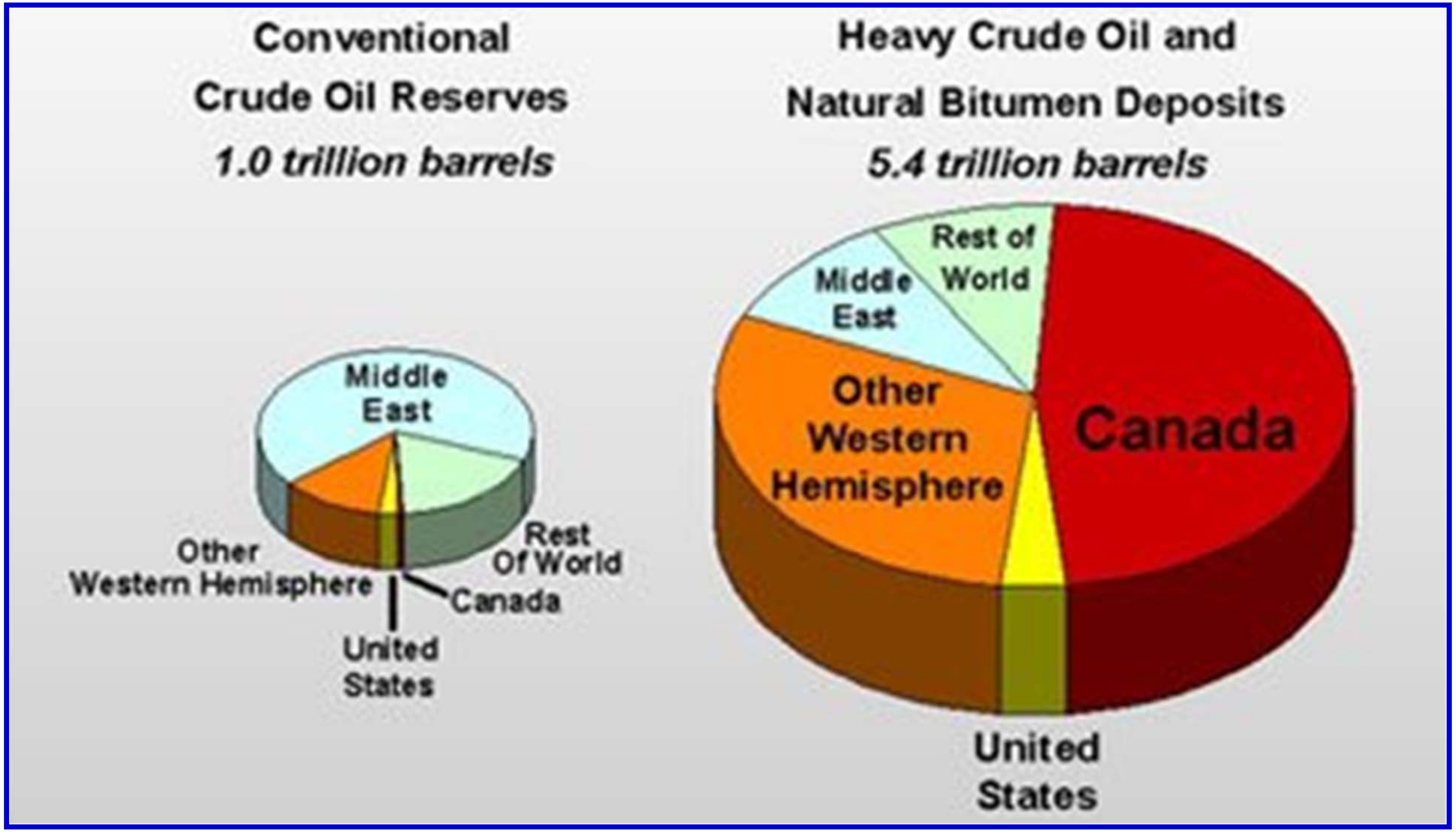
Scope

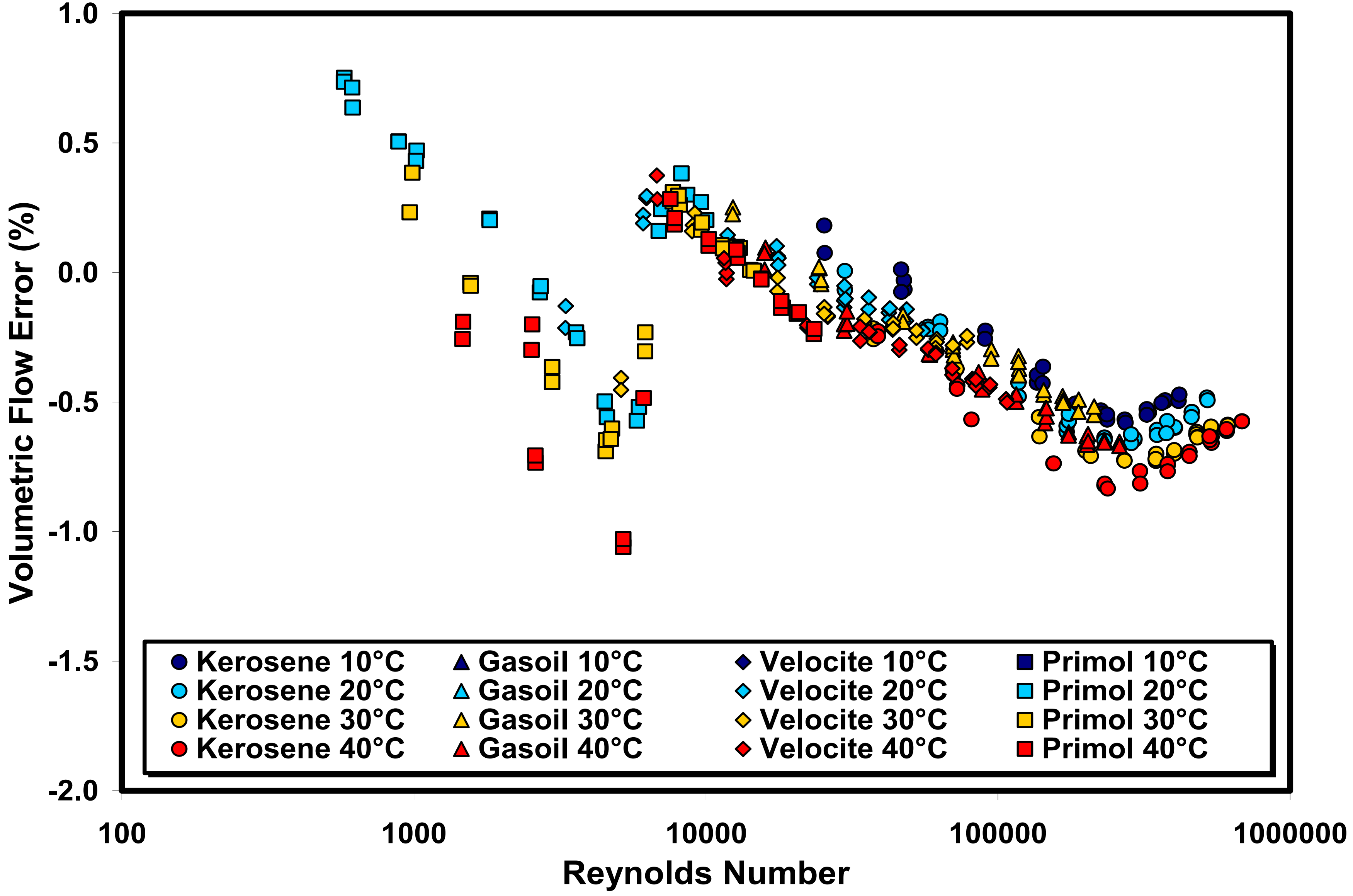
- 1 Difficult Reynolds numbers
  - 1.1 Heavy oil
  - 1.2 LNG
- 2 Difficult installations
  - 2.1 Emissions
  - 2.2 Flare gas
- 3 Difficult fluids
  - 3.1 Carbon dioxide
  - 3.2 Wet gas flow
    - Venturi tubes
    - Orifice plates

Difficult Reynolds numbers: 1.1 Heavy oil

- Worldwide reserves of heavy hydrocarbons now significantly outweigh conventional light crudes.



Ultrasonic 4” Multipath



Ultrasonic 4” Multipath

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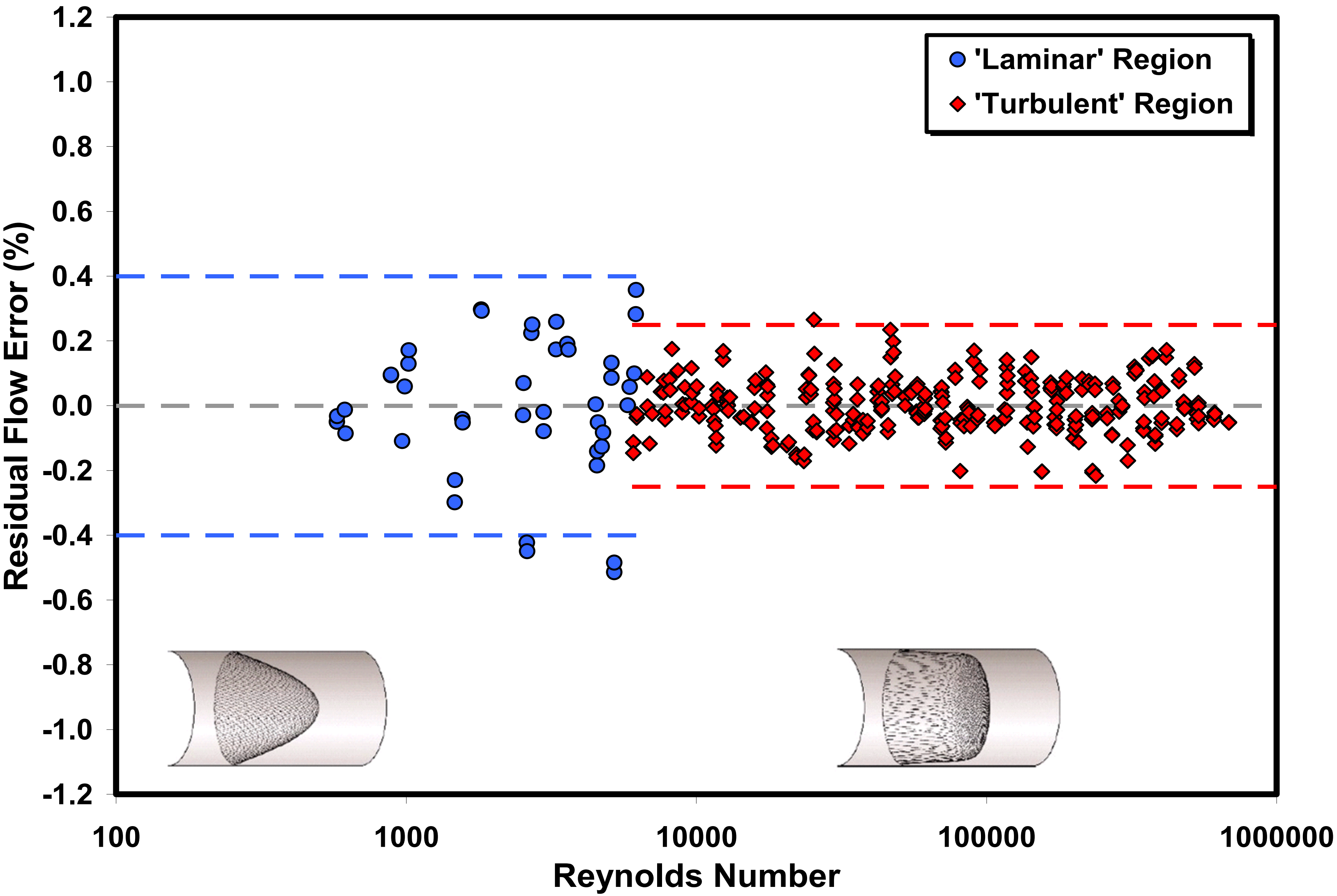
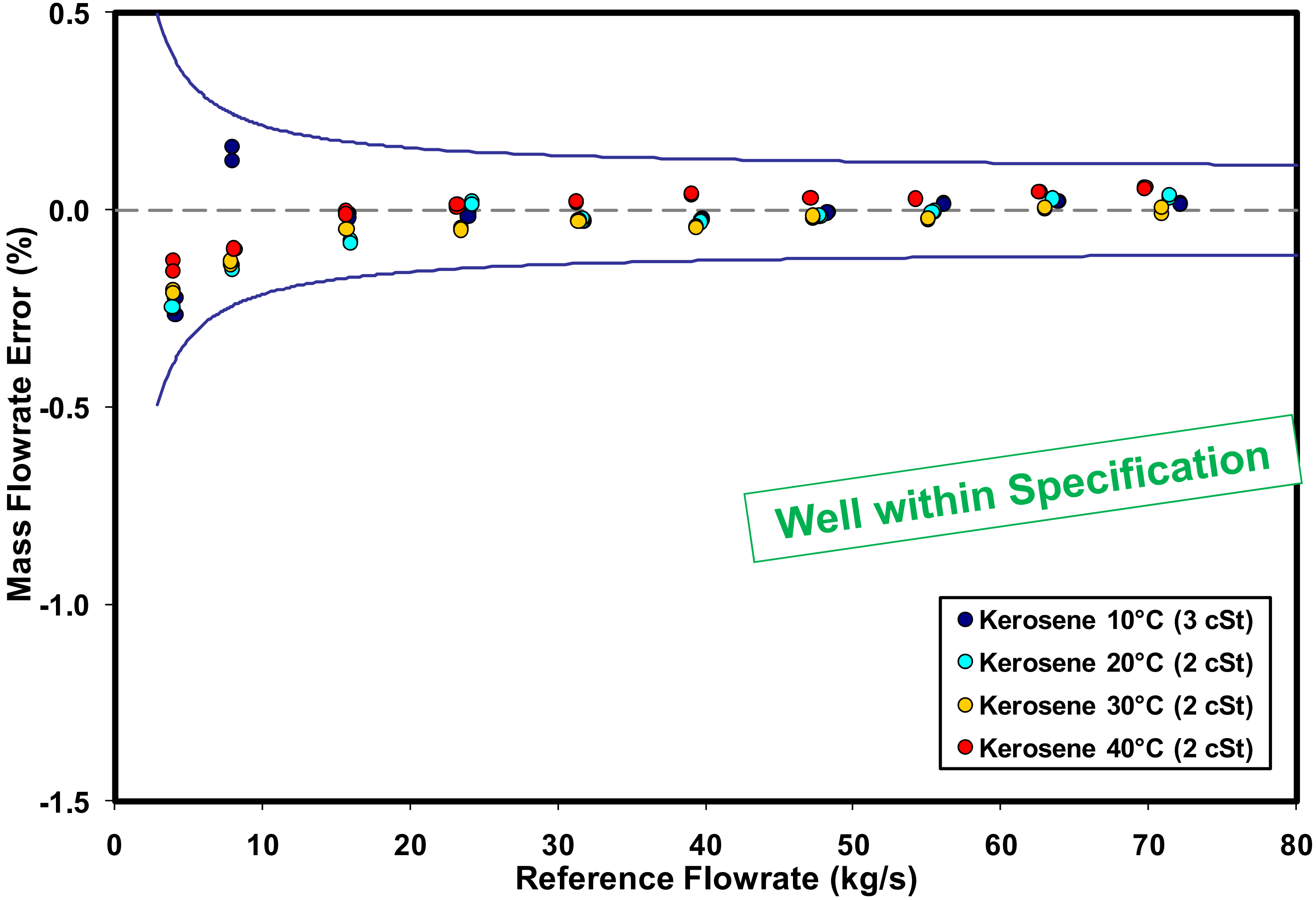


Coriolis – uncorrected data



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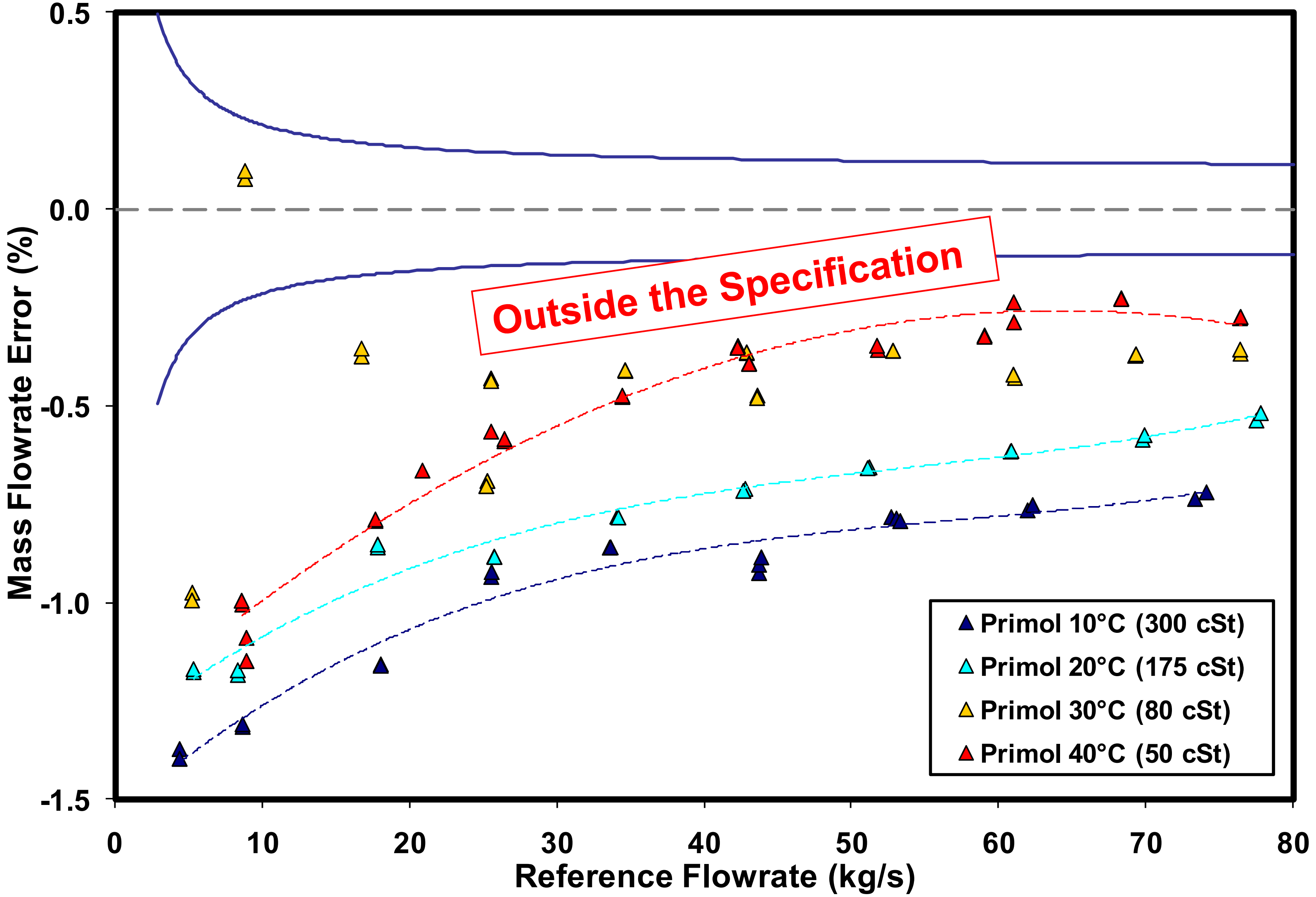

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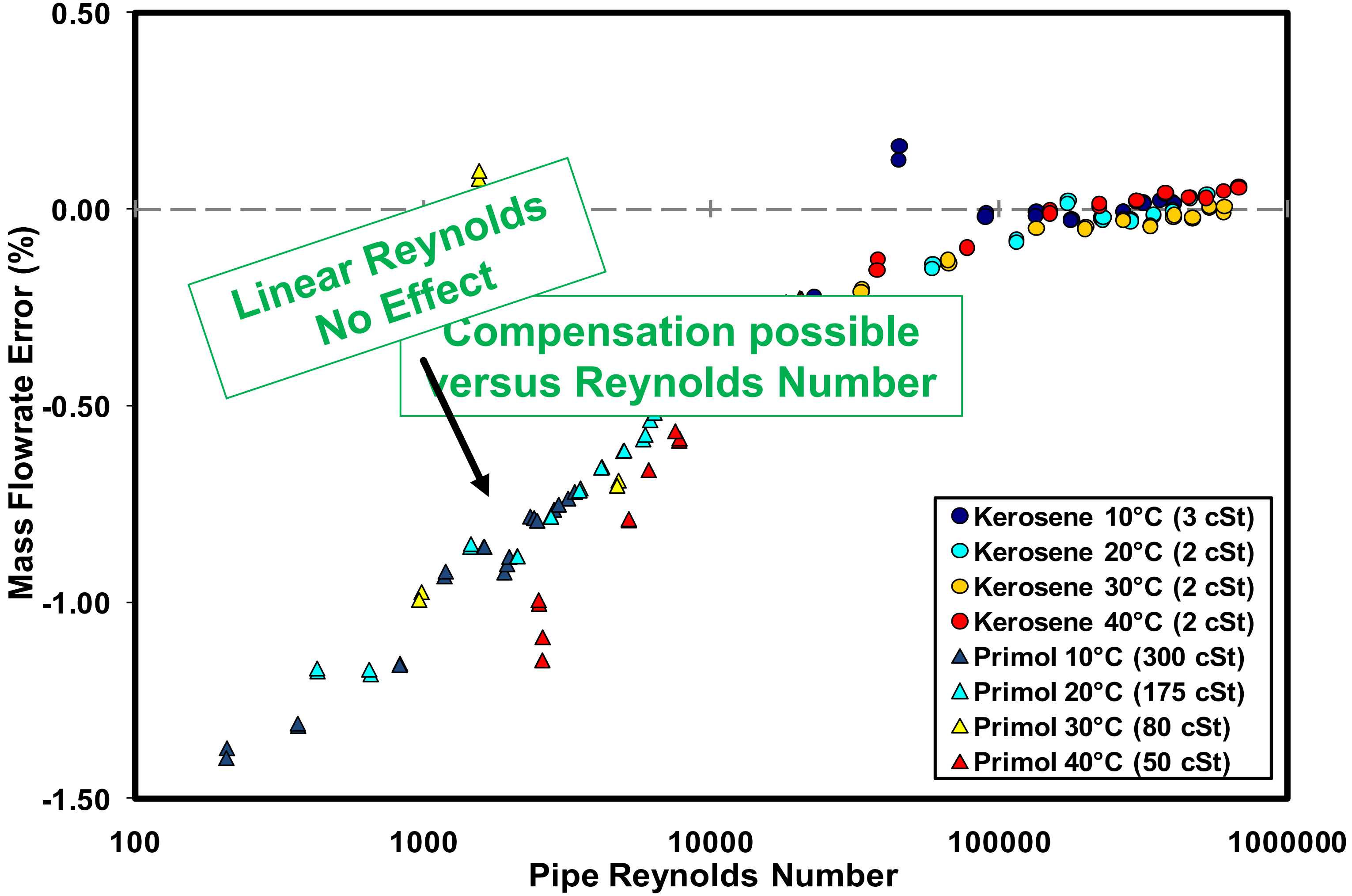


Linear Reynolds
No Effect

Compensation possible
versus Reynolds Number

1 Reynolds number issues

- 1.1 Heavy oil
  - Performance may be difficult through transition (ultrasonic)
  - Performance may be different below transition (Coriolis)
  - Air entrainment
  - Extension to 1500 cSt

- 1.2 LNG
  - The Reynolds number in LNG (or in pressurized hot water) is much higher than in cold water

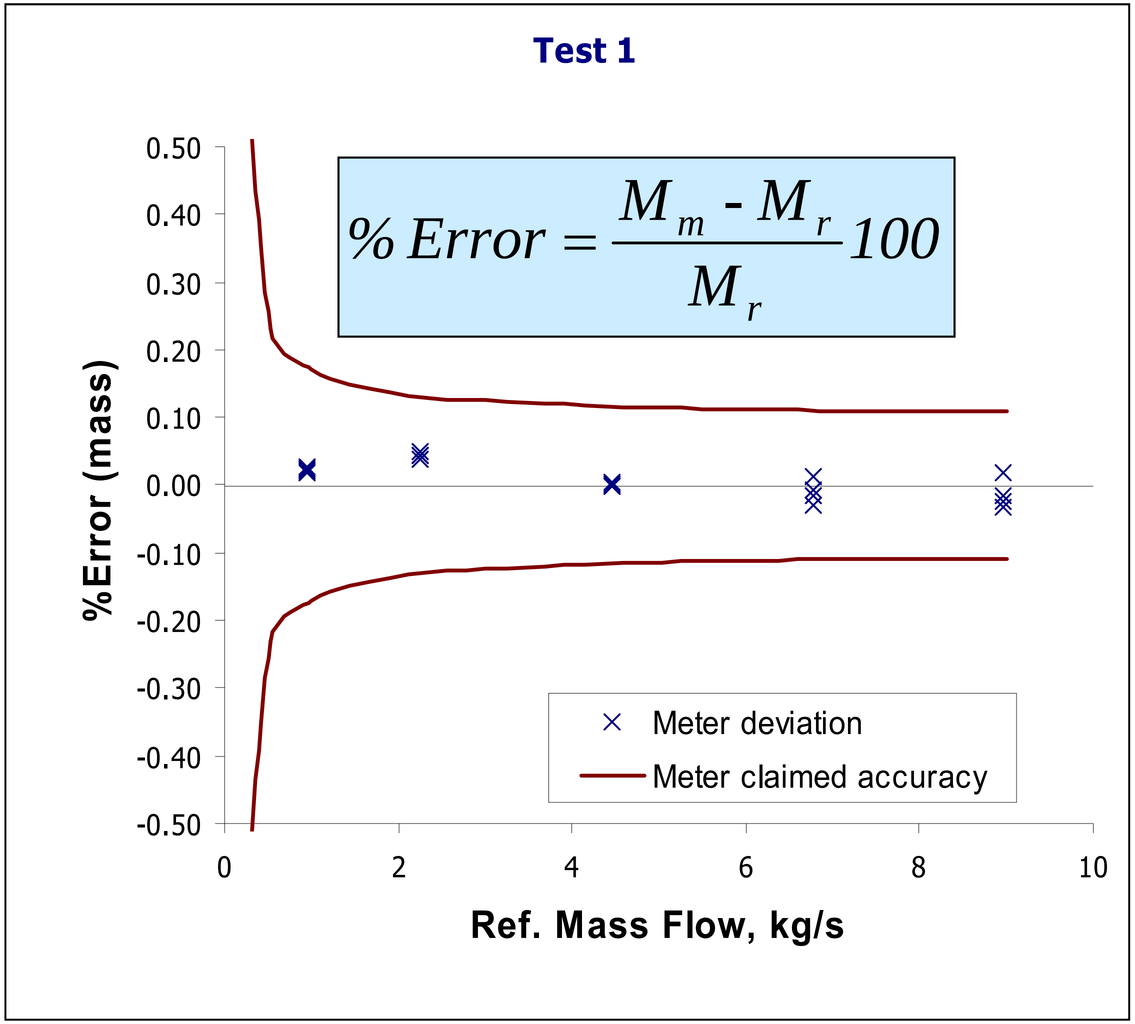
Difficult Reynolds numbers: 1.2 LNG

Most measurement is on board ship, but it would be good to use a flowmeter

Test Programme

- Flow meters:
  - – Coriolis
  - – (Ultrasonic)
- Test plan - performance evaluation:
  - – Water (20 °C) at NEL
  - – Liquid N_2 (-193 °C) at NIST
  - – Retest with Water

Coriolis – Water - Mass



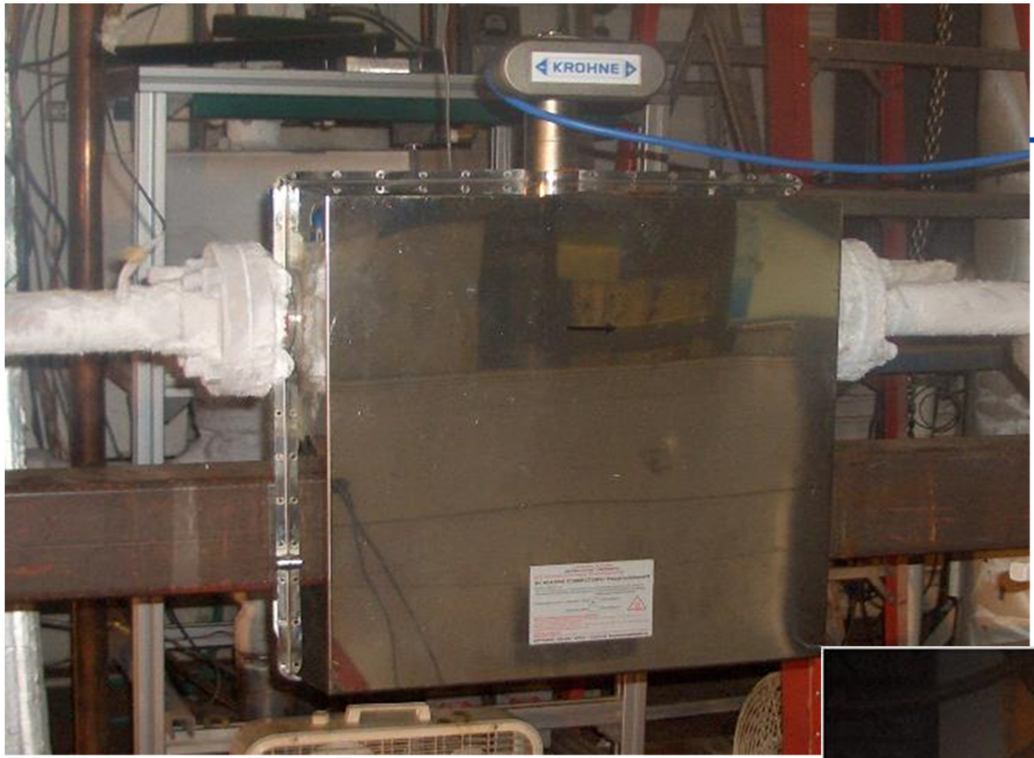
$$\% \, Error = \frac{M_m - M_r}{M_r} 100$$

Measurements:-

- 5 points over test range
- Each point repeated 4 times
- Tests repeated 4 times

Results:

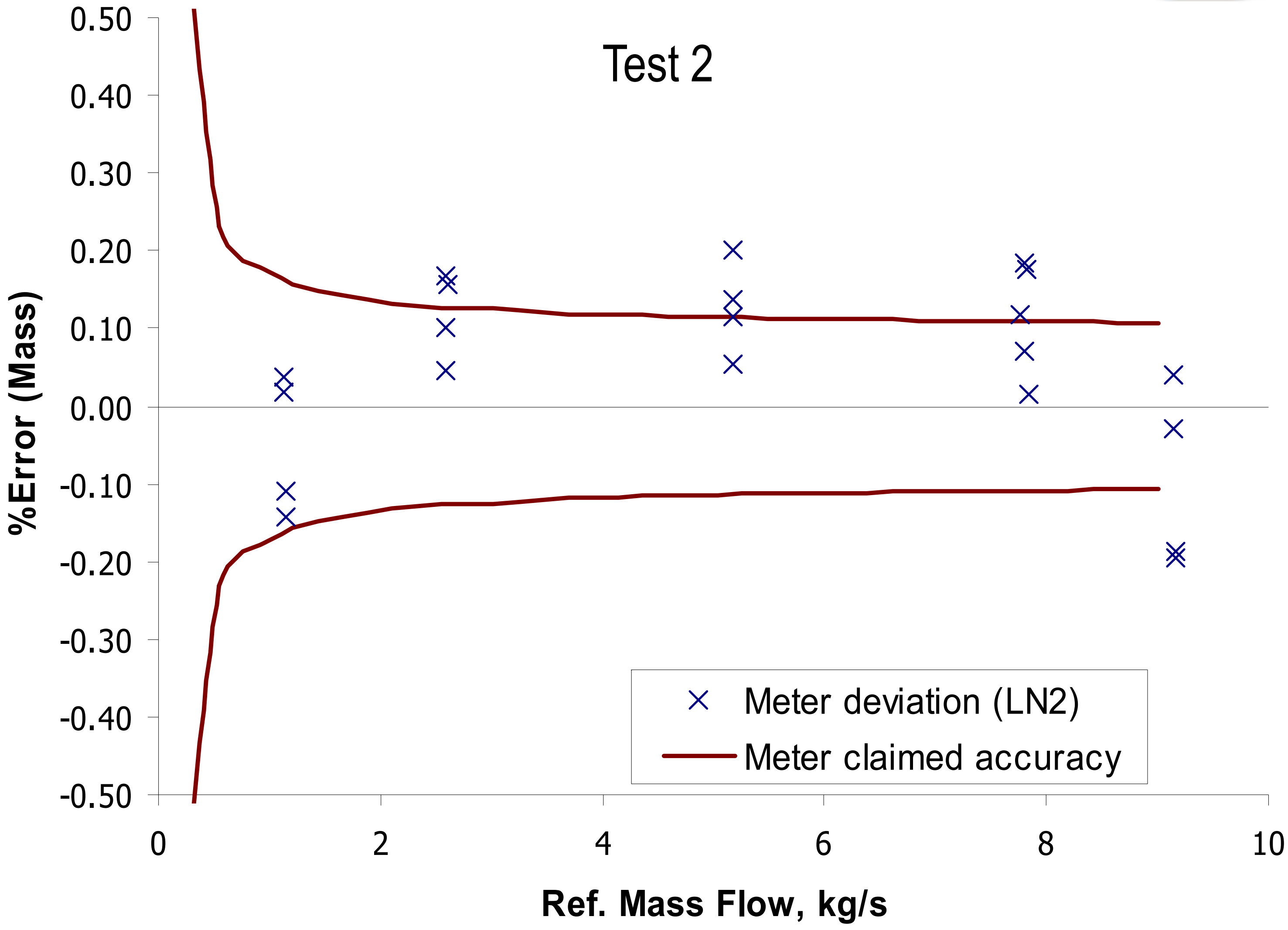
- Good repeatability
- Good reproducibility
- All measurements are within claimed accuracy



4 tests were taken with insulation jacket

One test was taken with no insulation jacket

Liquid N_2 Calibration Results- Mass



Results

- Coriolis:
  - Good results: within 0.2%
  - Water calibration can be successfully transferred to cryogenic conditions if allowance is made for the non-linear temperature dependence of the Young's Modulus of elasticity of stainless steel.

Next stage

- Coriolis:
  - Compare water results with LNG results

Difficult Installations: 2.1 Stack emissions

Stack emissions: are Pitot tubes a good method of flow measurement?

- Significant work was undertaken in the 1960s and 1970s to establish the uncertainty of flowrates measured with pitot tubes.
- Errors of less than 1% were regularly obtained if the utmost care was taken in good flow conditions.
- An uncertainty of not greater than 2% can be achieved by following ISO 3966 (: 4.1). To do this corrections are required and were determined together with the uncertainty.

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The problem: errors using Pitots

- Compressibility correction factor
- Head loss
- Transverse velocity gradient
- Reynolds number
- Turbulence
- Static hole error
- Wall proximity
- Blockage
- Misalignment
- Swirl
- Integration scheme
- Asymmetry
- Leakage
- Positioning
- Diameter
- Unsteadiness
- Vibration
- Differential pressure
- Density

Systematic, correctable over-reading

Transverse velocity gradient	0.4% ± 0.4%
Turbulence	1.25% ± 0.75%
Swirl	1.5% ± 1.5%
Blockage	0.4% ± 0.4%
Integration scheme (ISO 10780)	1%
TOTAL	4.5%

Problem

- Discarding good flow measurement in the quest for simplicity
- The stack emissions standards (e.g. ISO 10780) need to be changed.

Difficult Installations: 2.2 Flare gas

EU Emissions Trading Scheme

- Phase I (2005 – 2008) – Trial period
- Phase II (2008 – 2012) – Mandatory
  - Sets maximum uncertainty level on activity data (flowrate)
  - UK Offshore = Tier 2 (12.5% on m^3/yr)
  - Highest tier = Tier 1 (7.5% on m^3/yr)
- Phase III (2013 - 2020)
  - ❑ Free allocations will reduce to 80%, reducing annually to 0% in 2020
  - ❑ No free allowances for electrical power generation
  - ❑ Offshore electricity production will be hit hard
  - ❑ Direct-drive equipment will get allowances

Functions of a flare system

- Ultimately a safety relief system
  - Emergency Blow-Downs
  - Pressure relief
  - Venting of vessels etc. for maintenance

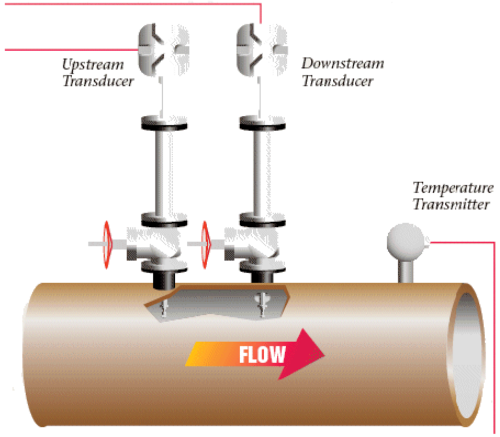
- c 30% of UK offshore CO_2 emissions

Flare metering - issues

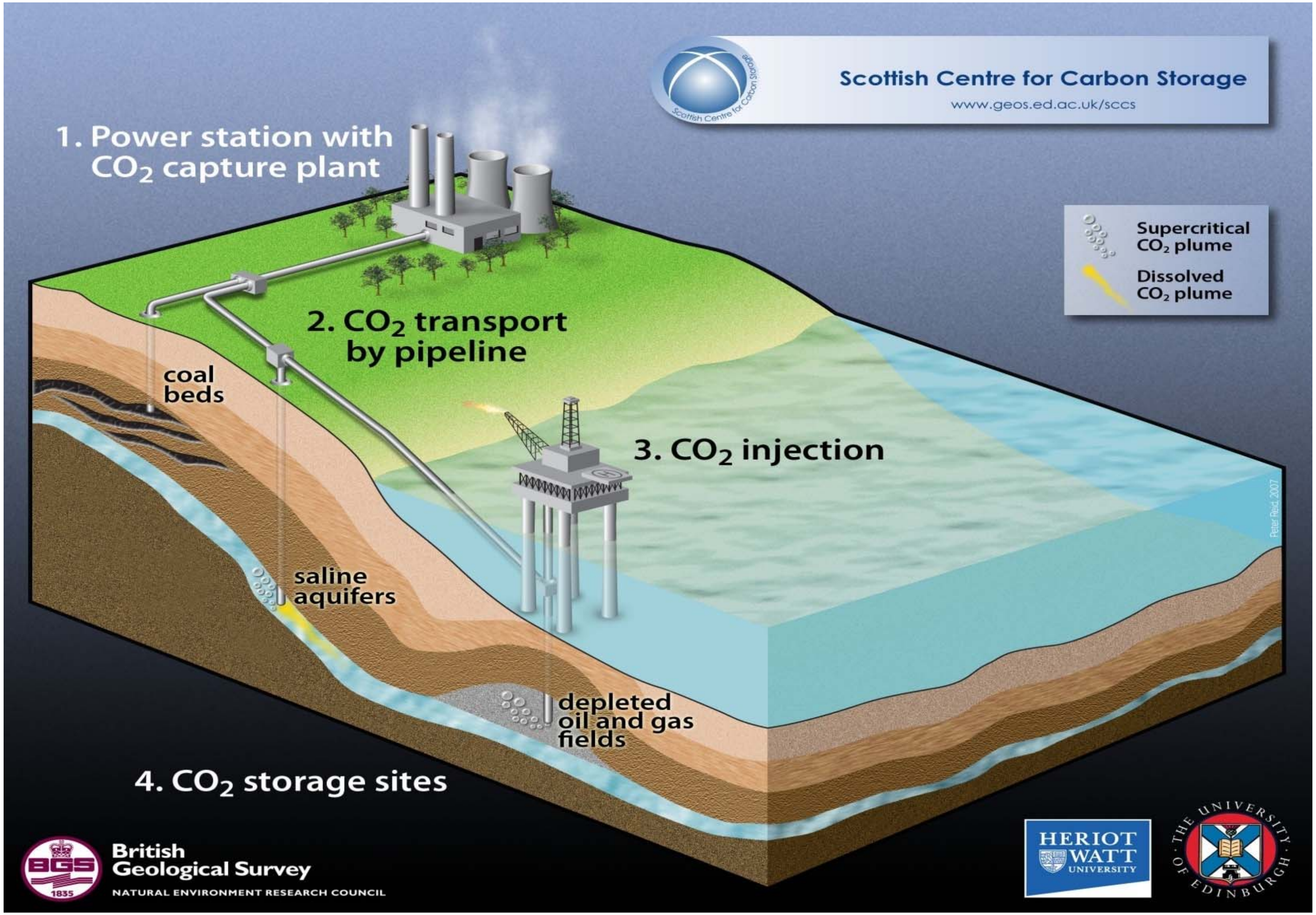
- Typically no calibration = no traceability to Standards
- Very wide velocity range (> 1 000:1)
- Minimal pressure drop required
- Large line sizes
- Liquids, solids, low temperatures
- Winds causing pulsations, noise
- Installation errors can be large

Ultrasonic Flare Gas Meters

- Most widely adopted technology for flare
- Very wide range (> 2 000:1 is quoted)
- Wide turndown, negligible pressure loss
- Can calculate Density = f(SOS, T, p) using proprietary correlations



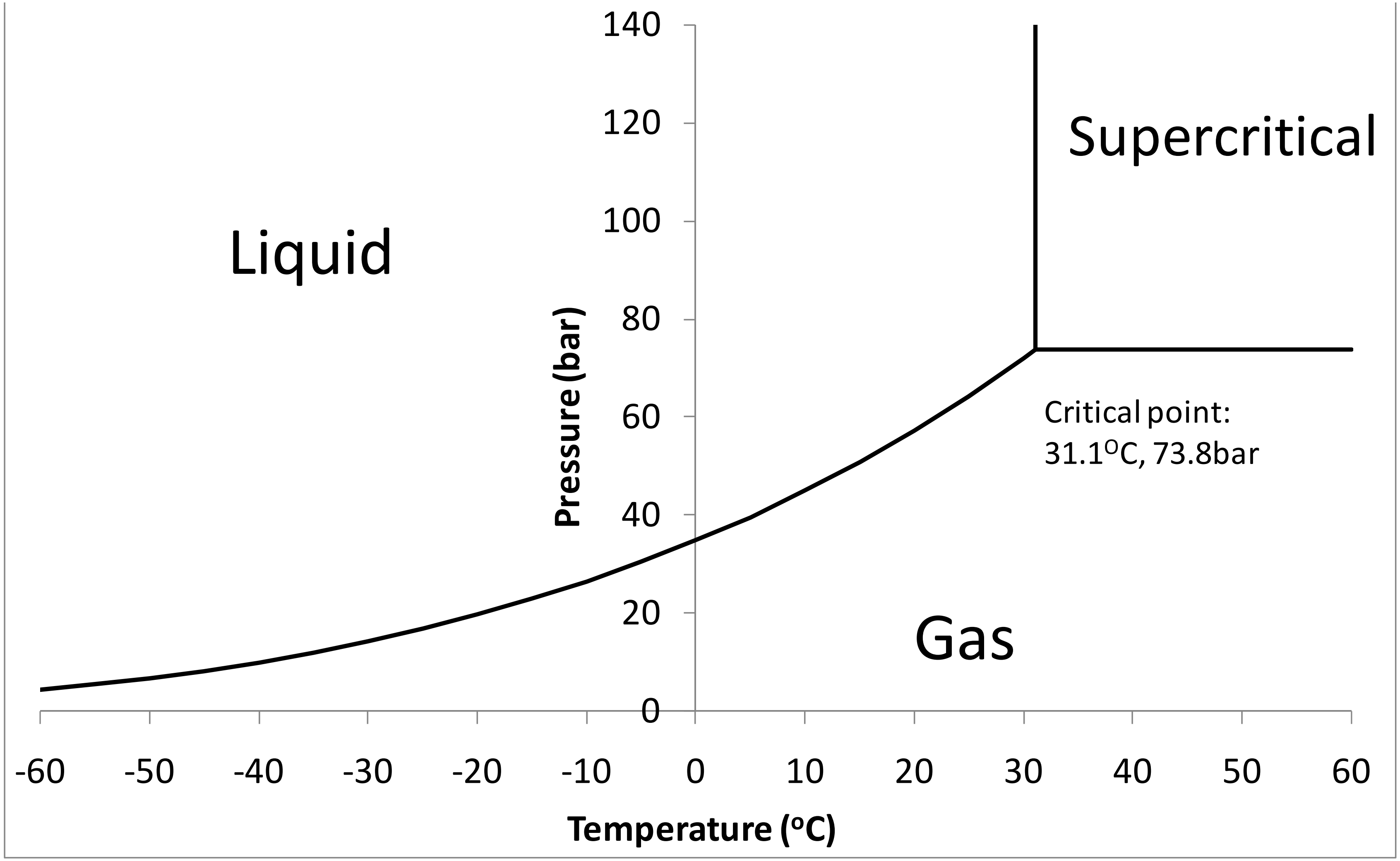
Difficult Fluids: 3.1 Carbon Capture & Storage



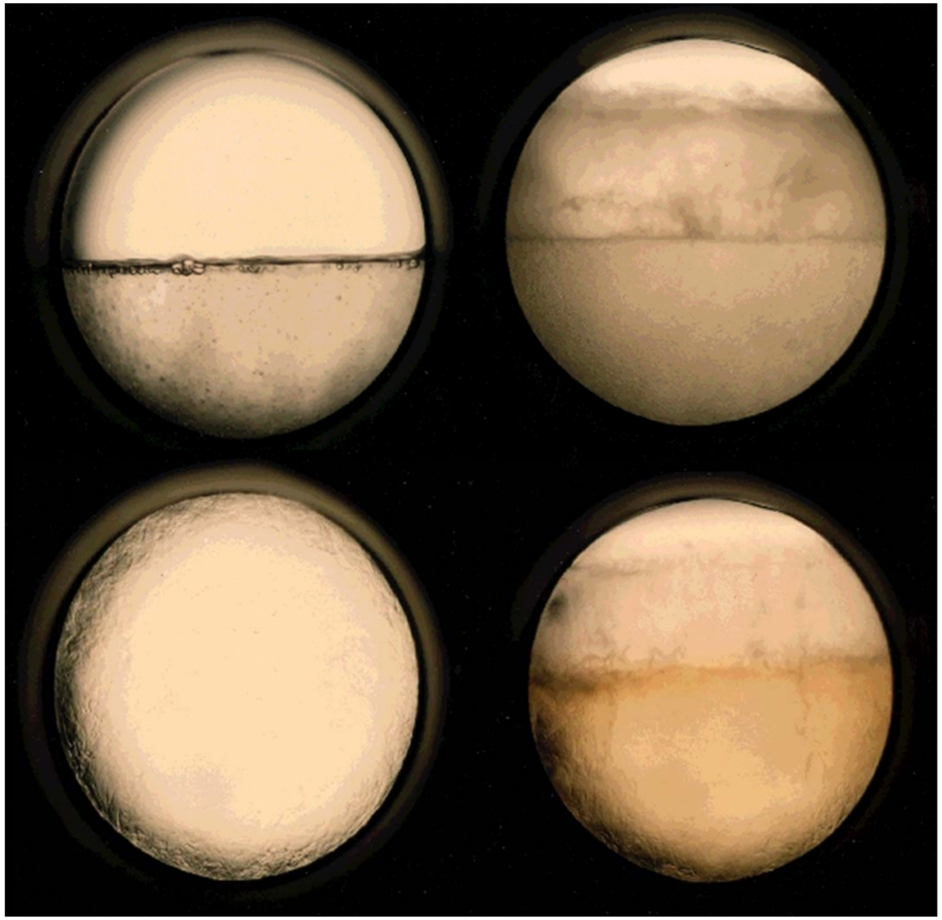
The issue

- Kyoto Protocol
- CO_2 could be captured and stored
- It will need to be measured
- Total UK emissions = 548 million tonnes
- Suppose mass flow uncertainty is 1.5%
- If CO_2 price = \$45 per tonne uncertainty ≈ \$375 million
- But at 5c per tonne uncertainty ≈ \$0.4 million

Pure CO_2 Phase Diagram



CO_2 going supercritical



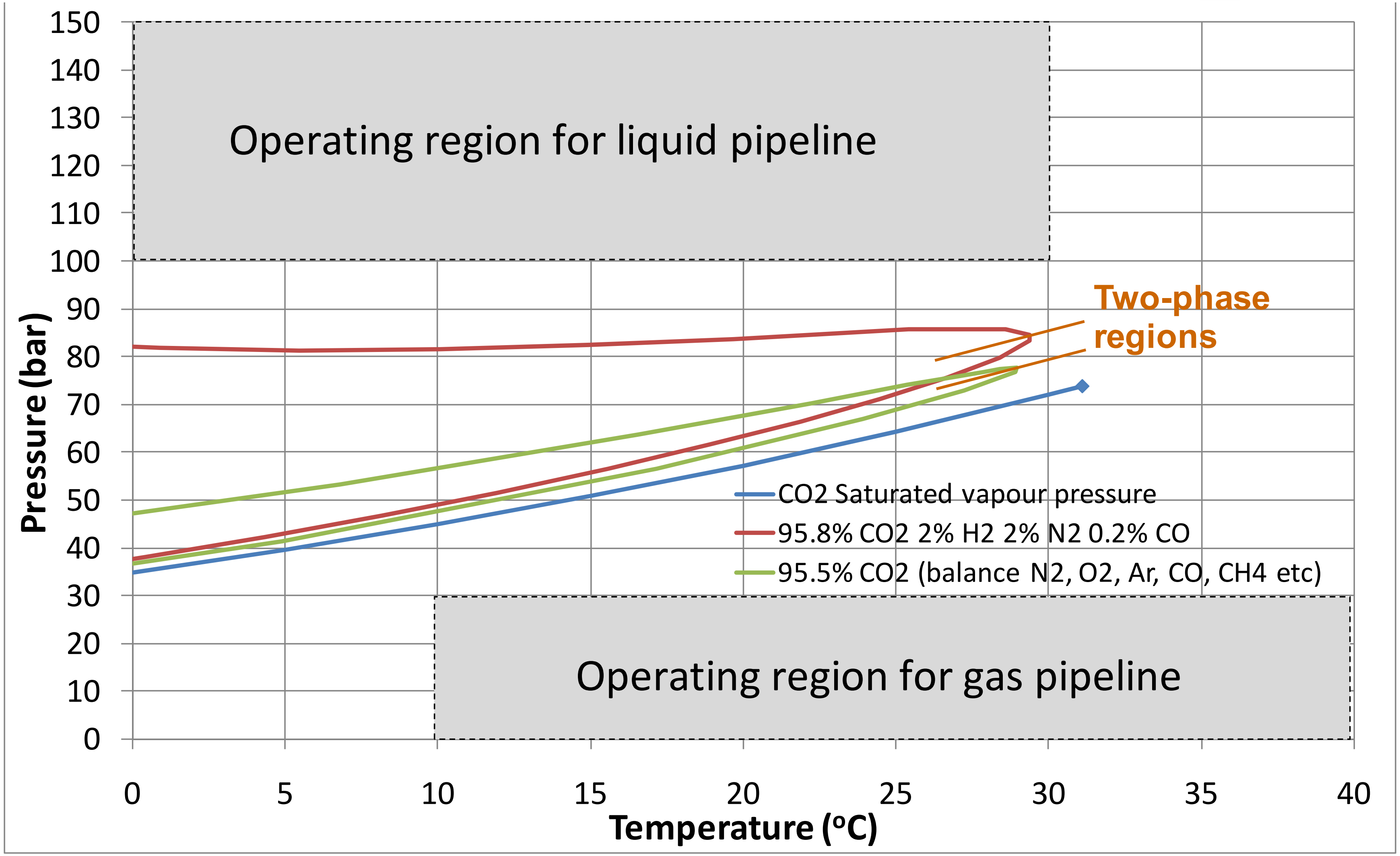
Liquid and vapour
phases in co-existence
– distinct meniscus

Liquid and vapour
phases in co-existence
– visible meniscus

Single phase
supercritical fluid – no
meniscus

Liquid and vapour densities
converging – barely visible
meniscus

Operating regions

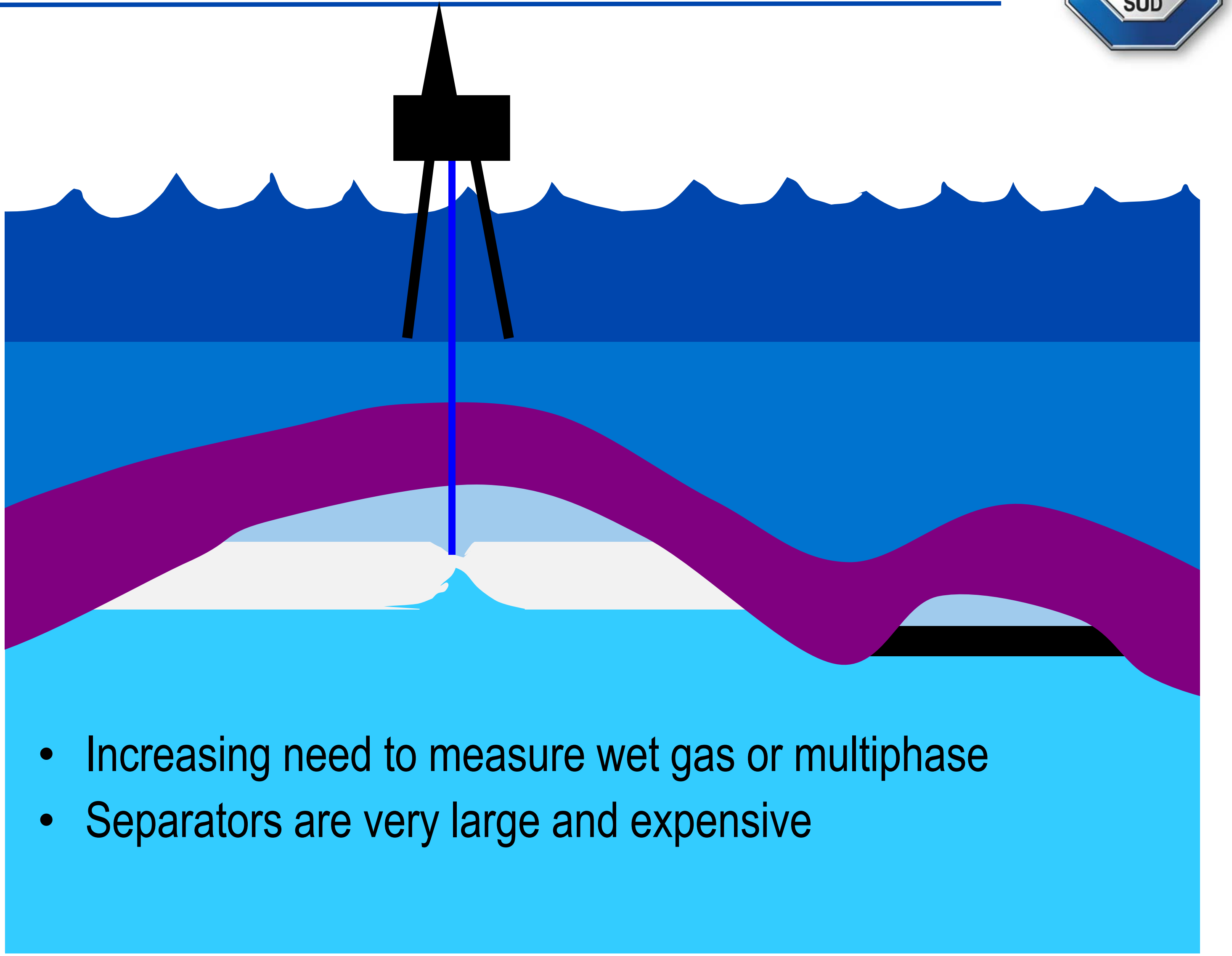


Potential CCS Metering Technologies

- CO_2 has been metered for 30 years in EOR applications
  - no legislation on accuracy (sacrificed for cost)
  - not as stringent on impurities
  - shorter pipe distances

- However, a number of metering technologies could be suitable
  - DP metering
  - volumetric metering
  - mass metering (Coriolis)
  - non-invasive metering

Difficult Fluids: 3.2 Wet gas

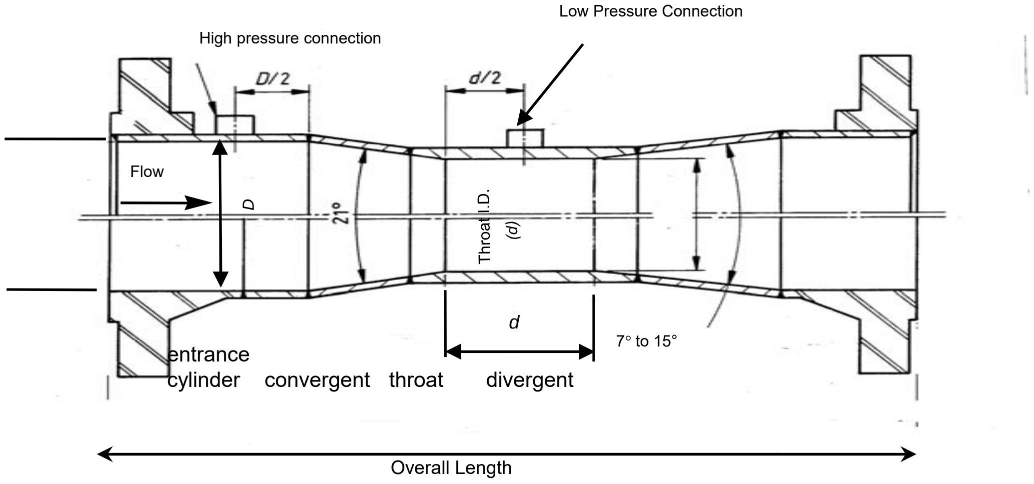


- Increasing need to measure wet gas or multiphase
- Separators are very large and expensive

Two possible ways of measuring wet gas

- Venturi tubes
- Orifice plates

Look at Venturi tubes in dry gas first



- In incompressible flow Bernoulli gives

$$q_m = \frac{1}{\sqrt{1-\beta^4}} \frac{\pi d^2}{4} \sqrt{2\rho\Delta p}$$

- In practical application

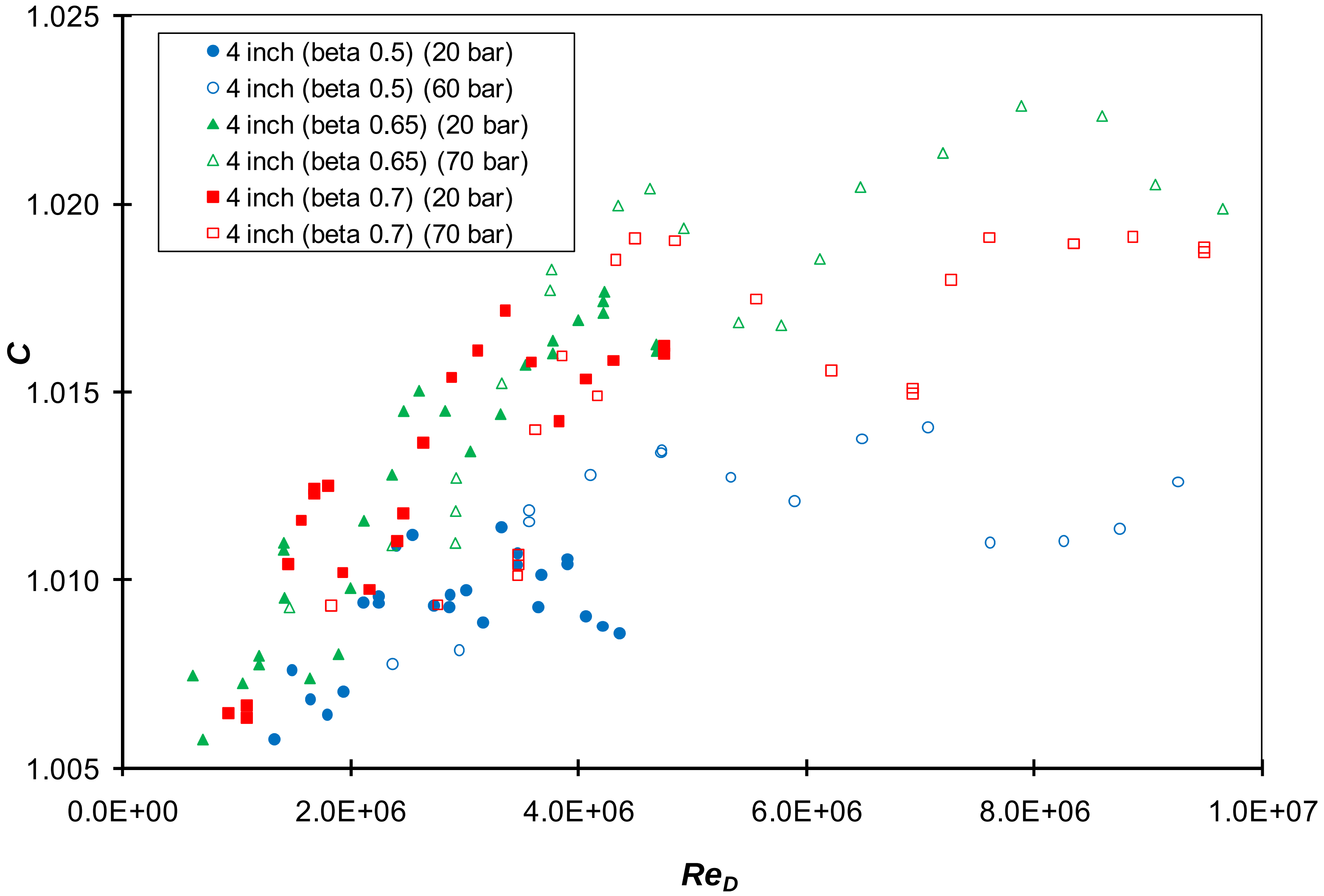
$$q_m = \frac{C\varepsilon}{\sqrt{1-\beta^4}} \frac{\pi d^2}{4} \sqrt{2\rho_1\Delta p}$$

Discharge coefficients

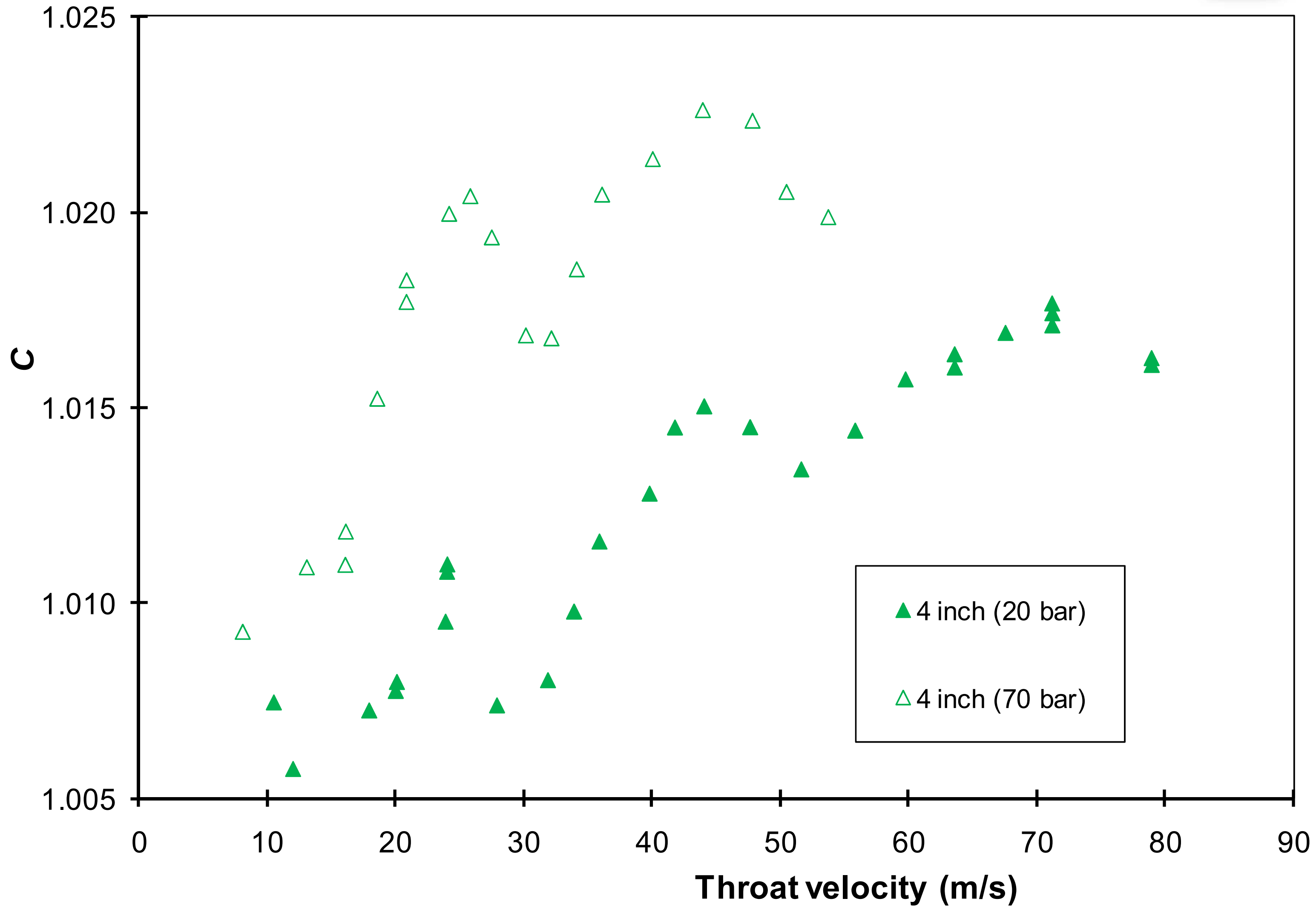
- Should the discharge coefficient, *C*, always be less than 1?

$$q_{m,gas} = \frac{C}{\sqrt{1-\beta^4}}\varepsilon\frac{\pi}{4}d^2\sqrt{2\Delta p\rho_{1,gas}}$$

4” (100 mm) Venturi tubes in gas: Surprise 1



C v throat velocity: 4” $\beta = 0.65$ Venturi

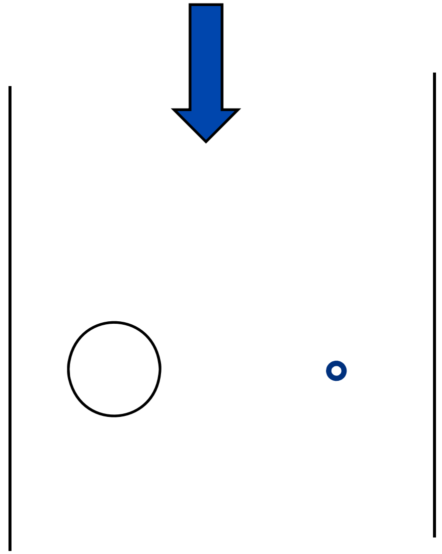


Static Hole Error

- The difference between the pressure measured with a tapping hole of finite size and that which would have been measured using an infinitely small hole:

$$\frac{dp}{\tau} = f(Re_{tap})$$

$$Re_{tap} = \frac{\sqrt{(\tau/\rho)}d_{tap}}{\nu}$$



- *dp* shift in pressure, τ wall shear stress, ρ density, ν kinematic viscosity, d_{tap} tapping diameter

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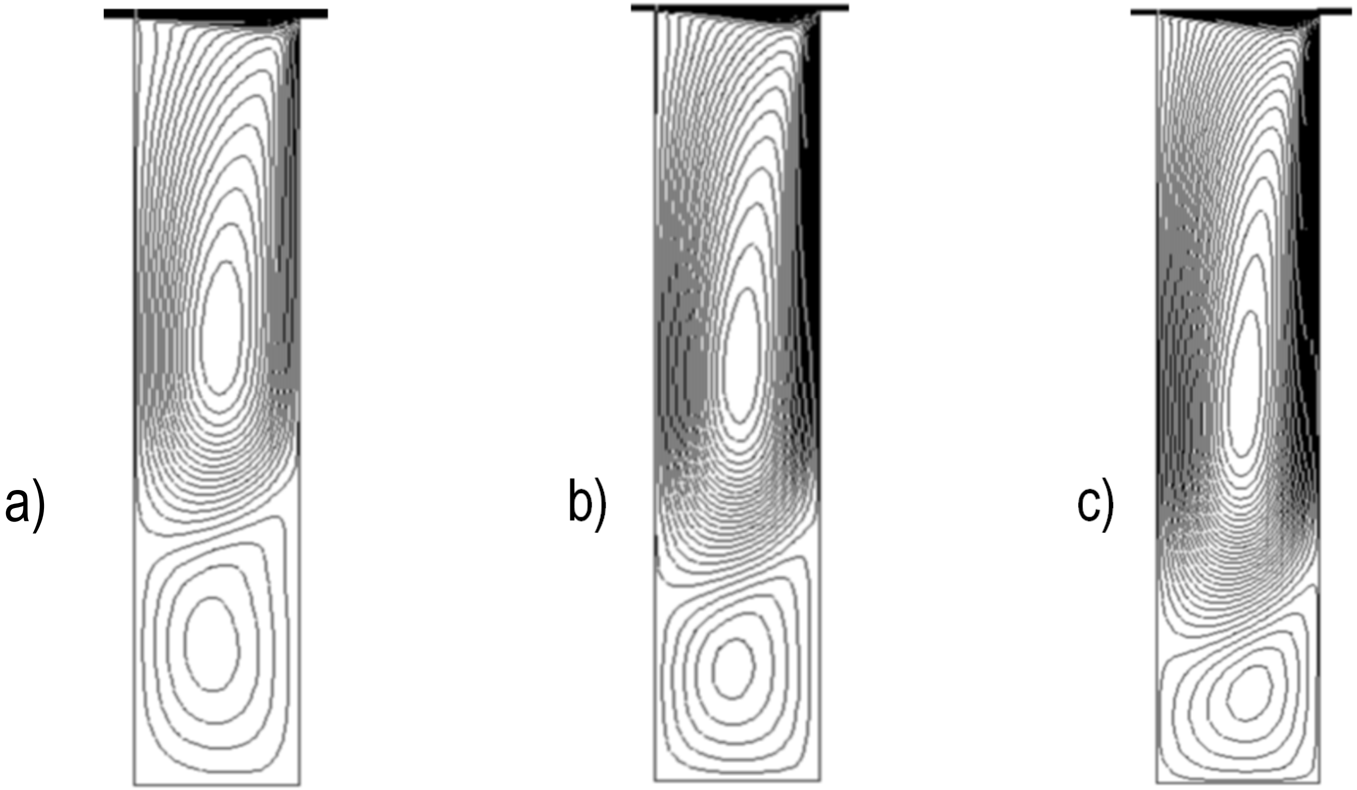
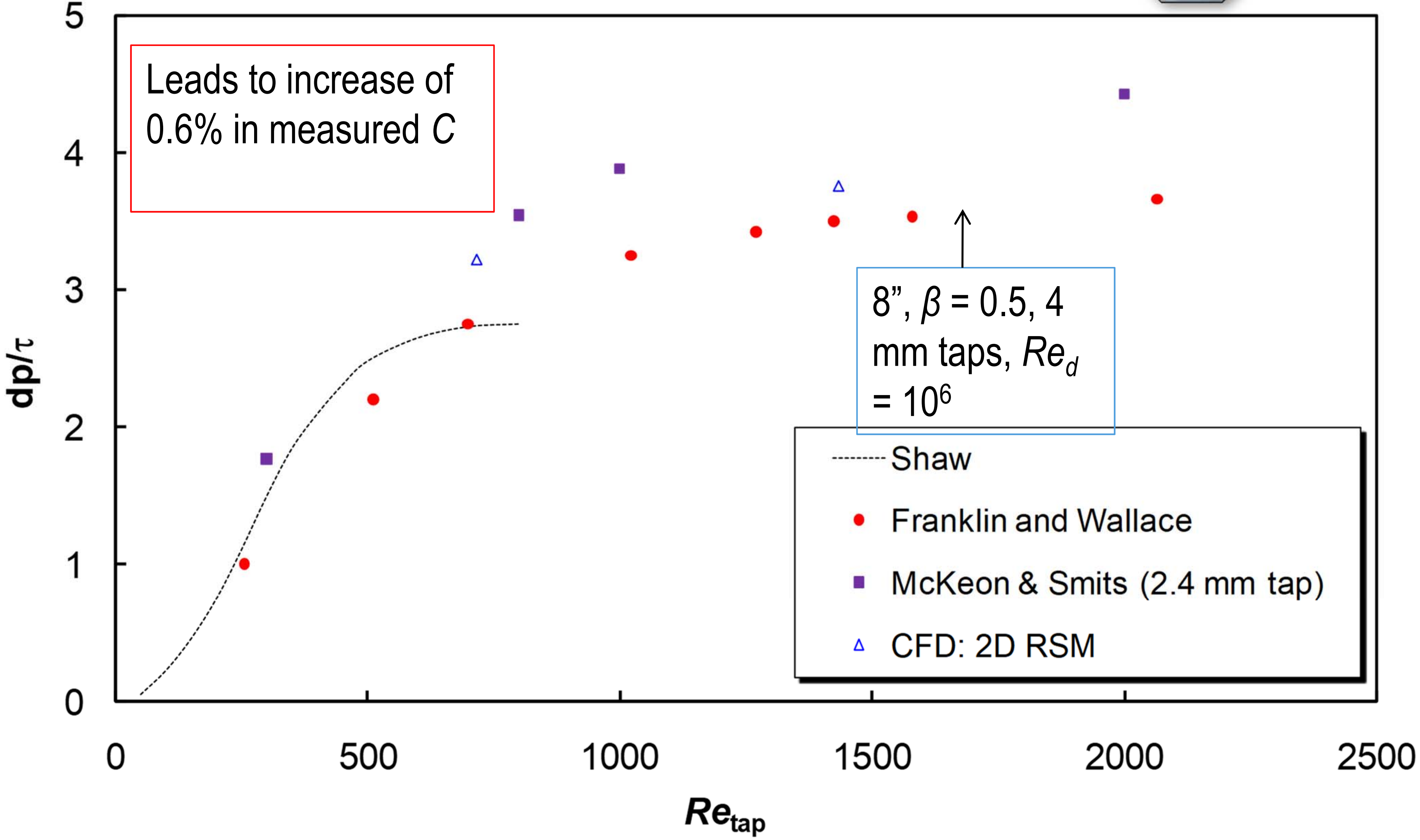
Streamline contours in pressure slot

RSM+wr model with Re_D at:
a) 2.0×10^6, b) 5.3×10^6, c) 2.0×10^7.



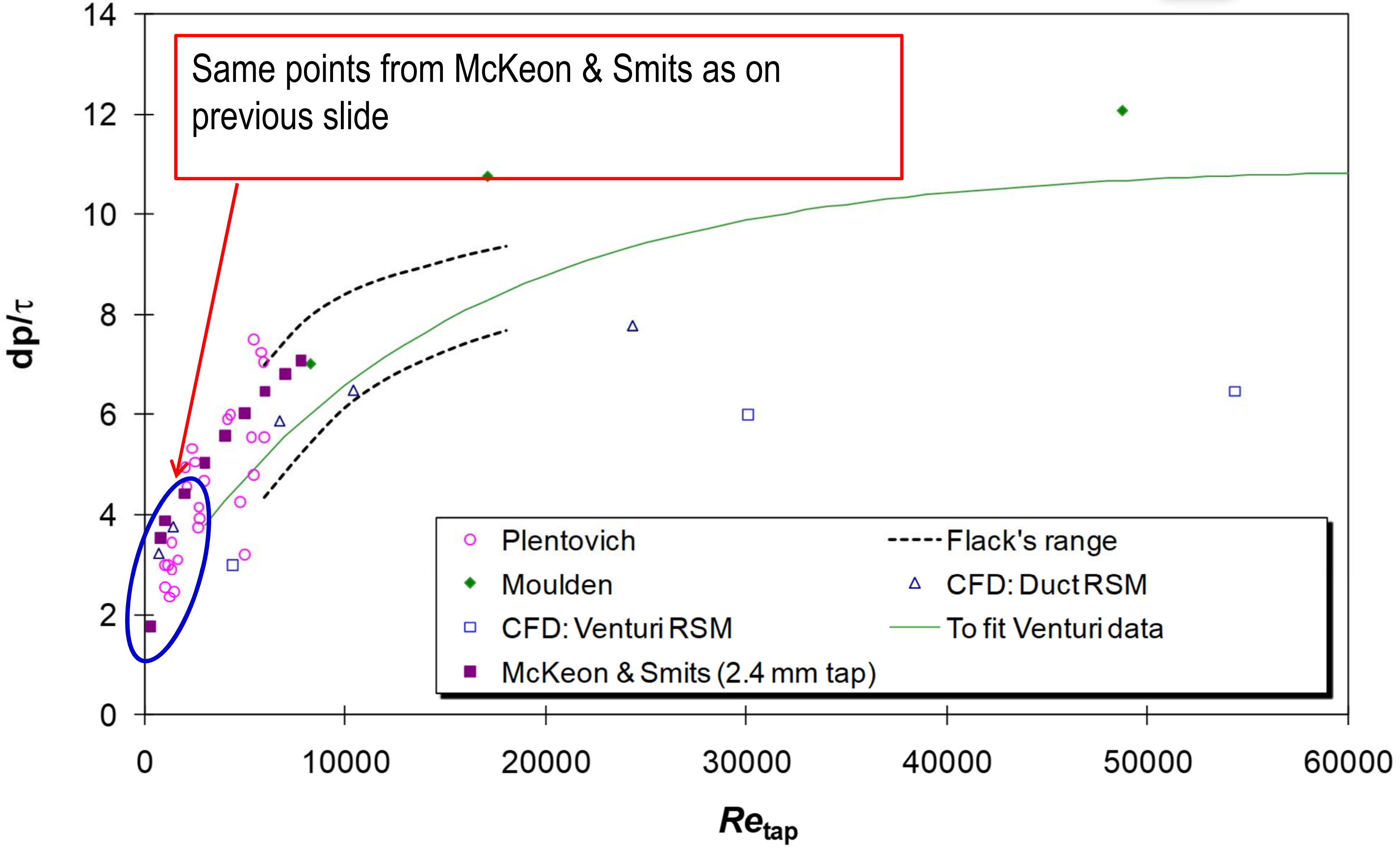
Static hole error: low Reynolds number ($Re_d < 2 \times 10^6$)



Leads to increase of 0.6% in measured *C*

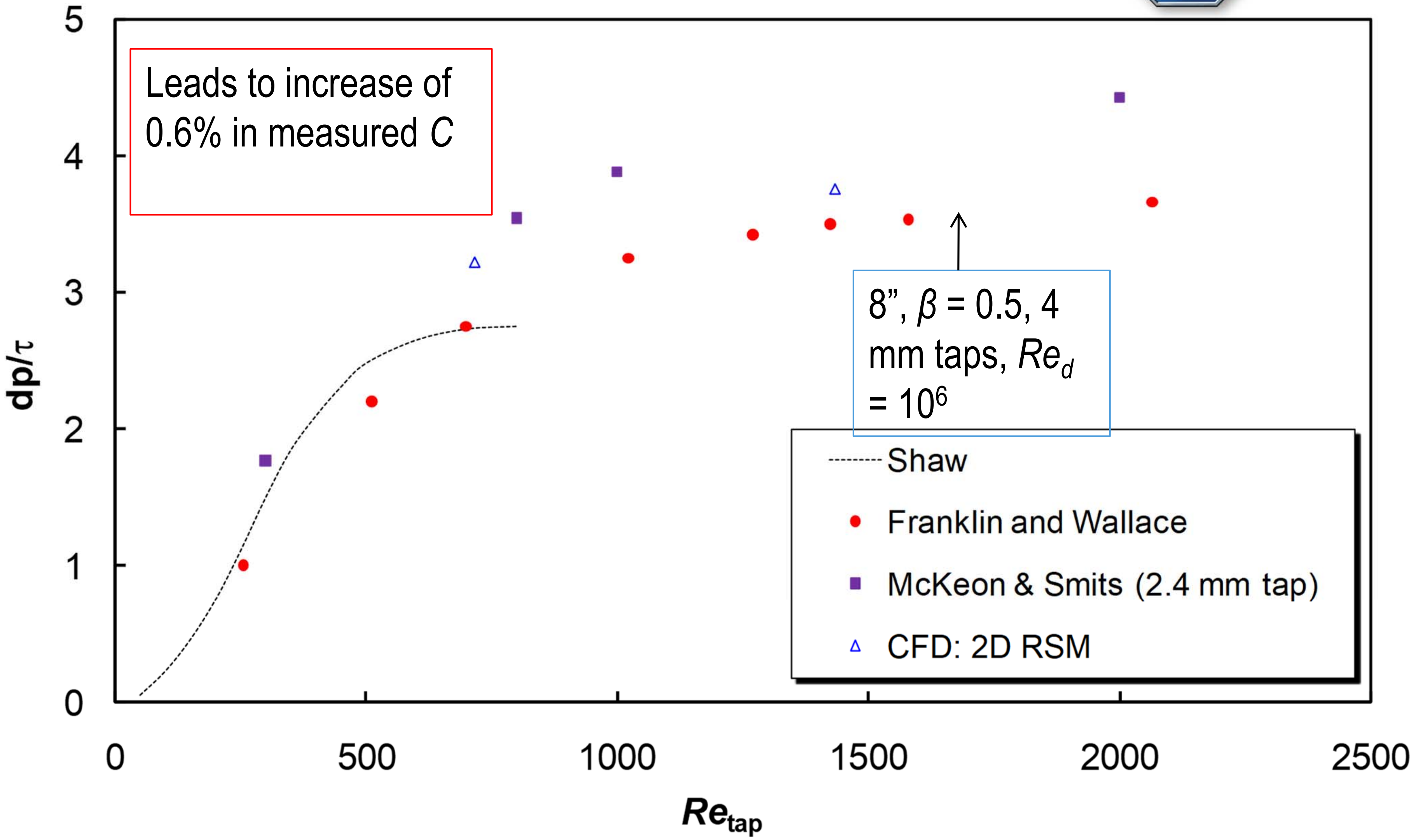
8”, $\beta = 0.5$, 4 mm taps, $Re_d = 10^6$

Static hole error: high Reynolds number (up to $Re_d > 10^7$)



Same points from McKeon & Smits as on previous slide

Static hole error: low Reynolds number ($Re_d < 2 \times 10^6$)



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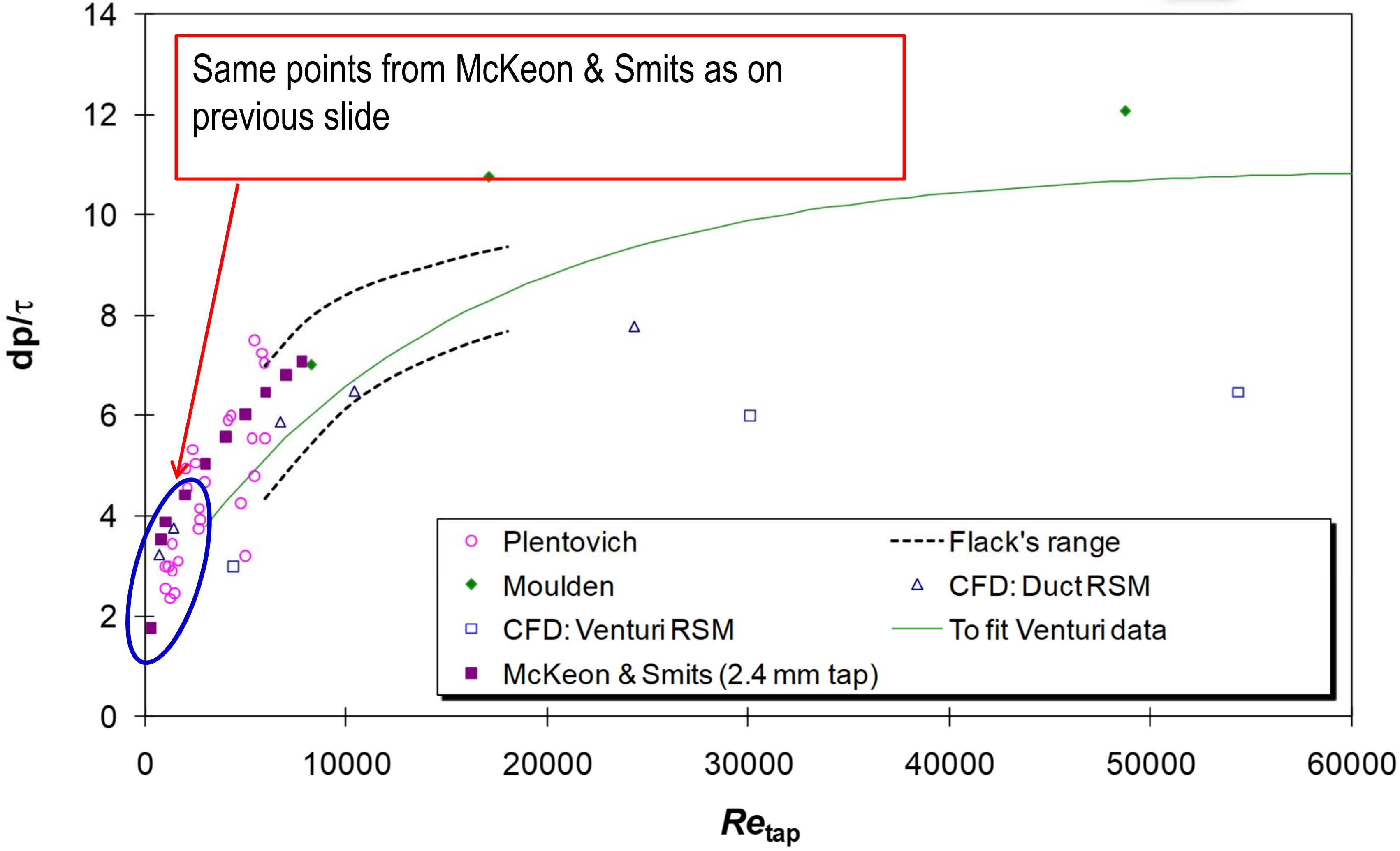
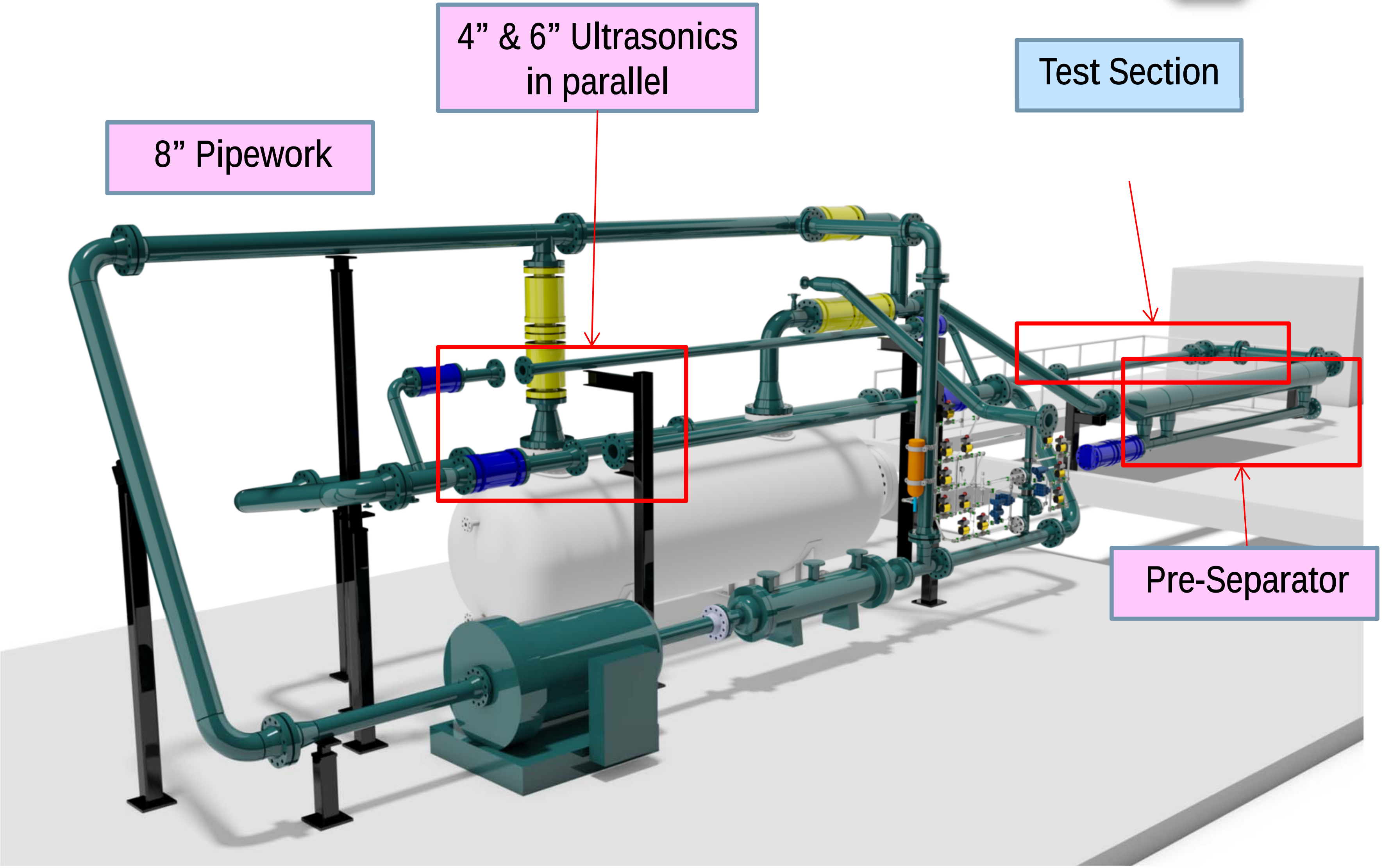


Same points from McKeon & Smits as on previous slide

Venturi discharge coefficient: why the surprise in the 1990s?

- Simple physical explanation of *C* was inadequate
- Literature (mostly c 1960 – 75) was not well known
- The extrapolation was wrong

Wet Gas Facility


8” Pipework

4” & 6” Ultrasonics in parallel

Test Section

Pre-Separator

Wet-gas correlations (ϕ is the overreading)

$$q_{m,\text{gas}} = \frac{C}{\sqrt{1-\beta^4}}\,\varepsilon\,\frac{\pi}{4}\,d^2\,\frac{\sqrt{2\Delta p\,\rho_{1,\text{gas}}}}{\phi}$$

$$X = \left(\frac{q_{m,\text{liquid}}}{q_{m,\text{gas}}}\right)\sqrt{\frac{\rho_{1,\text{gas}}}{\rho_{\text{liquid}}}}$$

$$\phi = \sqrt{1 + C_{\text{Ch}}X + X^2}$$

$$C_{\text{Ch}} = \left(\frac{\rho_{\text{liquid}}}{\rho_{1,\text{gas}}}\right)^n + \left(\frac{\rho_{1,\text{gas}}}{\rho_{\text{liquid}}}\right)^n$$

<u>Chisholm</u>

$n=0.25$

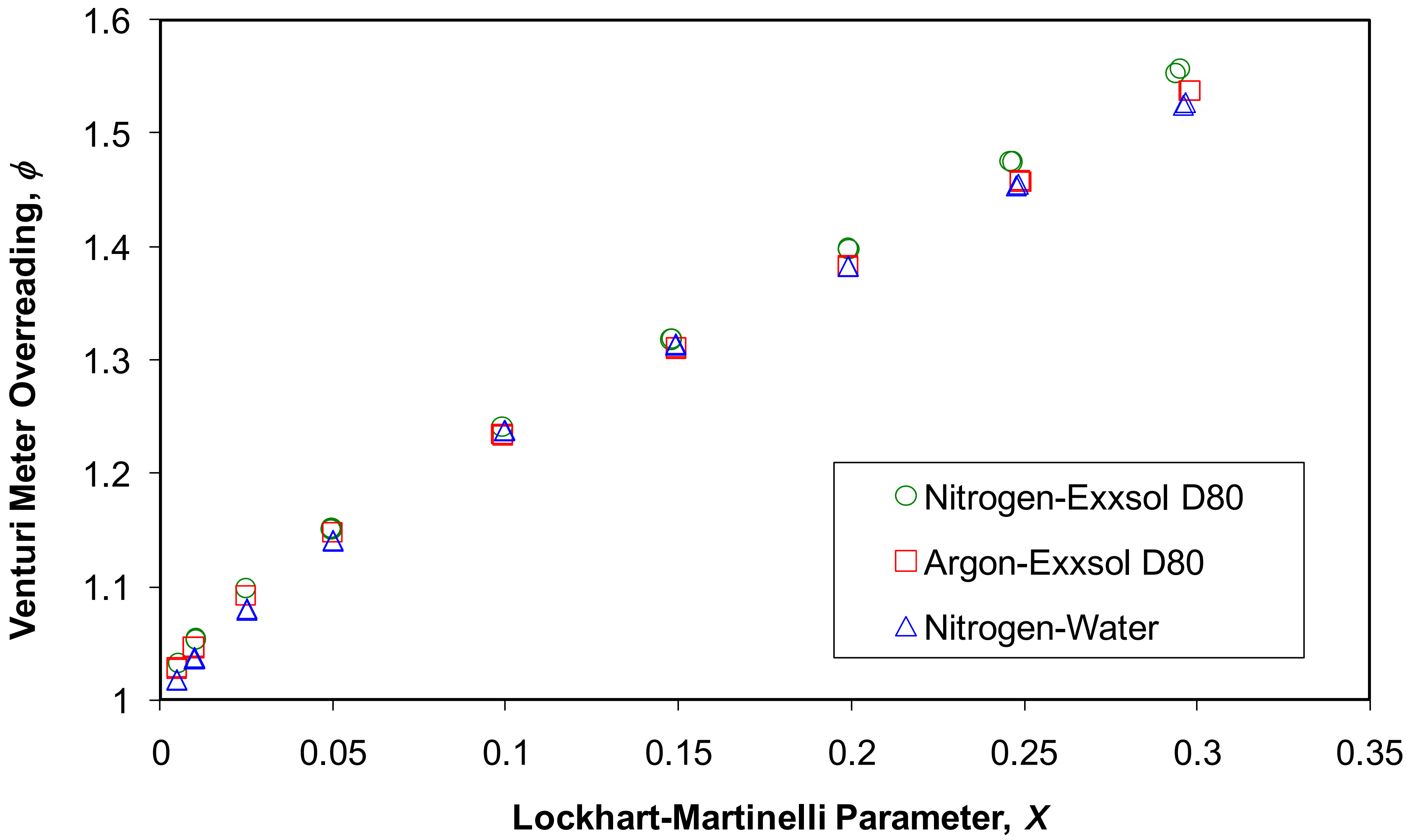
<u>de Leeuw</u>

$$Fr_{\text{gas}} = \frac{4q_{m,\text{gas}}}{\rho_{1,\text{gas}}\pi D^2\sqrt{gD}}\sqrt{\frac{\rho_{1,\text{gas}}}{\rho_{\text{liquid}}-\rho_{1,\text{gas}}}}$$

$$n = 0.41 \quad \text{for} \quad 0.5 \le Fr_{\text{gas}} < 1.5$$

$$n = 0.606\left(1-e^{-0.746Fr_{\text{gas}}}\right) \quad \text{for} \quad Fr_{\text{gas}} \ge 1.5$$

4” Venturi $\beta = 0.6$, $\rho_{1,gas}/\rho_{liquid} = 0.024$, $Fr_{gas} = 1.5$



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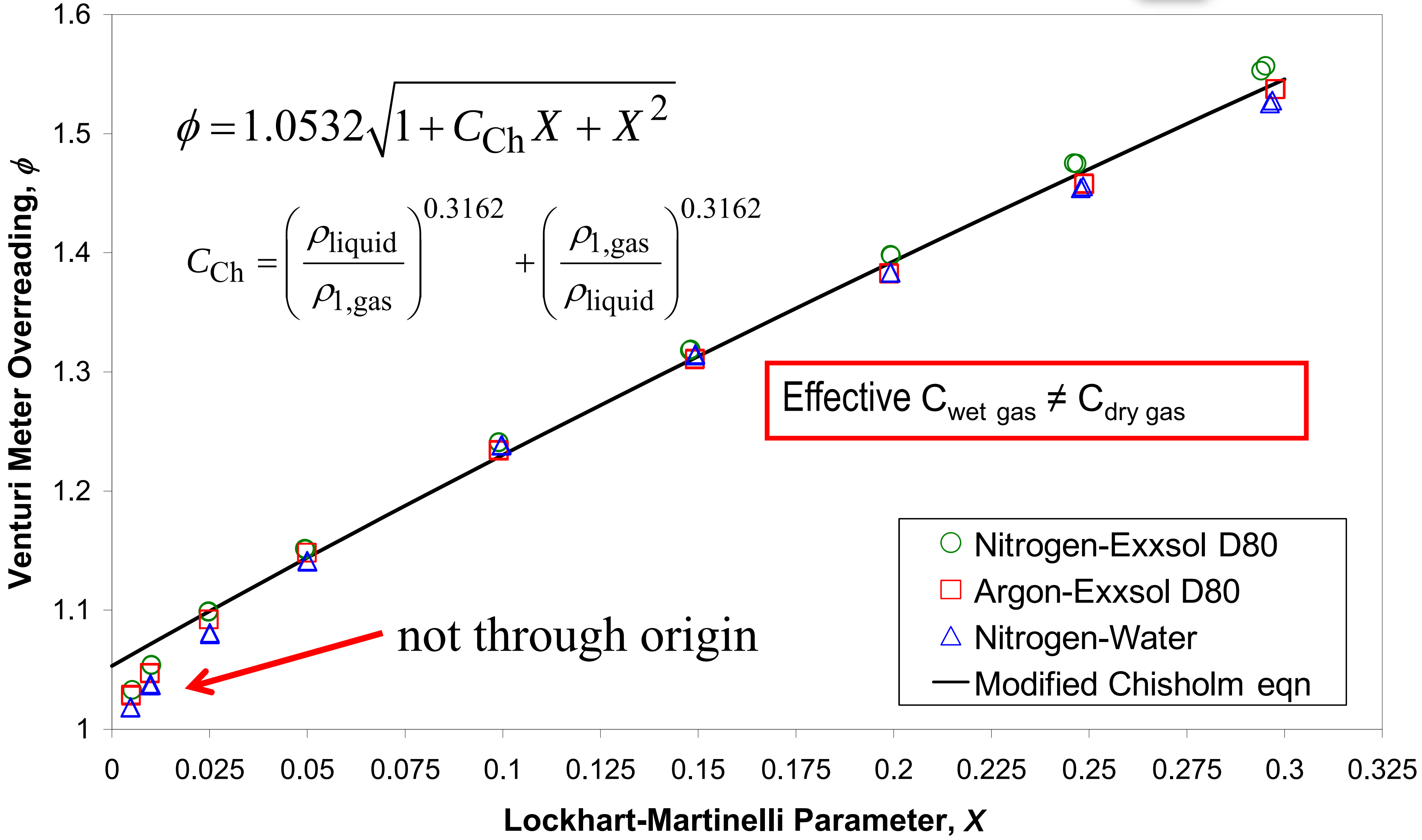


$$\phi = 1.0532\sqrt{1 + C_{Ch}X + X^2}$$

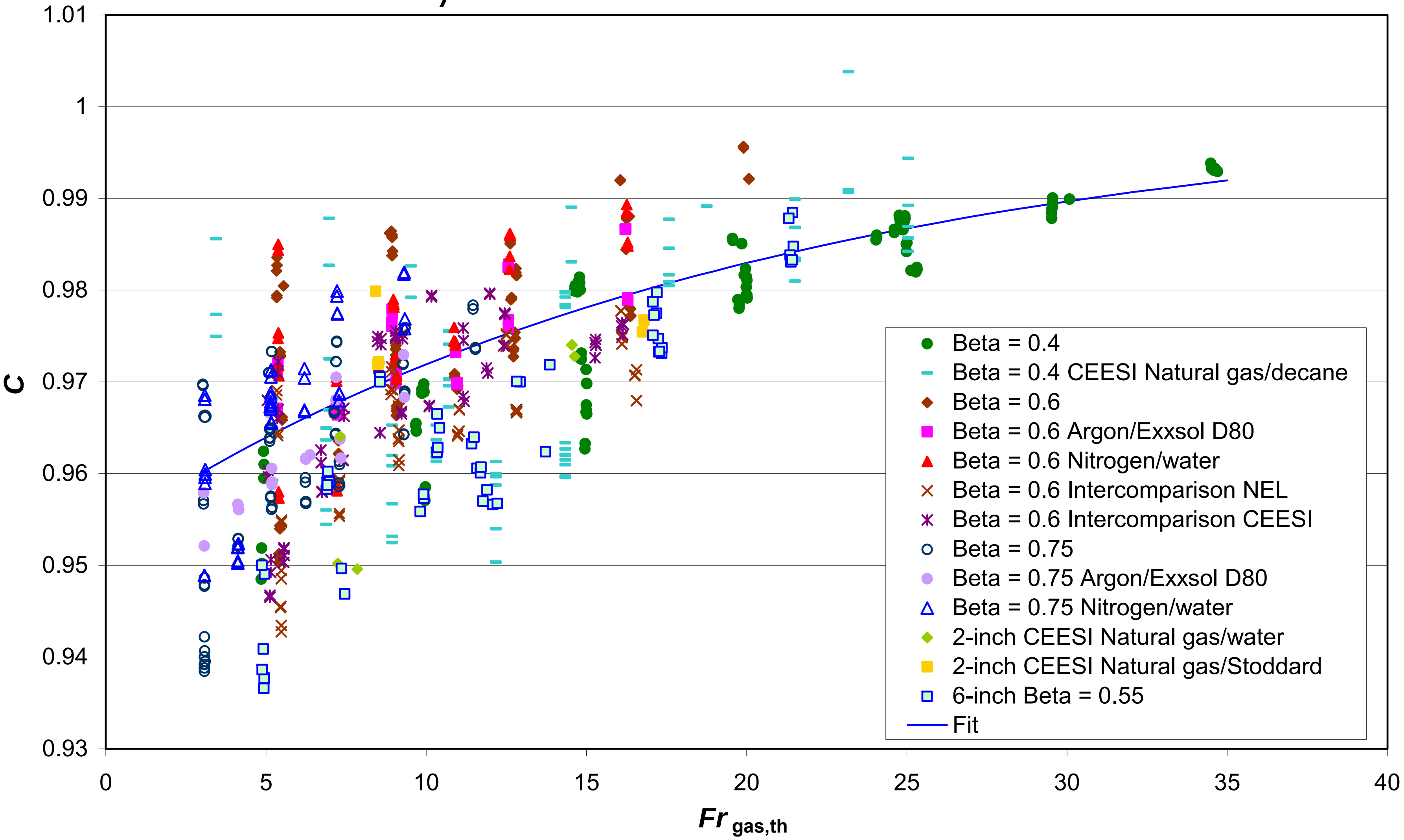
$$C_{Ch} = \left(\frac{\rho_{liquid}}{\rho_{1,gas}}\right)^{0.3162} + \left(\frac{\rho_{1,gas}}{\rho_{liquid}}\right)^{0.3162}$$

Effective $C_{wet\ gas} \neq C_{dry\ gas}$

not through origin

Wet-gas C based on 0.02 < *X* < 0.065

$$Fr_{\text{gas,th}} = \frac{Fr_{\text{gas}}}{\beta^{2,5}}$$



Determine new value for n and *C* using extended data set

$$n = \max(0.583 - 0.18\beta^2 - 0.578e^{-0.8Fr_{gas}/H}, 0.392 - 0.18\beta^2)$$

$$C = 1\text{-}0.0463\mathrm{e}^{-0.05Fr_{\mathrm{gas,th}}} \min\left(1, \sqrt{\frac{X}{0.016}}\right)$$

Limits of use

- $0.4 \le \beta \le 0.75$
- $0 < X \le 0.3$
- $3 < Fr_{\mathrm{gas,th}}$
- $0.02 < \rho_{\mathrm{gas}}/\rho_{\mathrm{liquid}}$
- $D \geq 50$ mm

$H =$ 1 for hydrocarbon
1.35 for water,
0.79 for very hot water

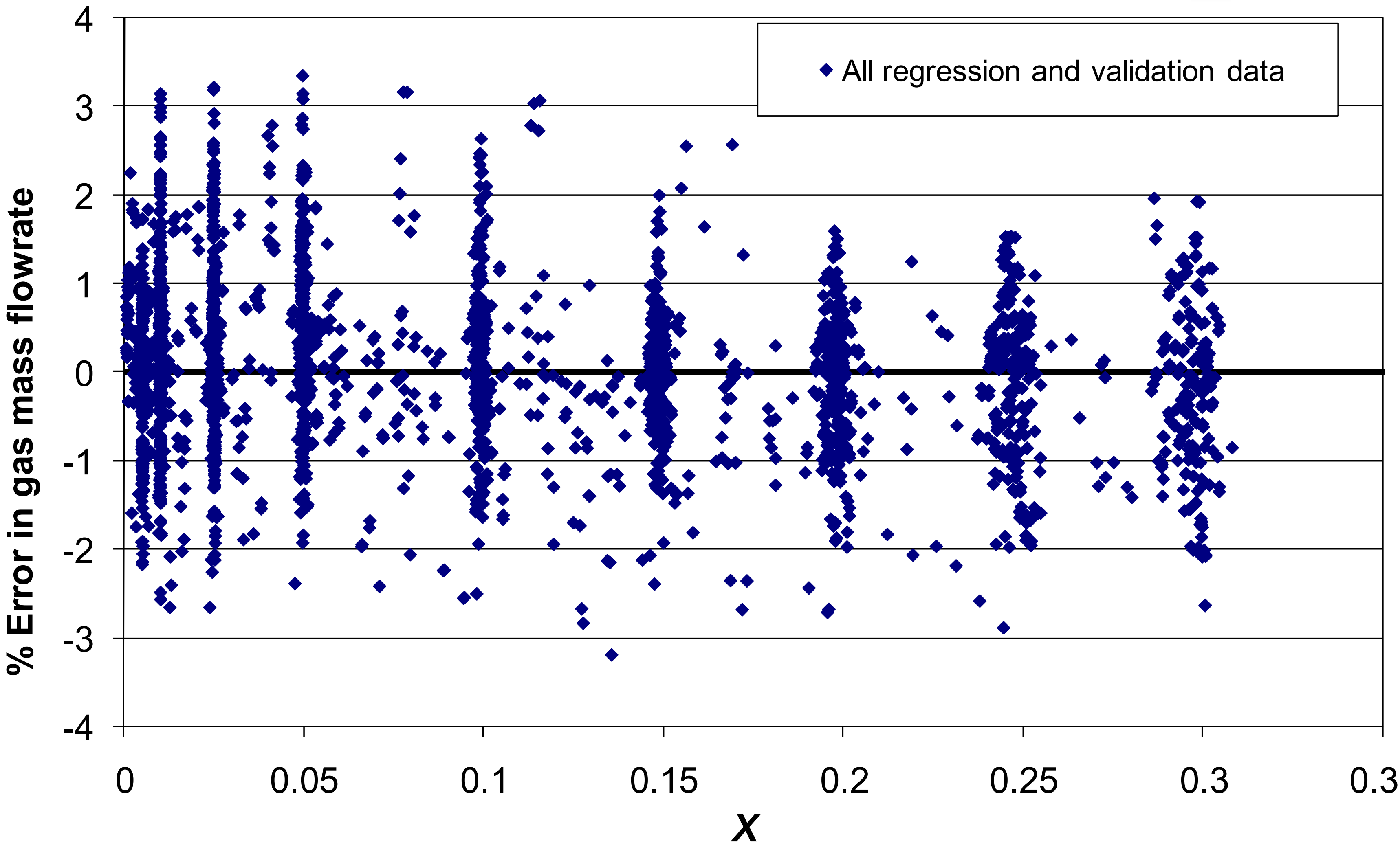
Use of wet-gas correlations for Venturi tubes

$$q_{m,\mathrm{gas}} = \frac{C}{\sqrt{1-\beta^4}}\varepsilon\frac{\pi}{4}d^2\frac{\sqrt{2\Delta p\rho_{1,\mathrm{gas}}}}{\phi}$$

$$\phi = \sqrt{1 + C_{\mathrm{Ch}}X + X^2} \qquad C_{\mathrm{Ch}} = \left(\frac{\rho_{\mathrm{liquid}}}{\rho_{1,\mathrm{gas}}}\right)^n + \left(\frac{\rho_{1,\mathrm{gas}}}{\rho_{\mathrm{liquid}}}\right)^n$$

If *C* is the dry-gas value this pattern is inadequate; there is an effective wet-gas discharge coefficient: Surprise 2

Wet-gas flow through Venturi tubes:
ISO/TR 11583 (NEL) equation: NEL database



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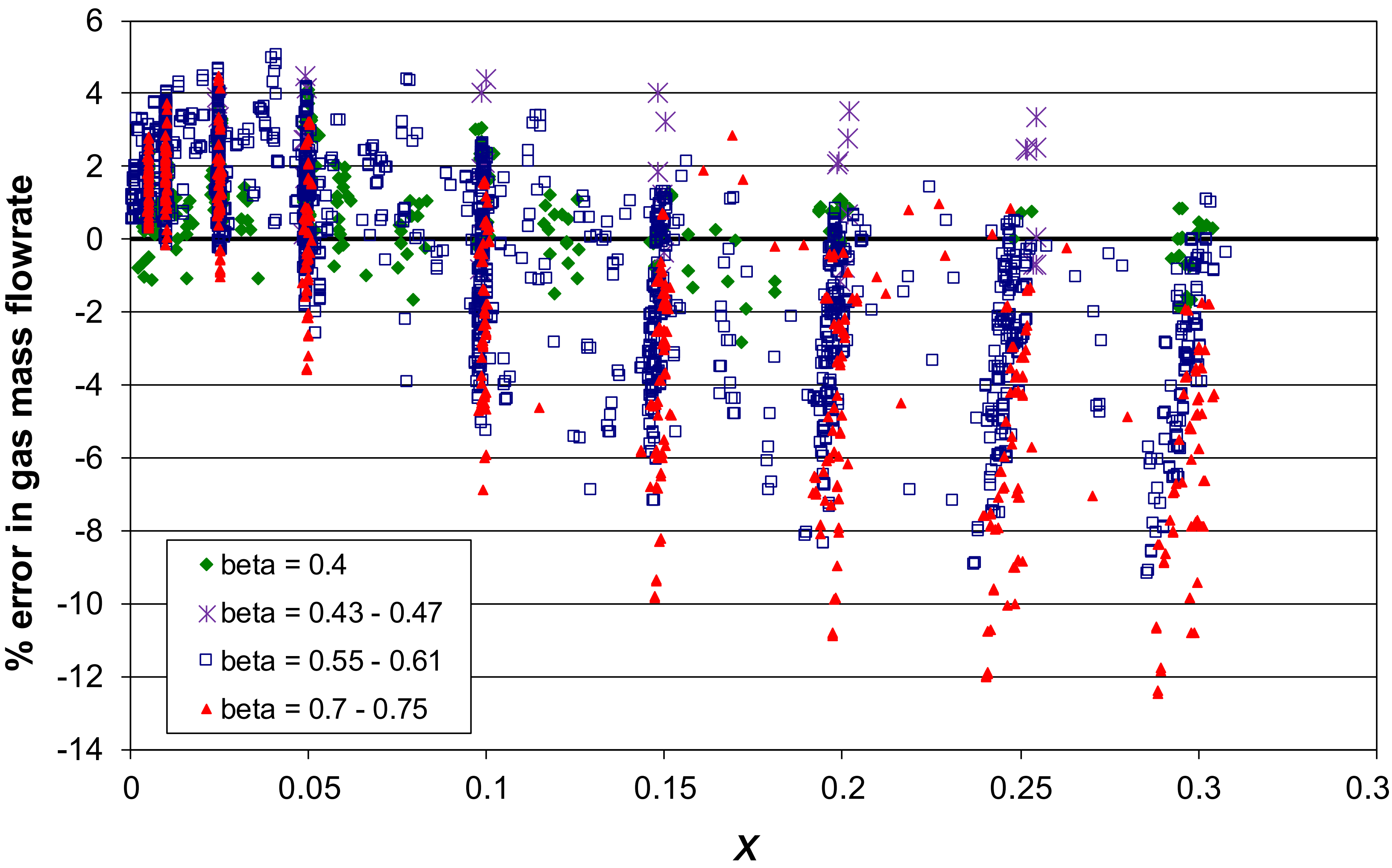
de Leeuw Equation: NEL database

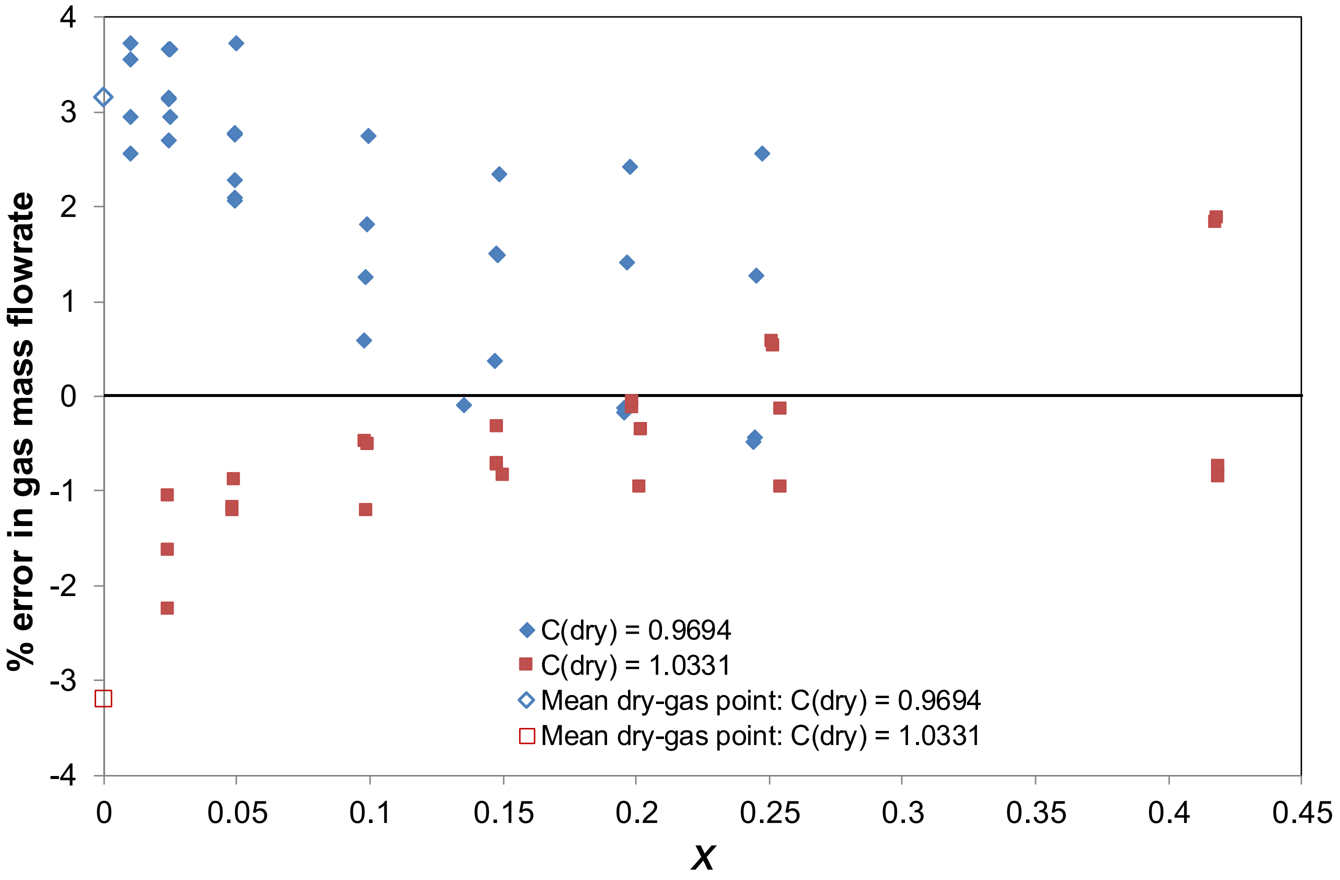


My theory

- In wet-gas flow there is a thin film of liquid on the wall.
- The dry-gas discharge coefficient no longer matters
- There is no resonance.

My theory

- In wet-gas flow there is a thin film of liquid on the wall.
- The dry-gas discharge coefficient no longer matters (there is no resonance).
- Errors for two Venturi tubes from the ISO/TR 11583 (NEL) Equation:

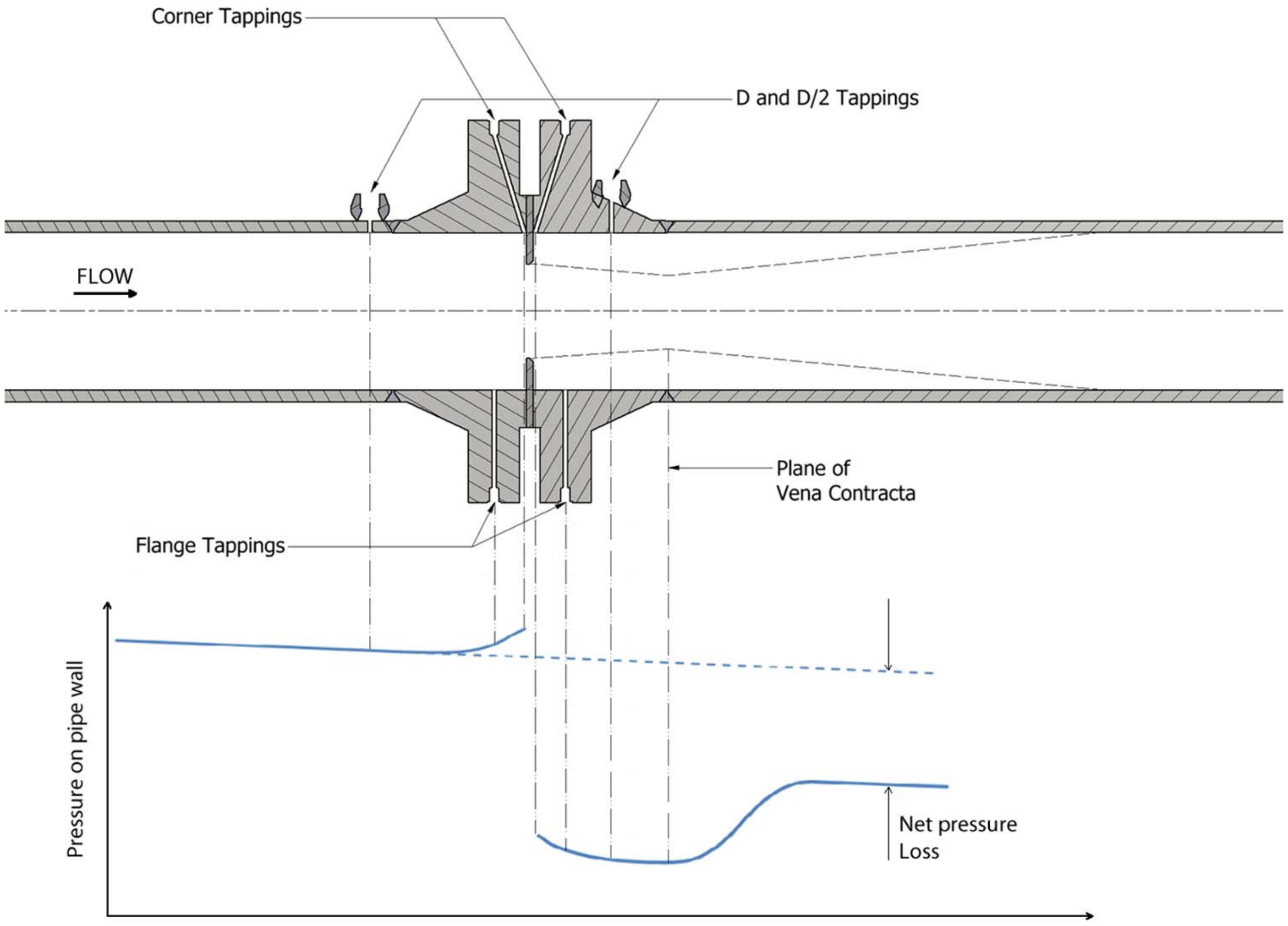


Surprise 3

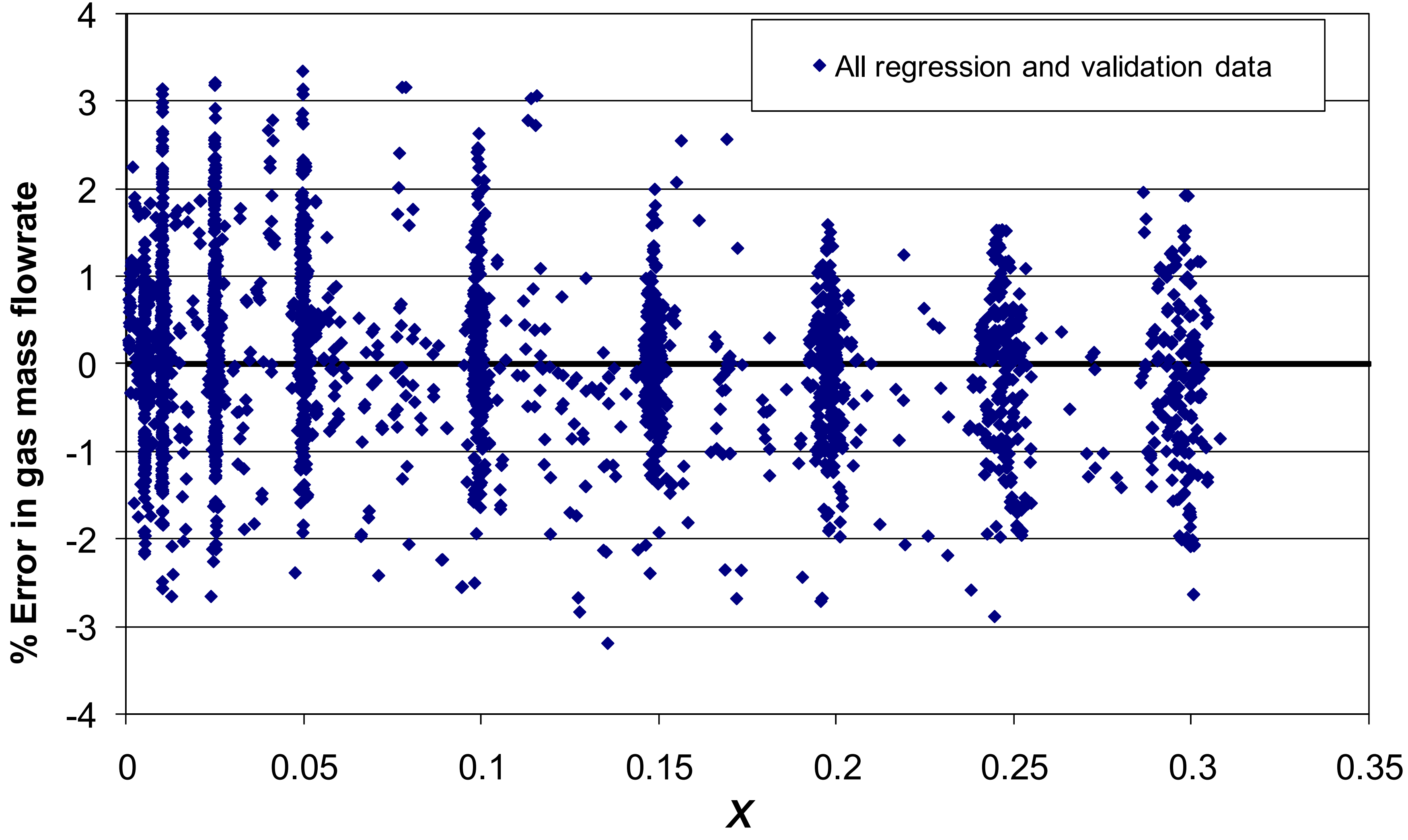
- Uncalibrated Venturi tube uncertainty
  - – Dry gas 3%
  - – Wet gas 2.5 to 3%

Wet gas

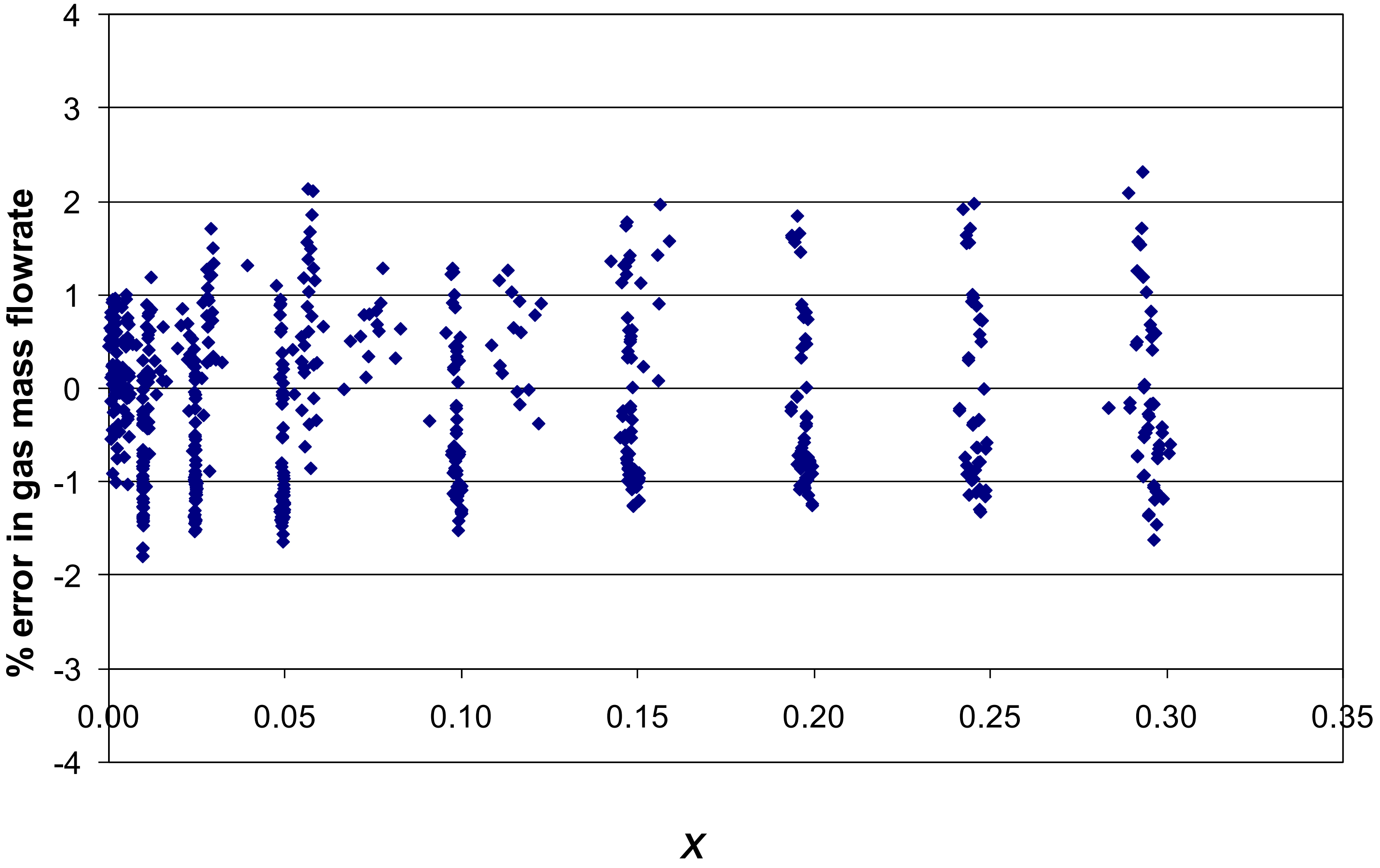
- Given an uncalibrated Venturi tube and an uncalibrated orifice plate, which has the lower uncertainty?



Wet-gas flow through Venturi tubes: ISO/TR 11583 (NEL) equation: NEL database



Wet-gas flow through orifice plates: ISO/TR 11583 (Steven) equation: NEL database



Wet gas: Surprise 4

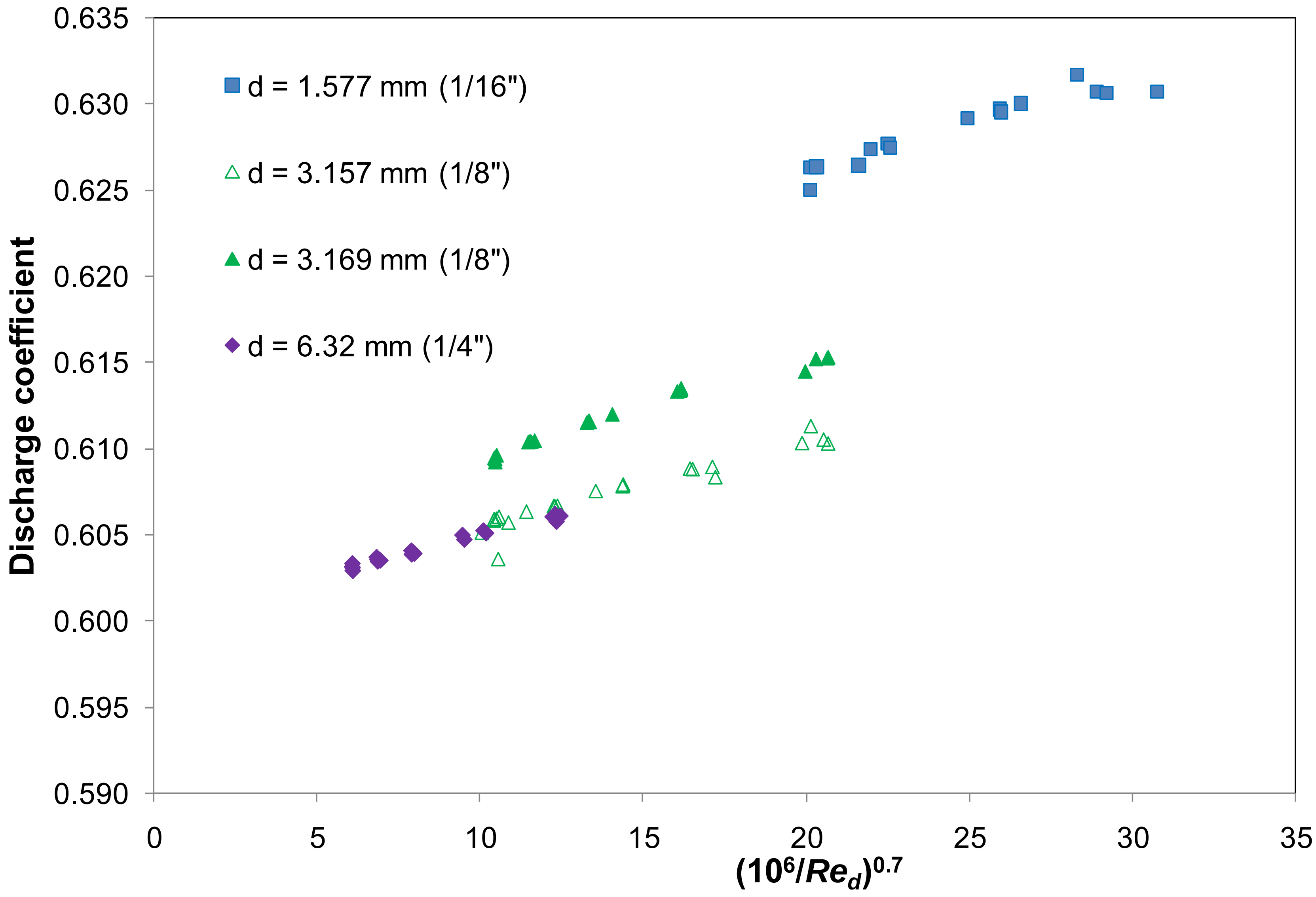
- For an uncalibrated Venturi tube and an uncalibrated orifice plate which has the lower uncertainty?

The orifice plate

Measurement over a range of 10000:1

- How can I measure natural gas in a 4” pipe as the flow declines over years over a flowrate range of 10000:1?

ConocoPhillips: 4” orifice run: spark-eroded plates



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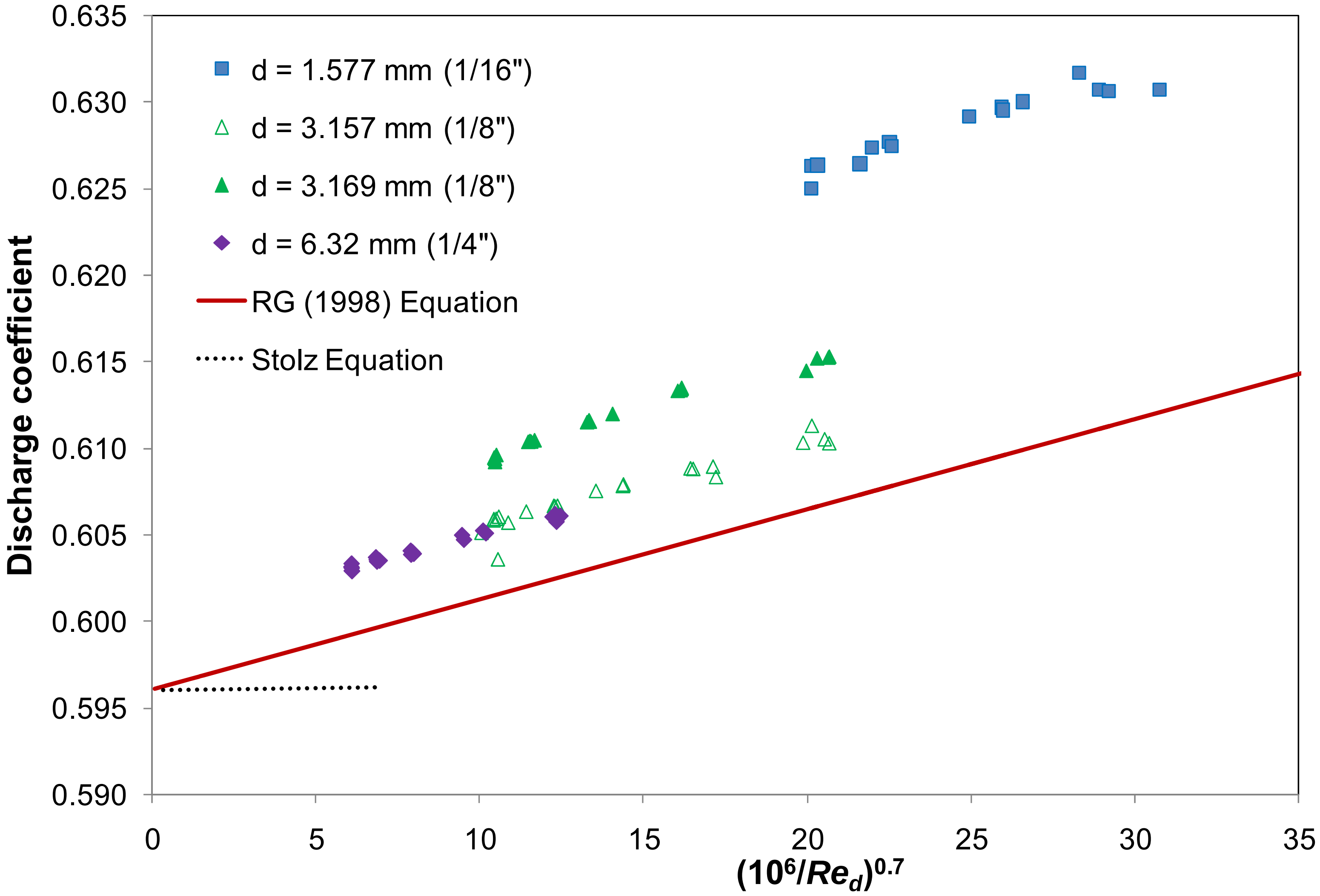
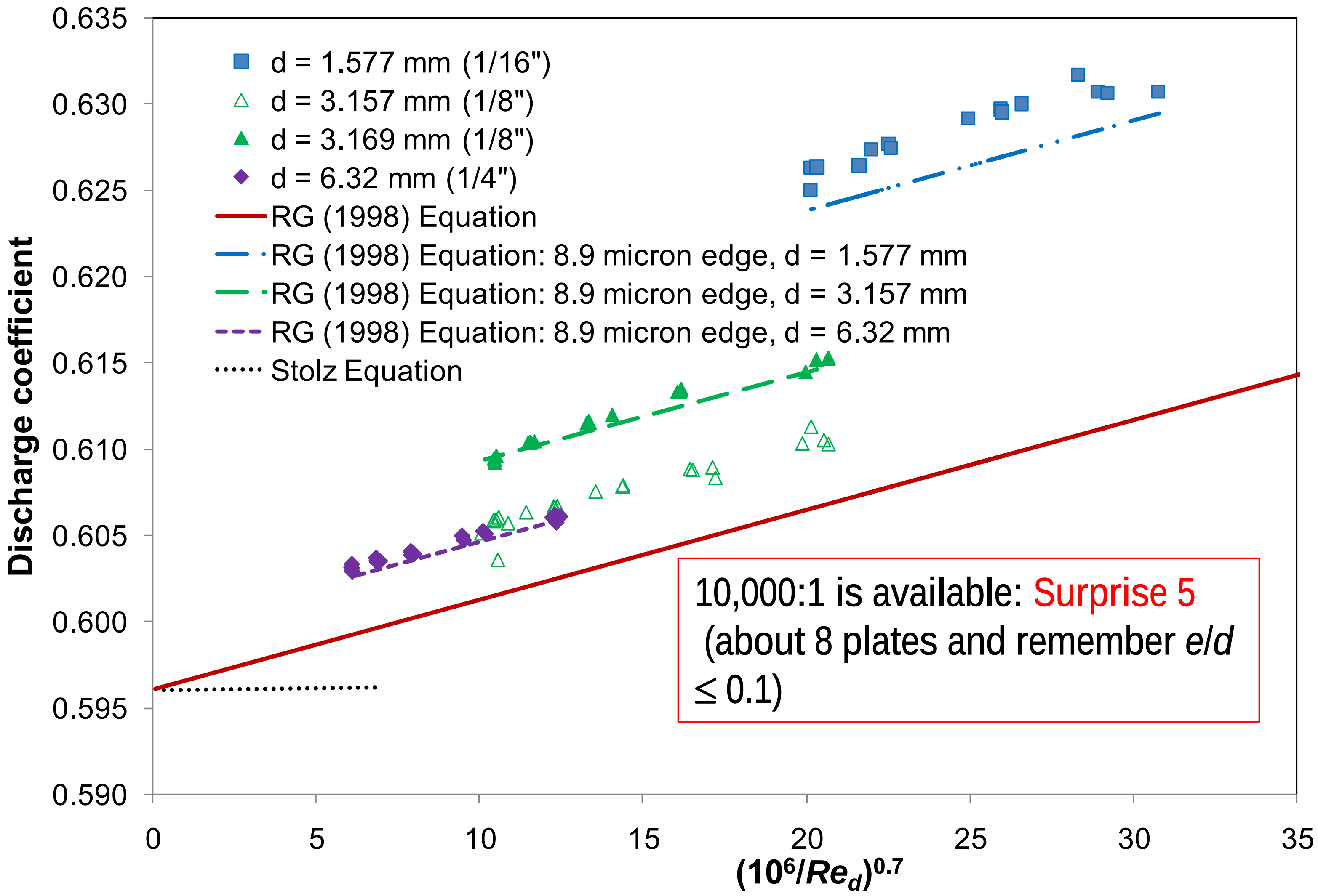


4” orifice run



10,000:1 is available: Surprise 5
(about 8 plates and remember *e*/*d* ≤ 0.1)

Discharge Coefficient, C

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

$$C = 0,5961 + 0,0261\,\beta^{2} - 0,216\beta^{8} + 0,000521\left(\frac{10^{6}\beta}{Re_D}\right)^{0,7}$$

$$+ (0,0188 + 0,0063A)\,\beta^{3,5}\left(\frac{10^{6}}{Re_D}\right)^{0,3}$$

$$A = (19000\beta/Re_D)^{0.8}$$

$$+ (0,043 + 0,080e^{-10L_1} - 0,123e^{-7L_1})\,(1-0,11A)\,\frac{\beta^{4}}{1-\beta^{4}}$$

$$- 0,031\,(M'_2 - 0,8\,M'^{1,1}_2)\,\beta^{1,3}$$

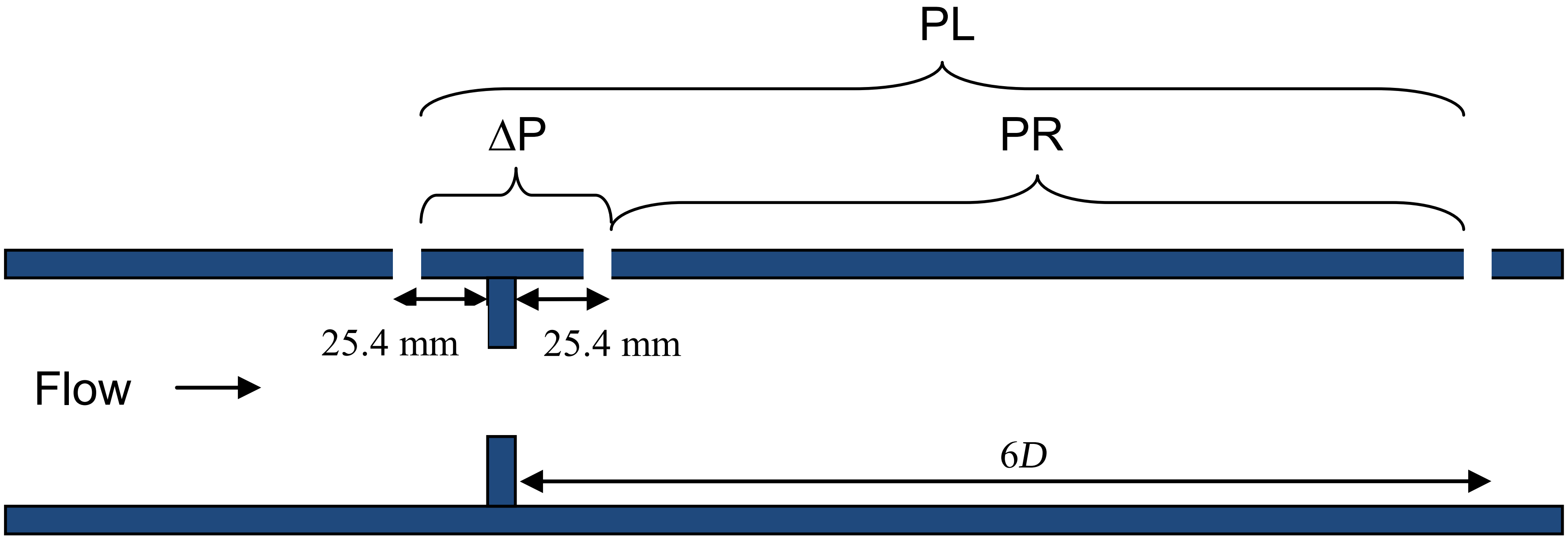
upstream and downstream tapping terms

It is 1988: will differential-pressure meters last another 30 years?

They have improved!

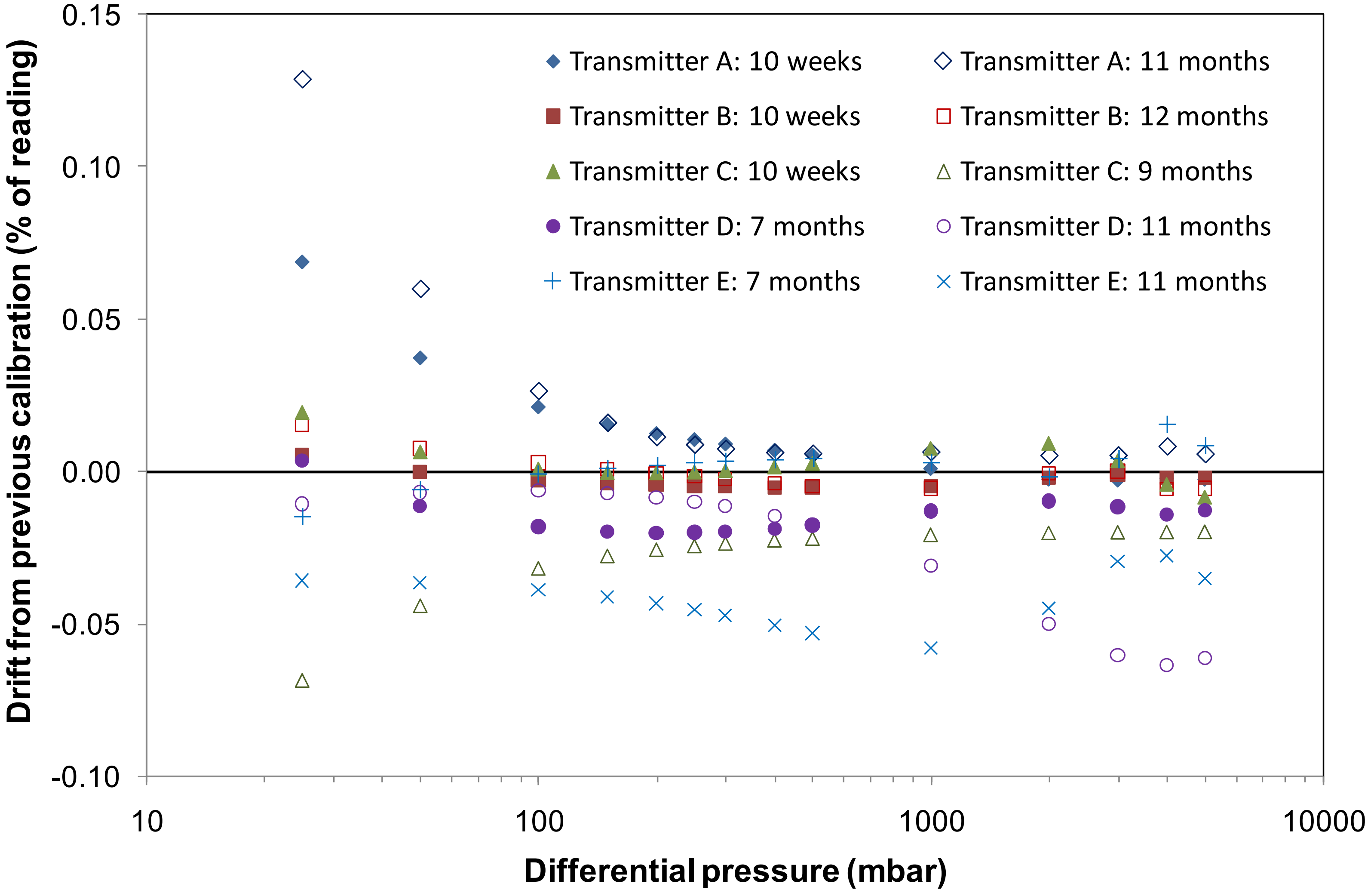
- Diagnostics
- Better dp transmitters
- Better standards

Diagnostics

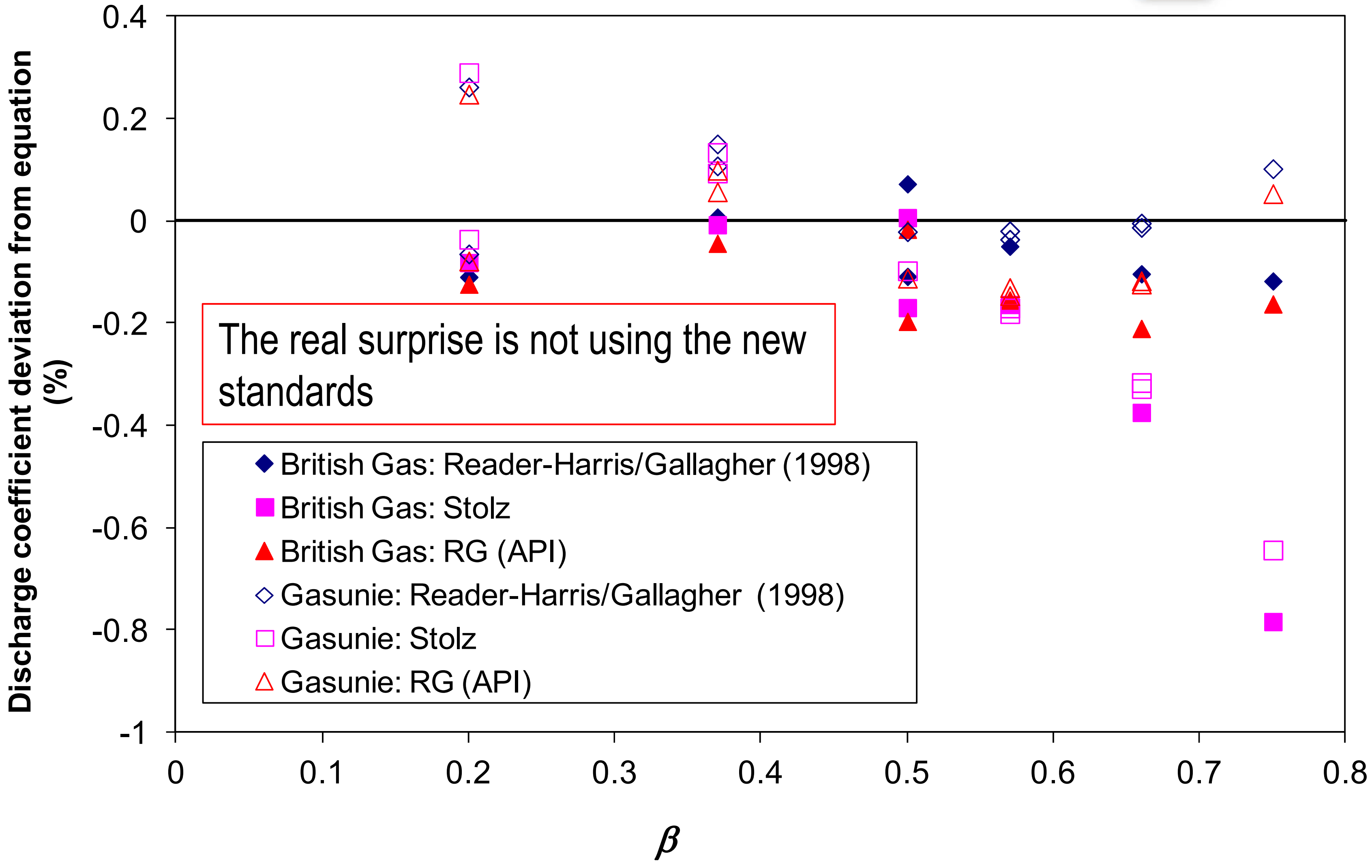


- Use PL/ΔP to show that a meter is out of specification, even to correct a measurement
- ‘Prognosis’ (DP Diagnostics)

Differential-pressure transmitters (Yokogawa EJX110A)



Better standards: 24” gas data: flange tappings



The real surprise is not using the new standards

Scope of this talk

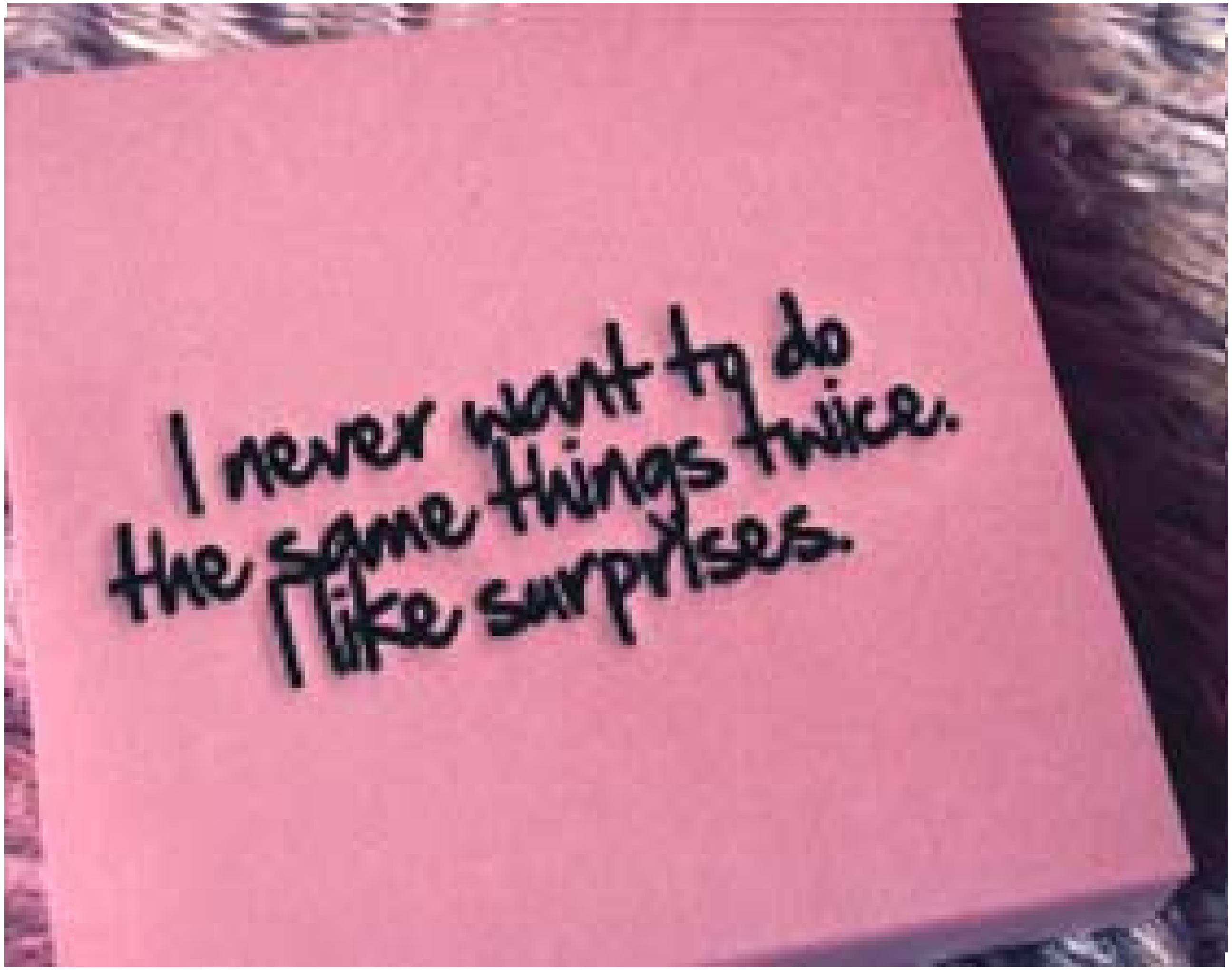
- 1 Difficult Reynolds numbers
  - 1.1 Heavy oil
  - 1.2 LNG
- 2 Difficult installations
  - 2.1 Emissions
  - 2.2 Flare gas
- 3 Difficult fluids
  - 3.1 Carbon dioxide
  - 3.2 Wet gas flow
    - Venturi tubes
    - Orifice plates
    - There are surprises

Even for flow metrologists…

- There are surprises
  - Discharge coefficients – greater than 1
  - Wet gas – orifice plates can perform very well
    - wet-gas Venturi tubes have a different effective discharge coefficient
  - 10000:1 – use a set of orifice plates
  - Pitot tube standards

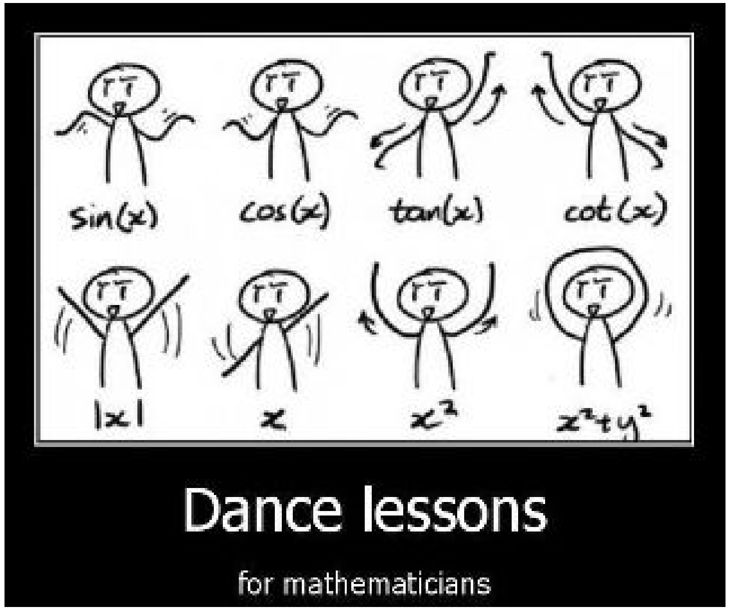
I never want to do
the same things twice.
I like surprises.

Written by a metrologist?



What do others think when at a party you say ‘I’m a metrologist?’

- Someone who makes minor and dull improvements on something that is well known?



Why are we surprised?

Why are we surprised?

- Too simple a physical model
  - ‘The Venturi-tube discharge coefficient just describes the friction loss’
  - ‘A single power of Reynolds number will be sufficient for an orifice plate’

Why are we surprised?

- Too simple a physical model
- Ignorance of other work
  - Static hole error
  - Better differential-pressure transmitters

Why are we surprised?

- Too simple a physical model
- Ignorance of other work
- False assumptions
  - Extrapolation will be OK
  - The discharge coefficient is the discharge coefficient
  - Damming up must be bad for wet-gas flow through orifice plates
  - Diagnostics cannot be used for differential-pressure meters
  - New meters must be better

Why are we surprised?

- Too simple a physical model
- Ignorance of other work
- False assumptions
- Standards that need to be improved
  - Pitot tubes for emissions

Acknowledgments

- The Flow Programme of UK BEIS
- NMIJ and the Metrology Club

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