Orifice plate pressure loss ratio: theoretical work in compressible flow and experimental work in CO_2

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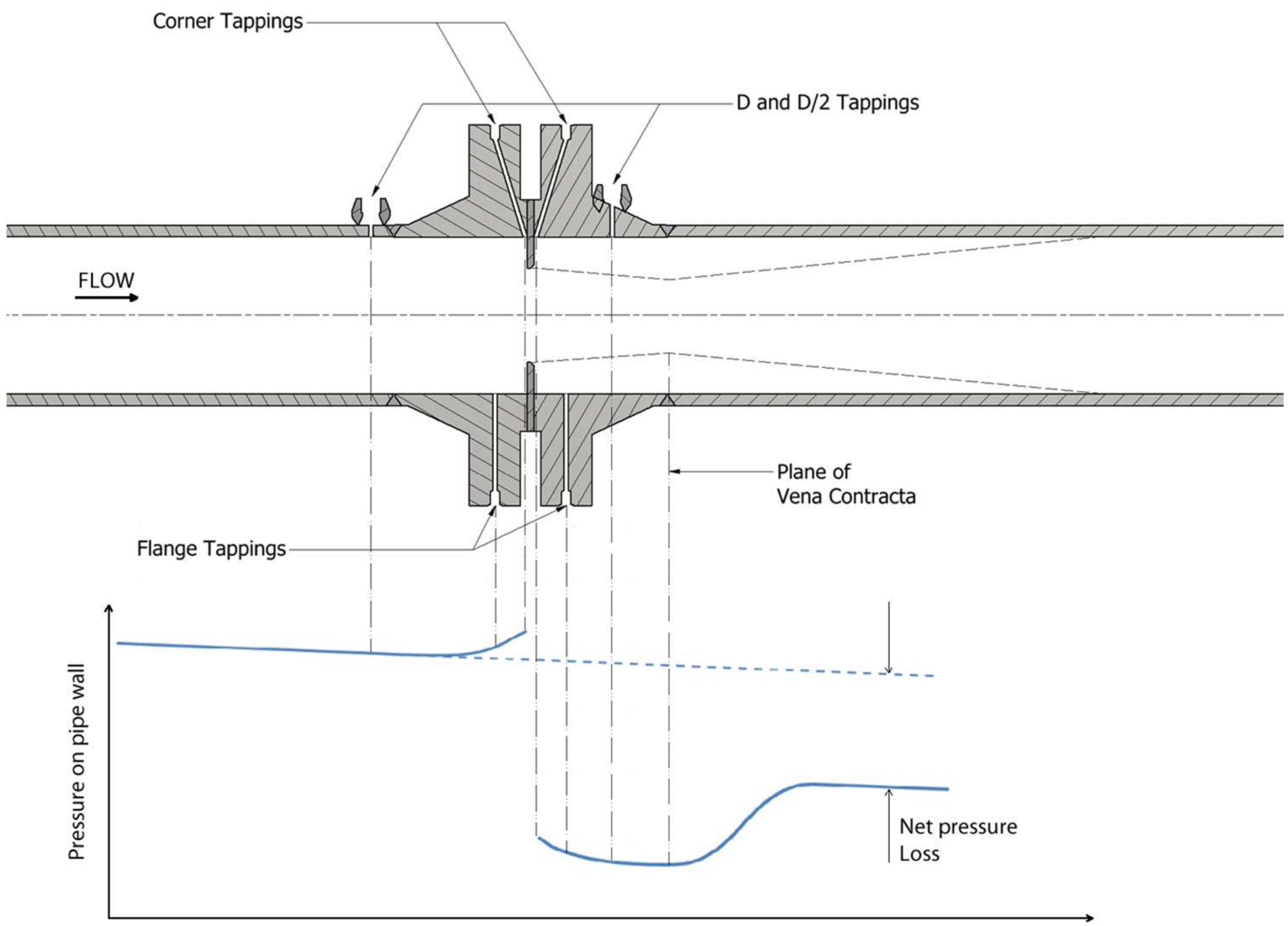
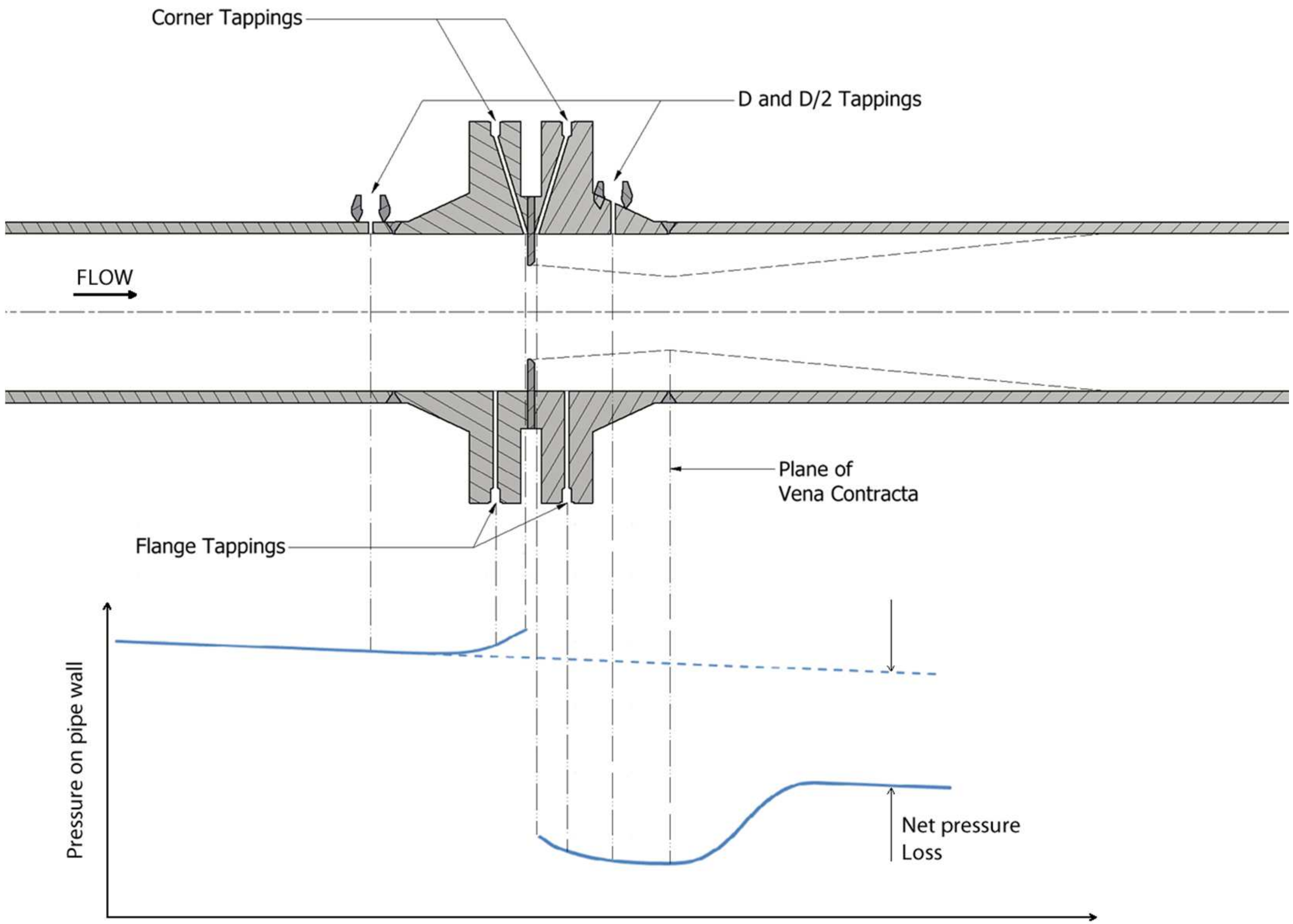
- **Diagnostics are not limited to ultrasonic meters**



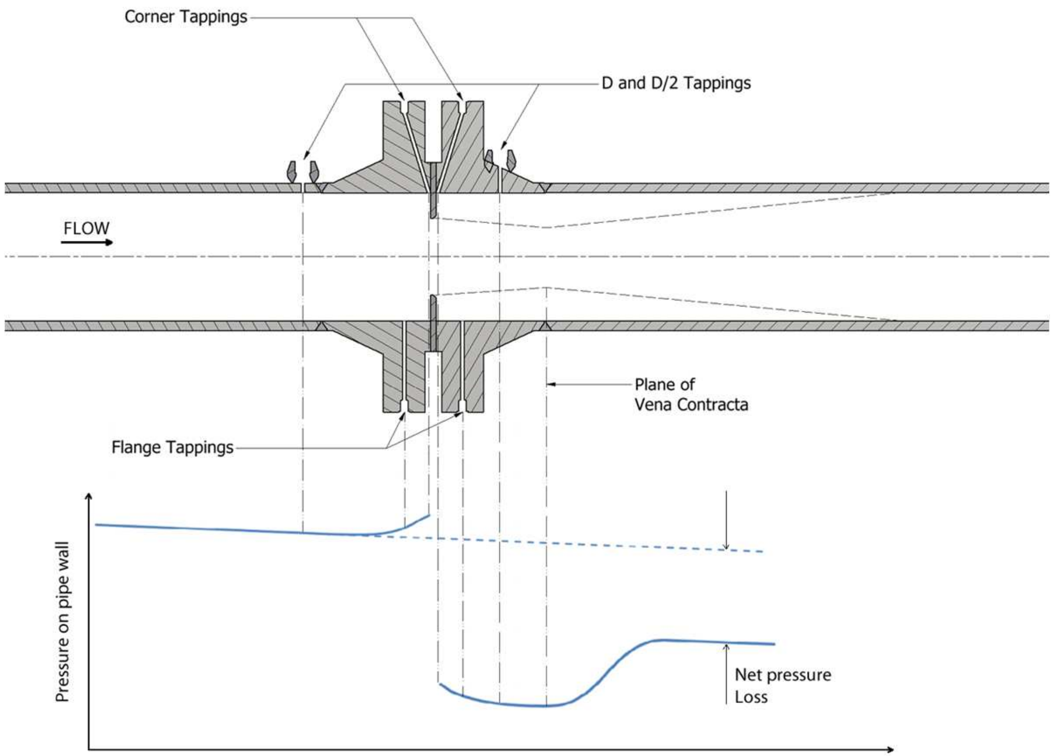
Diagnostic parameters

- **Corner pressure rise/dp (Martin, 1986), Pressure loss/dp (Steven, 2008)**



Diagnostics

- The pressure loss ratio (pressure loss/dp) is required for the design of orifice metering systems
- The measured pressure loss ratio is used in the orifice meter validation system developed by Steven of DP Diagnostics [3-7]



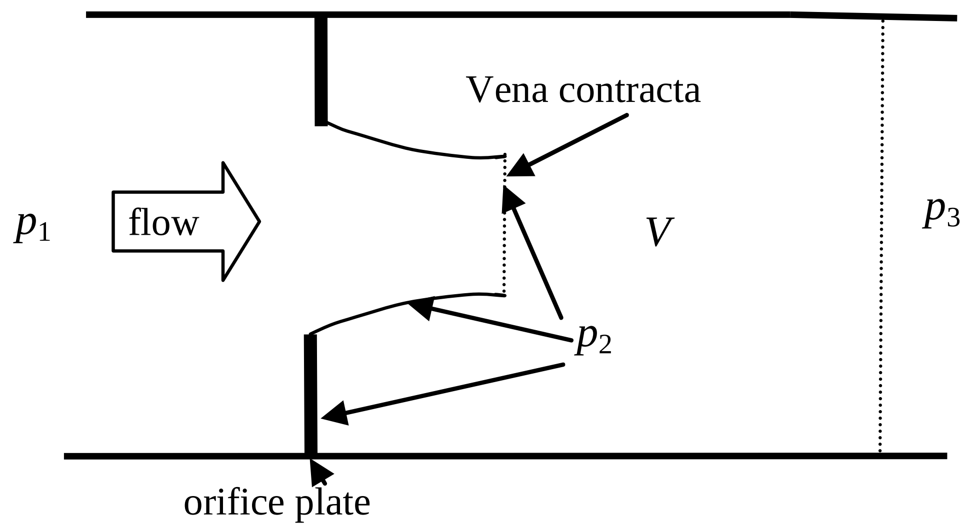
Can we predict the pressure loss?

- **Pressure loss ratio (5.4.1 of ISO 5167-2:2003) from Urner**

$$\frac{\Delta\varpi}{\Delta p} = \frac{\sqrt{1-\beta^4(1-C^2)} - C\beta^2}{\sqrt{1-\beta^4(1-C^2)} + C\beta^2}$$

- **This is for incompressible flow**

Can we predict the pressure loss in compressible flow?



Momentum theorem

$$\rho \frac{Du_i}{Dt} = \rho F_i + \frac{\partial \sigma_{ij}}{\partial x_j}$$

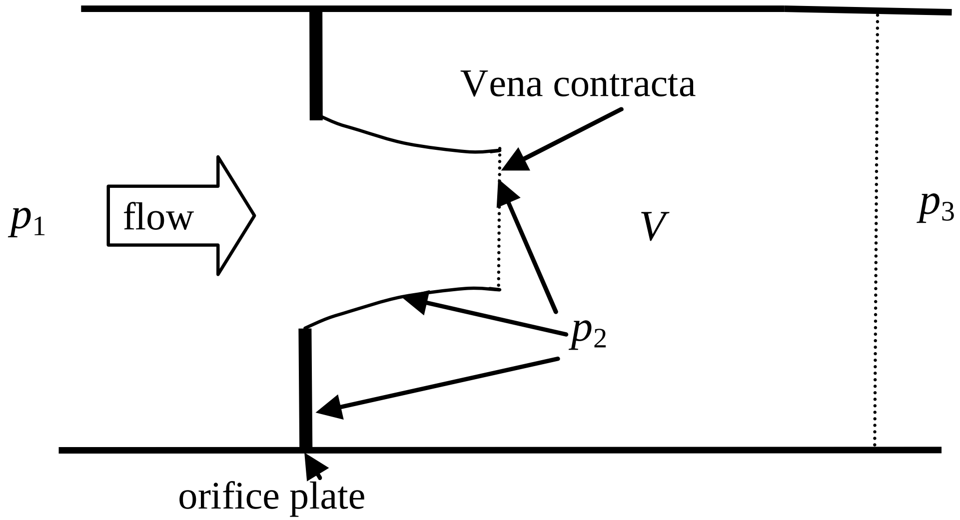
Integrate over *V*

$$\iiint_V \frac{\partial (u_i \rho)}{\partial t} dV = -\iint_A \rho u_i u_j n_j dA + \iiint_V F_i \rho dV + \iint_A \sigma_{ij} n_j dA$$

Gives (with steady flow and $\sigma_{ij} = -p\,\delta_{ij}$)

$$0 = \rho_2 A_c u_c^2 - \rho_3 A_p u_3^2 - p_3 A_p + p_2 A_p$$

Can we predict the pressure loss in compressible flow?



Bernoulli's theorem

$$\frac{\kappa}{\kappa-1}\frac{p_1}{\rho_1}+\frac{1}{2}u_1{}^2=\frac{\kappa}{\kappa-1}\frac{p_2}{\rho_2}+\frac{1}{2}u_c{}^2$$

Orifice equation

$$u_1=\frac{\beta^2 C\varepsilon}{\sqrt{1-\beta^4}}\sqrt{\frac{2\left(p_1-p_2\right)}{\rho_1}}$$

Mass conservation

$$A_p\rho_1 u_1=A_c\rho_2 u_c=A_p\rho_3 u_3$$

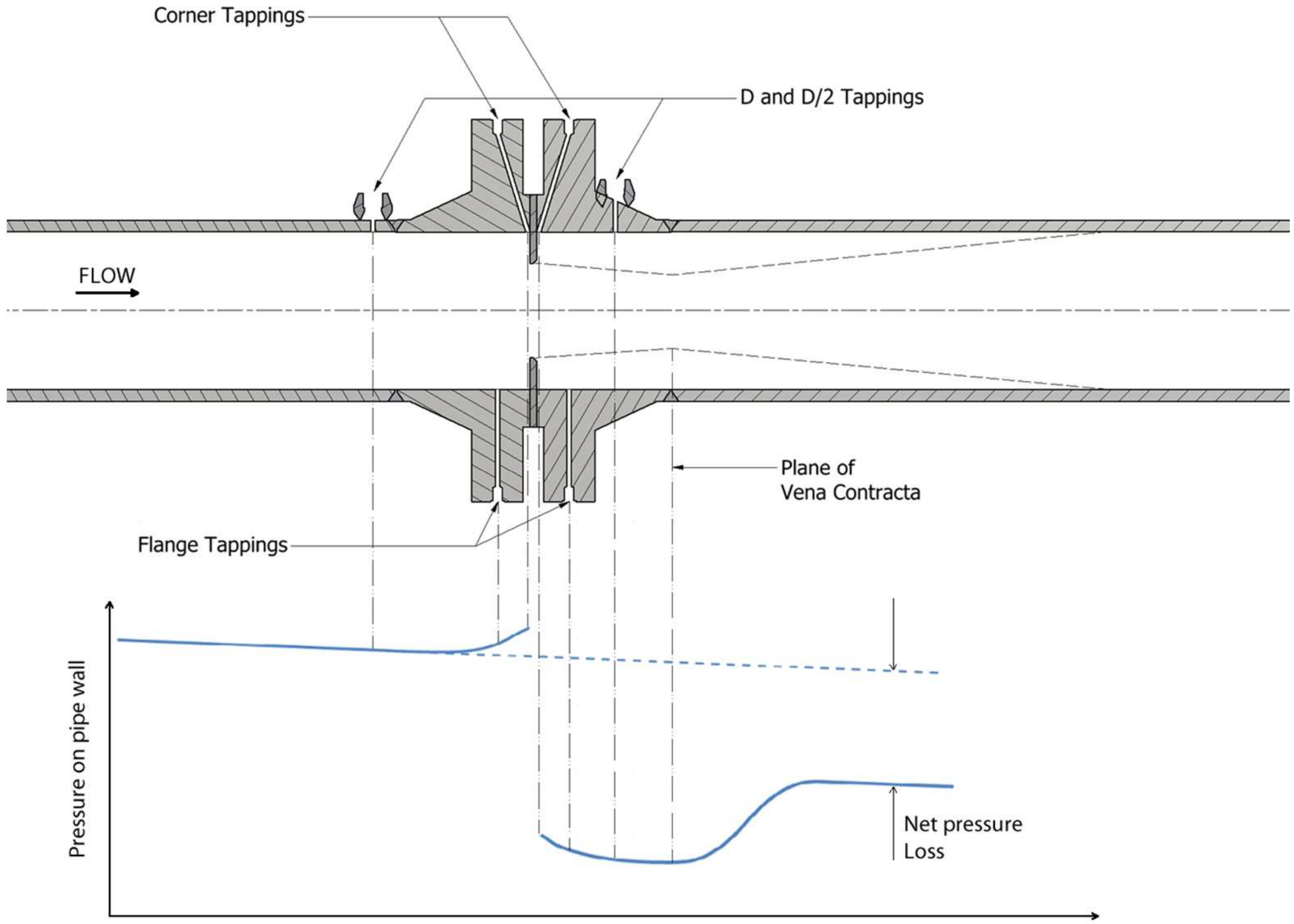
- The equations do not have a closed-form solution, but can be solved by iteration.
- They give $\frac{p_1 - p_3}{p_1 - p_2}$
  - p_1 is the pressure c. 1D upstream of the orifice plate
  - p_2 is the pressure c. D/8 downstream of the orifice plate
  - p_3 is the pressure c. 6D downstream of the orifice plate
- For diagnostics we require $\frac{p_{up} - p_3}{p_{up} - p_{down}}$
  - p_{up} is the pressure at the upstream tapping
  - p_{down} is the pressure at the downstream tapping

Measured PLR v Actual PLR (with downstream tapping at D/8)

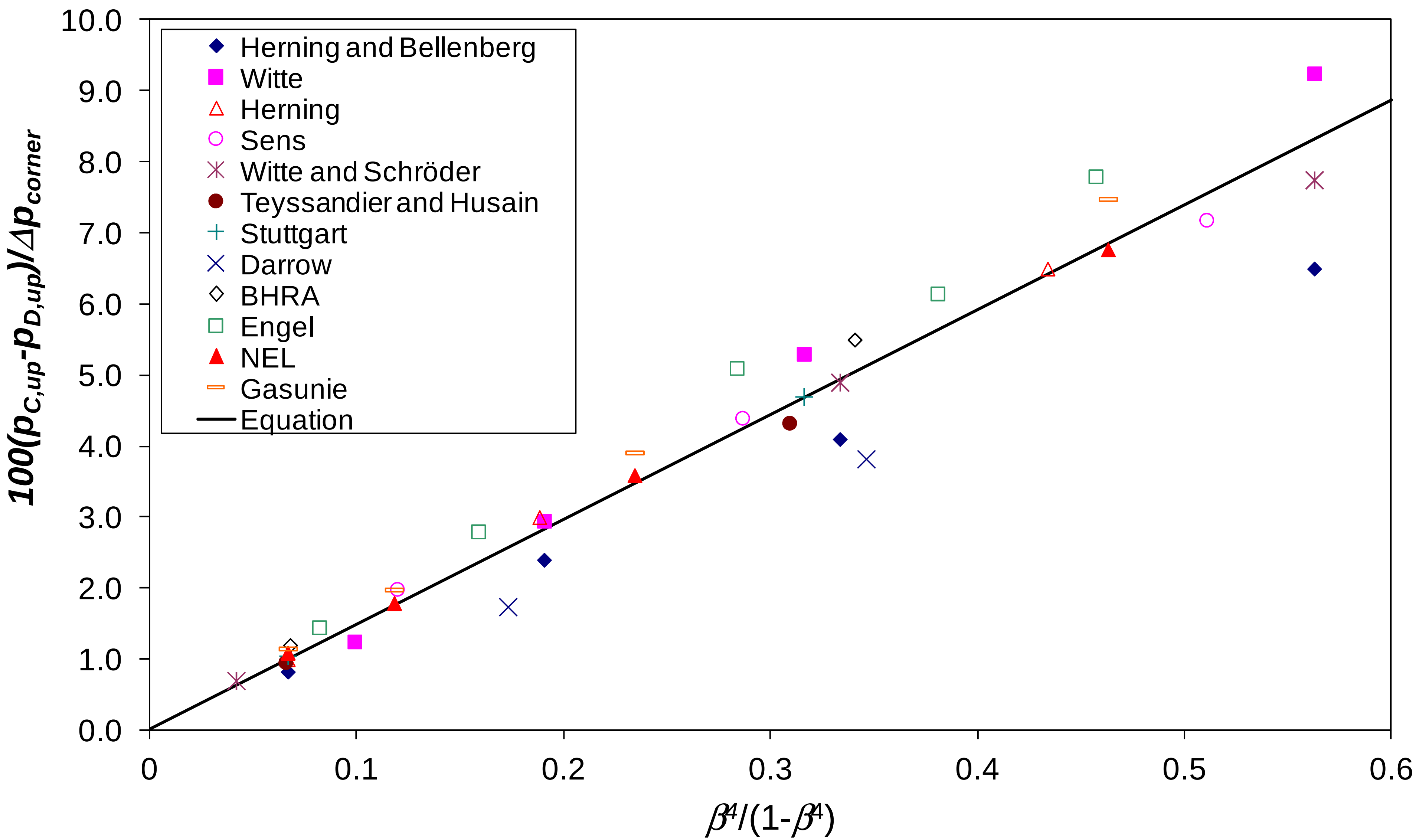
flow measurement services

- $$\Delta\varpi = \Delta\varpi_{measured} - p_{rise}$$
  $$\Delta p_{Dtodn} = \Delta p_{measured} - p_{rise}$$

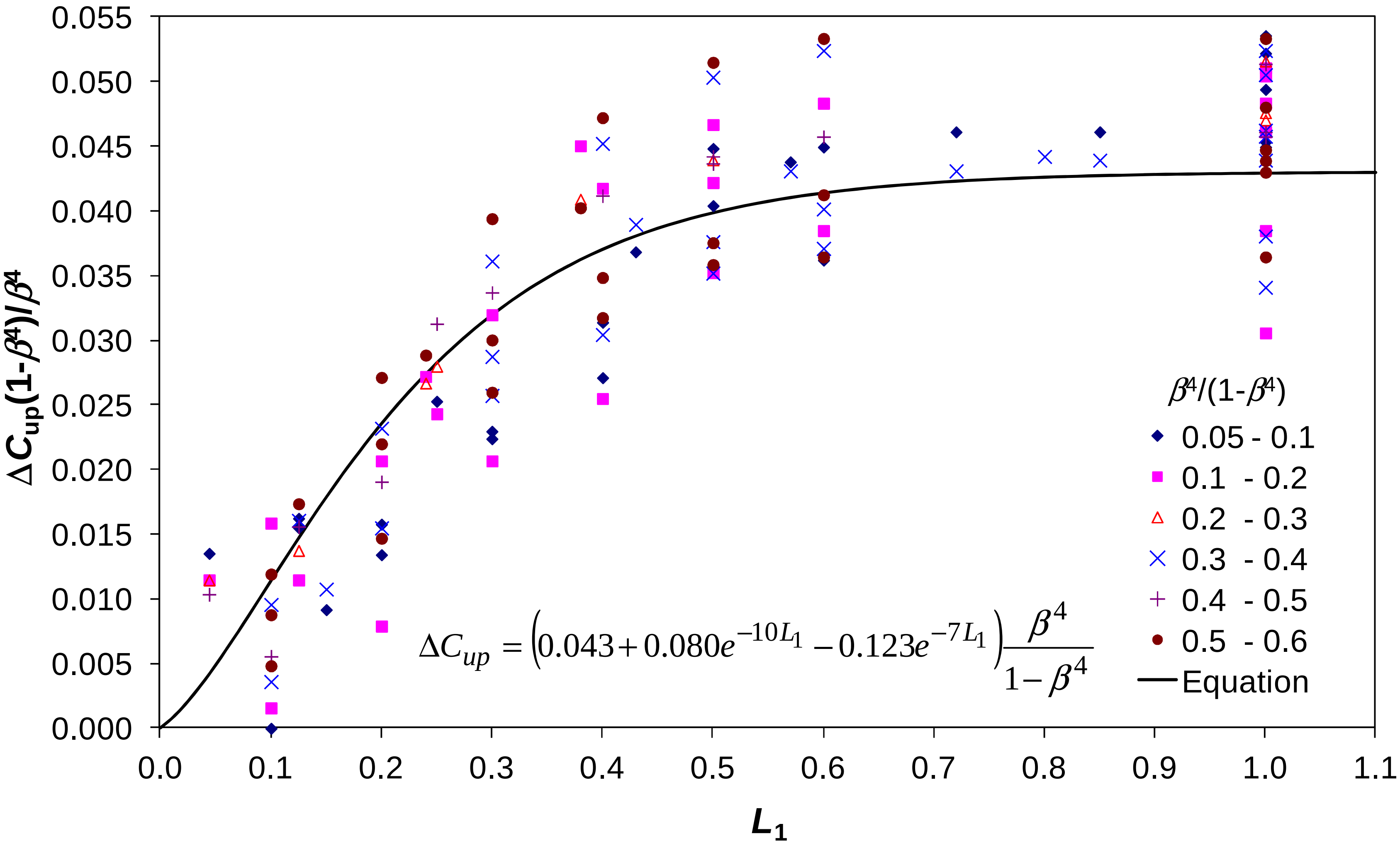
$$\frac{\Delta\varpi_{measured}}{\Delta p_{measured}} = \frac{\Delta\varpi + p_{rise}}{\Delta p_{Dtodn} + p_{rise}} = \frac{\dfrac{\Delta\varpi}{\Delta p_{Dtodn}} + \dfrac{p_{rise}}{\Delta p_{Dtodn}}}{1 + \dfrac{p_{rise}}{\Delta p_{Dtodn}}}$$



Pressure rise into the corner

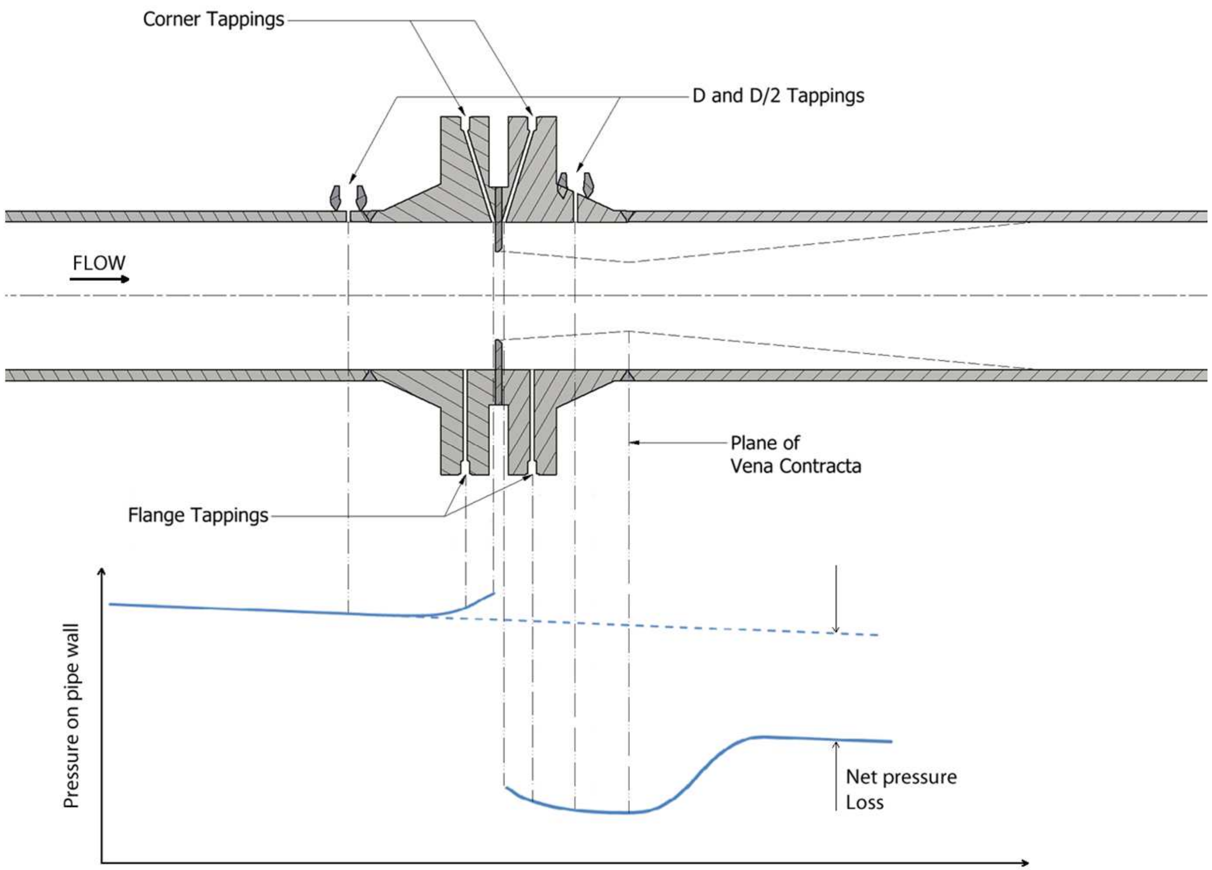


Pressure rise into the corner



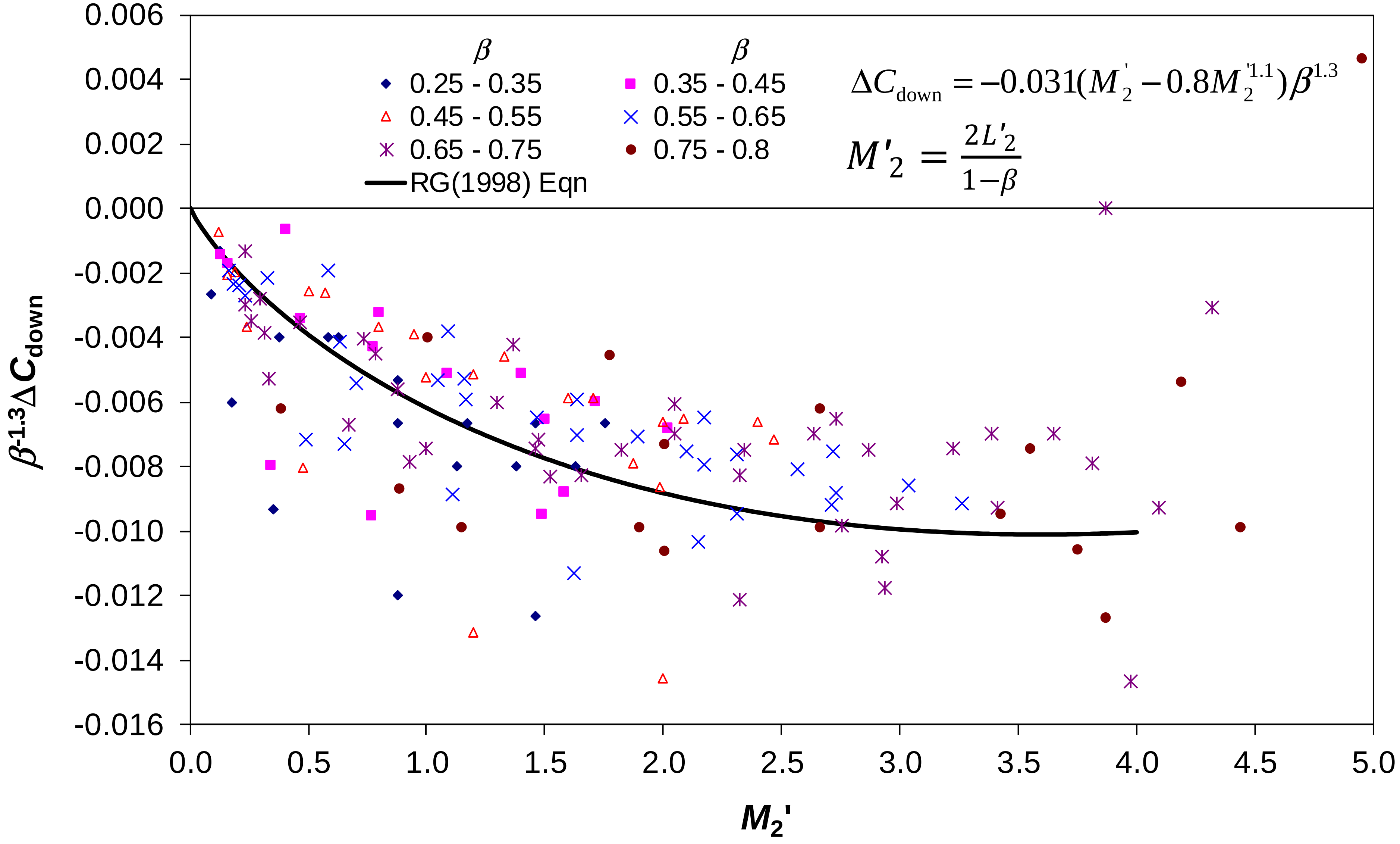
$$\frac{p_{rise}}{\Delta p_{Dtodn}} \approx \frac{2}{0.6} 1.033\left(0.123e^{-7L_1} - 0.080e^{-10L_1} - 0.00011\right)\frac{\beta^4}{1-\beta^4}$$

- **Take account of downstream tapping location**



- **Take account of friction loss: assume that due to a pipe of length $4.5\beta D$ of friction factor $\lambda = 0.0125$**

Pressure profile downstream of the orifice plate



Incompressible equation (with slight modification to friction term)

flow measurement services

$$\frac{\Delta\overline{\omega}_{meas}}{\Delta p_{flange}} = \frac{\dfrac{p_{rise}}{\Delta p_{DandP}} + \dfrac{\sqrt{1\text{-}\beta^4\left(1\text{-}C_{DandP}{}^2\right)} - C_{DandP}\beta^2}{\sqrt{1\text{-}\beta^4\left(1\text{-}C_{DandP}{}^2\right)} + C_{DandP}\beta^2}}{1+\dfrac{p_{rise}}{\Delta p_{DandP}} - \dfrac{\Delta p_{fdowntoP}}{\Delta p_{DandP}}}$$

$$+\frac{0.05625\beta^5 C_{DandP}{}^2\varepsilon^2}{1\text{-}\beta^4}$$

where

$$\frac{p_{rise}}{\Delta p_{DandP}} = \frac{2}{C_{DandP}}\frac{14.78}{14.30}\left(0.123\mathrm{e}^{-7L_1}\text{-}0.080\mathrm{e}^{-10L_1}\text{-}0.00011\right)\frac{\beta^4}{1\text{-}\beta^4}$$

$$\frac{\Delta p_{fdowntoP}}{\Delta p_{DandP}} = \frac{2}{C_{DandP}}0.031(M'_{2P}\text{-}0.8M'_{2P}{}^{1.1}\text{-}(M'_2\text{-}0.8M'_2{}^{1.1}))\beta^{1.3}$$

Fitting the calculations

- β = 0.2, 0.4, 0.6 and 0.75
- Δp = 50, 100, 200, 500, 1000 mbar
- p = 4, 13.3 and 22 bar for CO_2 and p = 4, 15 and 60 bar for nitrogen
- 8" (200 mm) flange tappings

The previous equation was fitted by these data (standard deviation 0.00021) with an additional term $+0.52\,(1-\varepsilon)\kappa\beta^{2.2}$

Test using calculated values with an ideal gas (Joule-Thomson coefficient = 0):

- β = 0.2, 0.4, 0.6 and 0.75
- Δp = 50, 100, 200, 500, 1000 mbar
- κ = 1.2, 1.4 and 1.67
- p = 4, 13.3, 22 and 60 bar
- 100 mm, 200 mm and 400 mm flange tappings

The standard deviation was 0.00024

Compressible equation

$$\frac{\Delta\overline{\omega}_{meas}}{\Delta p_{flange}} = \frac{\dfrac{p_{rise}}{\Delta p_{DandP}} + \dfrac{\sqrt{1-\beta^4\left(1-C_{DandP}{}^2\right)} - C_{DandP}\beta^2}{\sqrt{1-\beta^4\left(1-C_{DandP}{}^2\right)} + C_{DandP}\beta^2}}{1+\dfrac{p_{rise}}{\Delta p_{DandP}} - \dfrac{\Delta p_{fdowntoP}}{\Delta p_{DandP}}}$$

$$+\frac{0.05625\beta^5 C_{DandP}{}^2\varepsilon^2}{1-\beta^4} \quad +0.52\,(1-\varepsilon)\kappa\beta^{2.2}$$

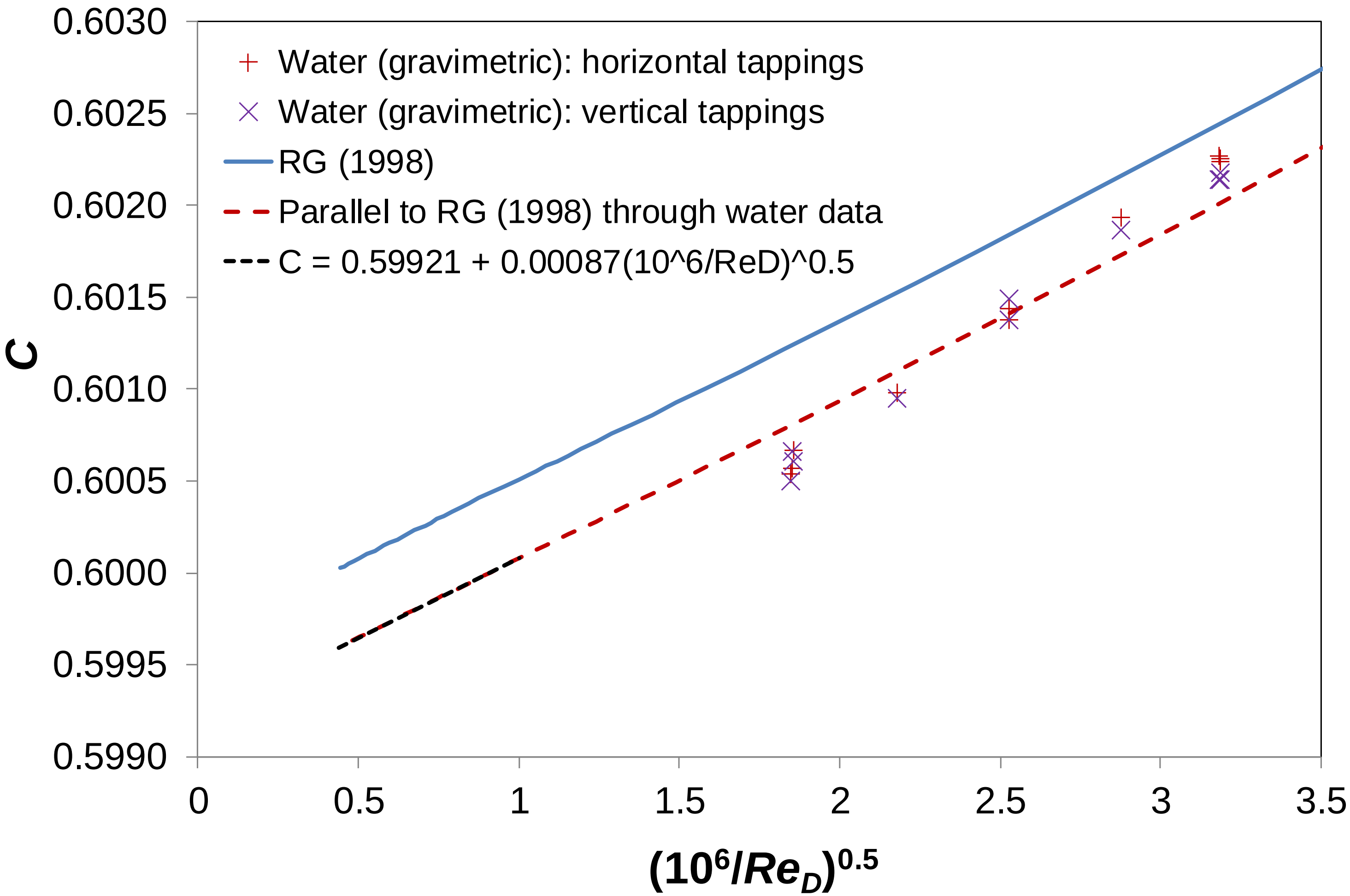
where

$$\frac{p_{rise}}{\Delta p_{DandP}} = \frac{2}{C_{DandP}}\frac{14.78}{14.30}\left(0.123e^{-7L_1}-0.080e^{-10L_1}-0.00011\right)\frac{\beta^4}{1-\beta^4}$$

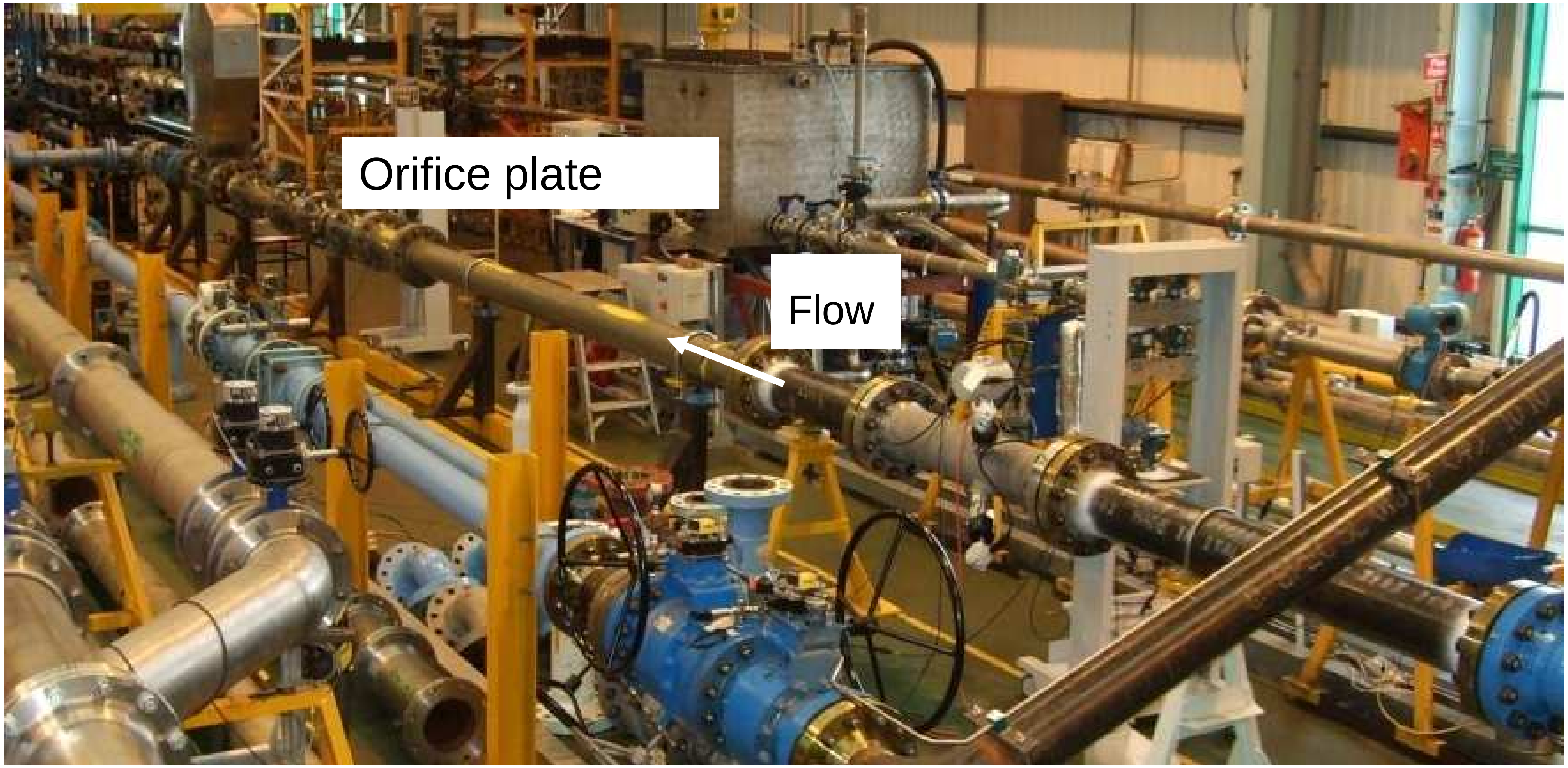
$$\frac{\Delta p_{fdowntoP}}{\Delta p_{DandP}} = \frac{2}{C_{DandP}}0.031\left(M'_{2P}-0.8M'_{2P}{}^{1.1}-\left(M'_2-0.8M'_2{}^{1.1}\right)\right)\beta^{1.3}$$

Experimental data: water test

- 8”, β = 0.4, CO_2
- Initial test in water:



Test in CO_2

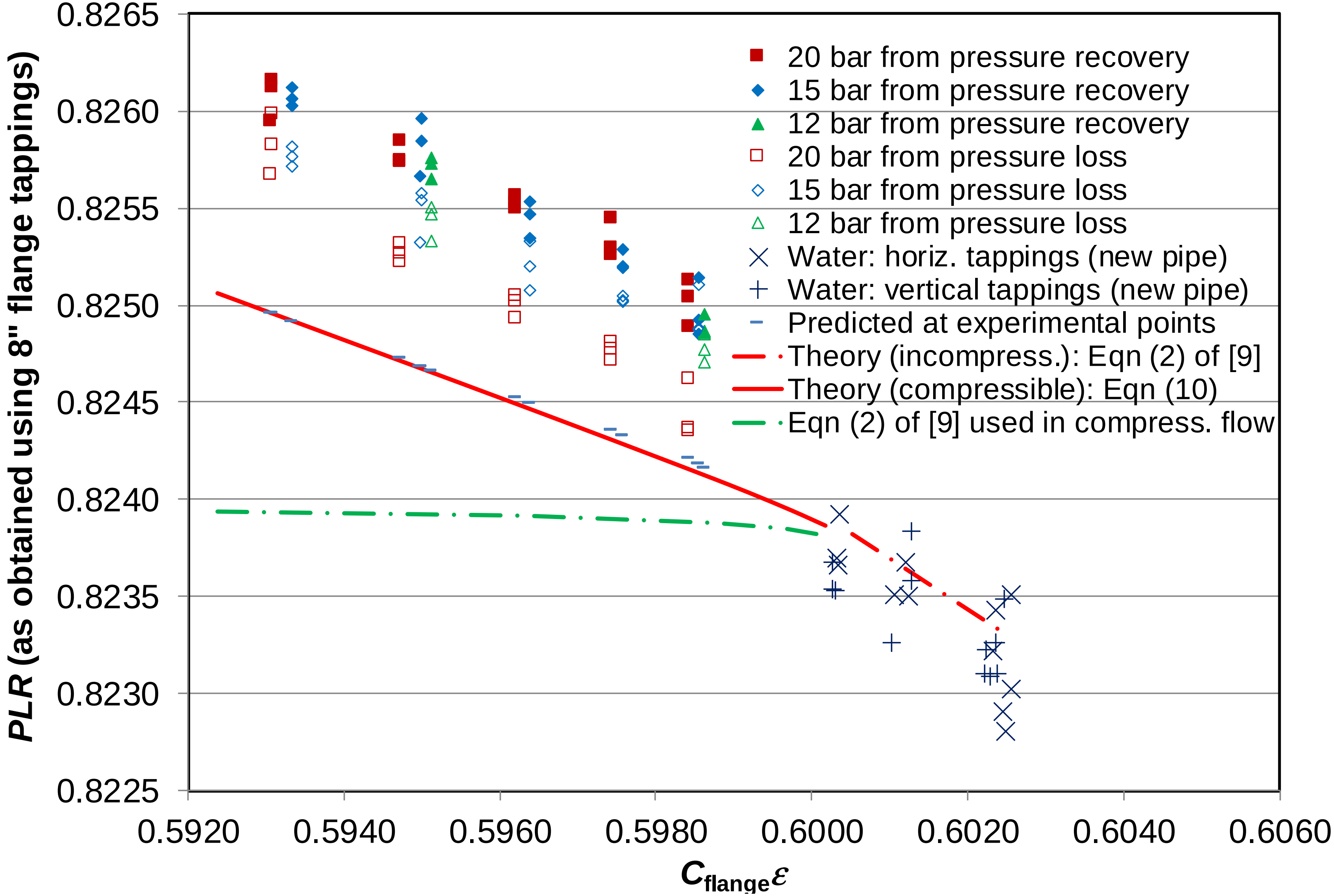


Measured differential pressures

- the differential pressure: from the upstream flange tapping to the downstream flange tapping, ΔP.
- the measured pressure loss: from the upstream flange tapping to 6*D* downstream of the orifice plate, PL.
- the measured pressure recovery from the downstream flange tapping to 6*D* downstream of the orifice plate, PR.

These three measured differential pressures are used in the orifice meter validation system developed by Steven of DP Diagnostics [3-7].

Measured pressure loss ratio (PLR) (=PL/ΔP, = 1-PR/ΔP)



Conclusions

- A correlation for PLR in dry gas based on theory has been obtained
- It deviates from the experimental data that have been obtained in CO_2 by only 0.0008
- Further work is required to prove the correlation
  - different diameter ratios
  - different pipe diameters
  - different gaseous phase compositions
- No problems with orifice plates in CO_2

Acknowledgments

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