Application of the Reciprocal Rate Index Analysis Method to Section 4 Tests

IPS-5.3-22

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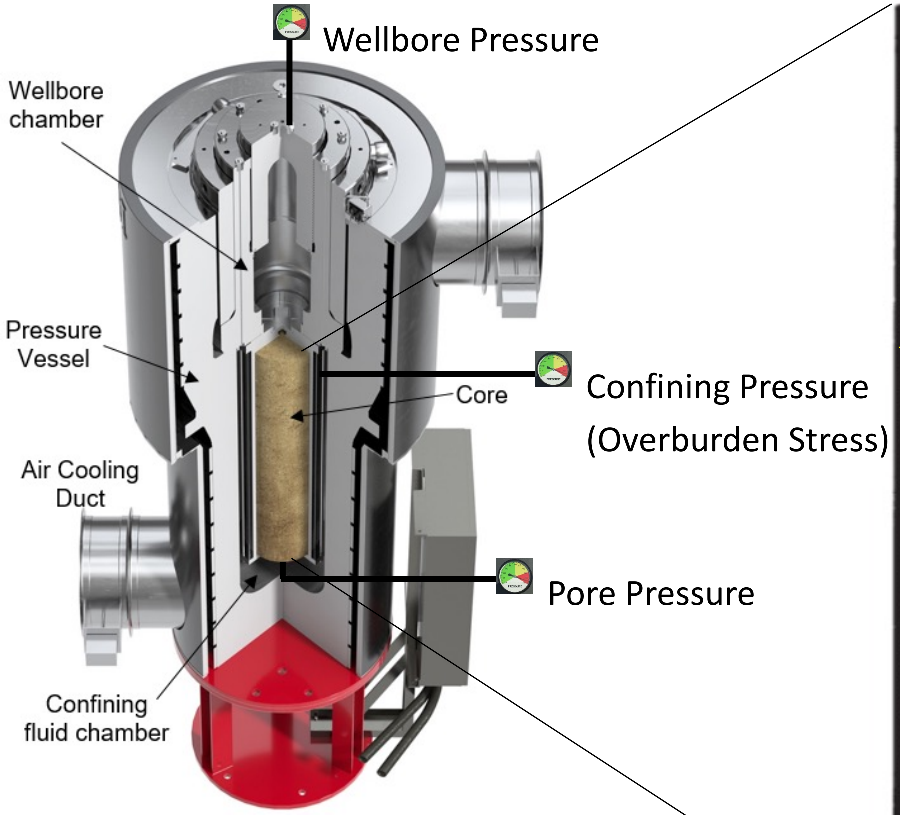
Outline

- Radial flow test for CFE
  - Data reduction approach given in API RP 19B
  - Application Example
- Axial flow test for PR
  - Data reduction approach given in API RP 19B
  - Application Example
- The viscosity-corrected reciprocal rate index approach
  - Application and assessment
- So what?

Background: Radial Flow Test for CFE

- Sandstone core
- Deep penetrating charge
- Axi-radial pressure/flow configuration
- Production-direction gas flow
- 70 °F Post-Shot Flow
- Core Flow Efficiency metric (CFE) used to evaluate flow performance



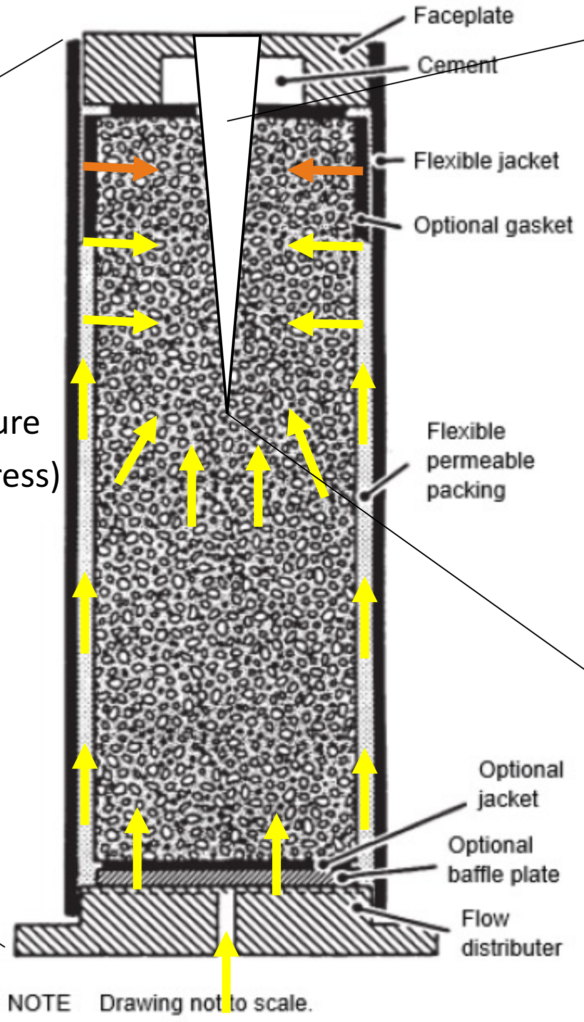
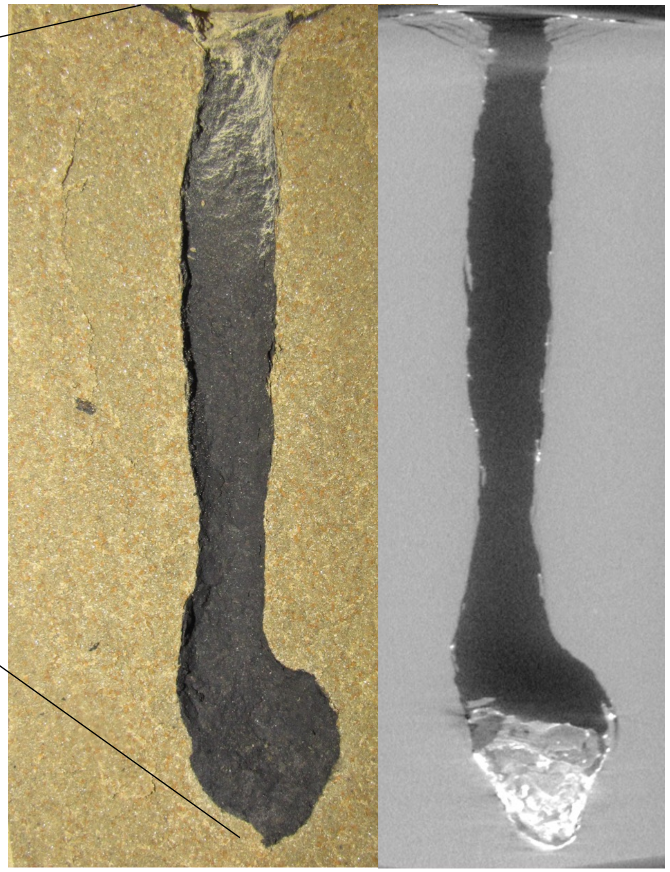


Figure 10—Typical Radial-flow Geometry



Data reduction approach given in API RP 19B

Gas Flow Data Reduction (API 2021)

- 4.4.11.5 Core Flow Efficiency: CFE shall be defined according to Eqn(16):

$$CFE(Q_m) = \frac{PI_{actual}}{PI_{ideal}} = 5.79 \times 10^6 \times \frac{\left(\frac{\mu}{2 k_h \beta \pi D_{op}} \ln\left(\frac{R_{core}}{R_{tunnel}}\right) + \frac{c_f}{\sqrt{k_h}\,\beta} \frac{Q_m}{(2\pi L)^2 L_{eff}}\right)}{a_{1,actual} + a_{2,actual}\, Q_m}$$

- Eqn(16) assumes
  - The ordinary differential equation
    $$-\frac{dp}{dR} = \frac{\mu}{k}\left(\frac{Q_m}{\rho A}\right) + \frac{c_f \rho}{\sqrt{k}}\left(\frac{Q_m}{\rho A}\right)^2$$
  - The radial flow model, $A = 2\pi R L_p$; no hemispherical cap flow
  - Ideal gas law
  - $PI = Q_m/(\bar{p}\Delta p)$
- After integration:
  - $\bar{p}\Delta p = \frac{\mu Q_m}{2\pi\beta k L_p} \ln\left(\frac{R_{core}}{R_{tunnel}}\right) + \frac{c_f}{\sqrt{k}\beta} \frac{Q_m^2}{(2\pi L_p)^2 L_{eff}}$
  - $a_1 = \frac{\mu}{2\pi\beta k L_p} \ln\left(\frac{R_{core}}{R_{tunnel}}\right); a_2 = \frac{c_f}{\sqrt{k}\beta(2\pi L_p)^2 L_{eff}}$
  - $\bar{p}\Delta p = a_1 Q_m + a_2 Q_m^2$
    - This is a two-term 2nd-order polynomial

American Petroleum Institute. (2021). API RP 19B 3RD ED (2021) Evaluation of Well Perforators; Third Edition, July 2021.

Data reduction approach given in API RP 19B

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- $\bar{p}\Delta p = Q_m(a_1 + a_2 Q_m)$

- Eqn(16) has the form:

$$CFE(Q_m) = \left(\frac{Q_m}{\bar{p}\Delta p}\right)_{actual} \cdot \left(\frac{\bar{p}\Delta p}{Q_m}\right)_{ideal}$$

$$= \frac{(\bar{p}\Delta p)_{ideal}}{(\bar{p}\Delta p)_{actual}}\Bigg|_{Q_m}$$

$$= \frac{[\cancel{Q_m}(a_1 + a_2 Q_m)]_{ideal}}{[\cancel{Q_m}(a_1 + a_2 Q_m)]_{actual}}$$

$$= \frac{a_{1,ideal} + a_{2,ideal} Q_m}{a_{1,actual} + a_{2,actual} Q_m}$$

American Petroleum Institute. (2021). API RP 19B 3RD ED (2021) Evaluation of Well Perforators; Third Edition, July 2021.

Data reduction approach given in API RP 19B

Gas Flow Data Reduction (API 2021)

- Evaluation of a_1 and a_2 for radial flow requires fitting a quadratic curve to a plot of the average pressure times the pressure difference vs. the mass flow rate as shown in Figure 14.

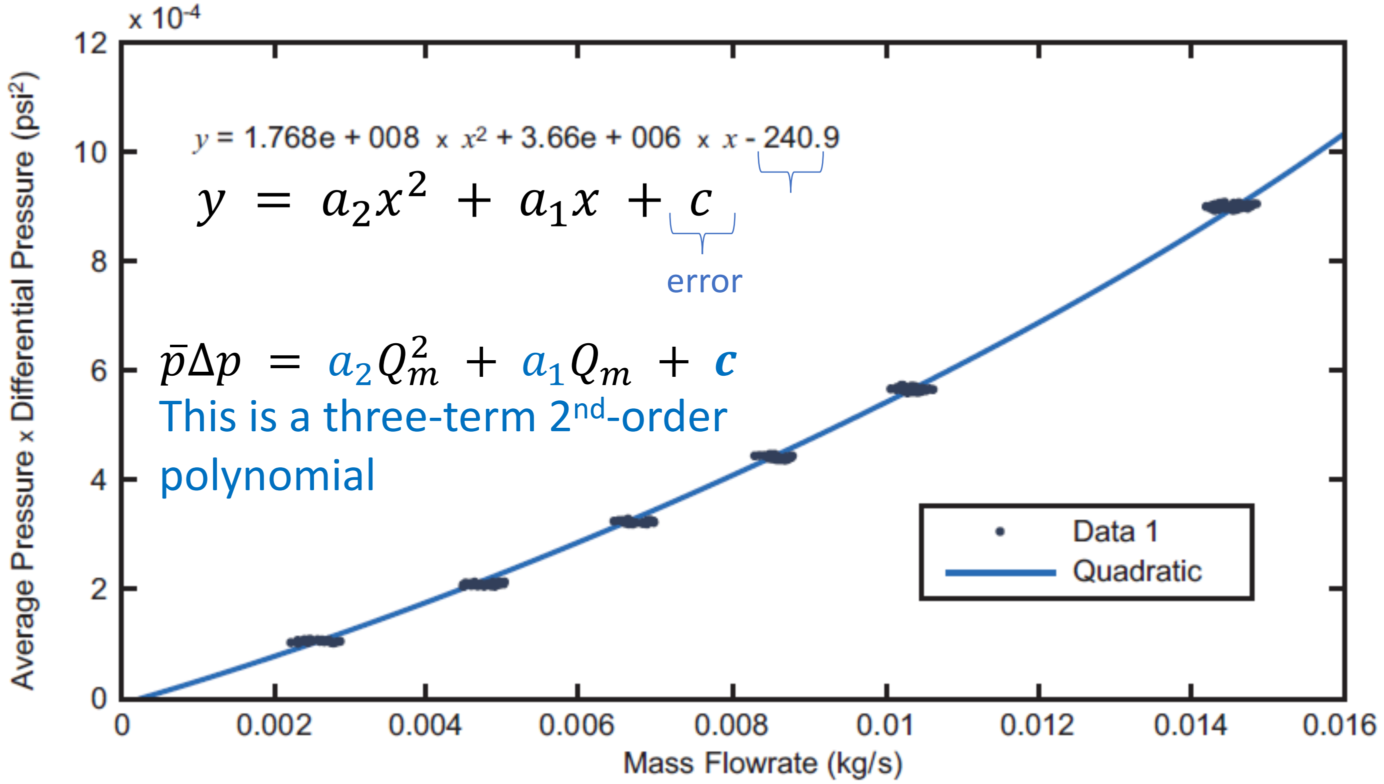


Figure 14—Post-Shot Radial Flow for a Gas Saturated Core

- 4.4.11.5 Core Flow Efficiency: CFE shall be defined according to Eqn(16):

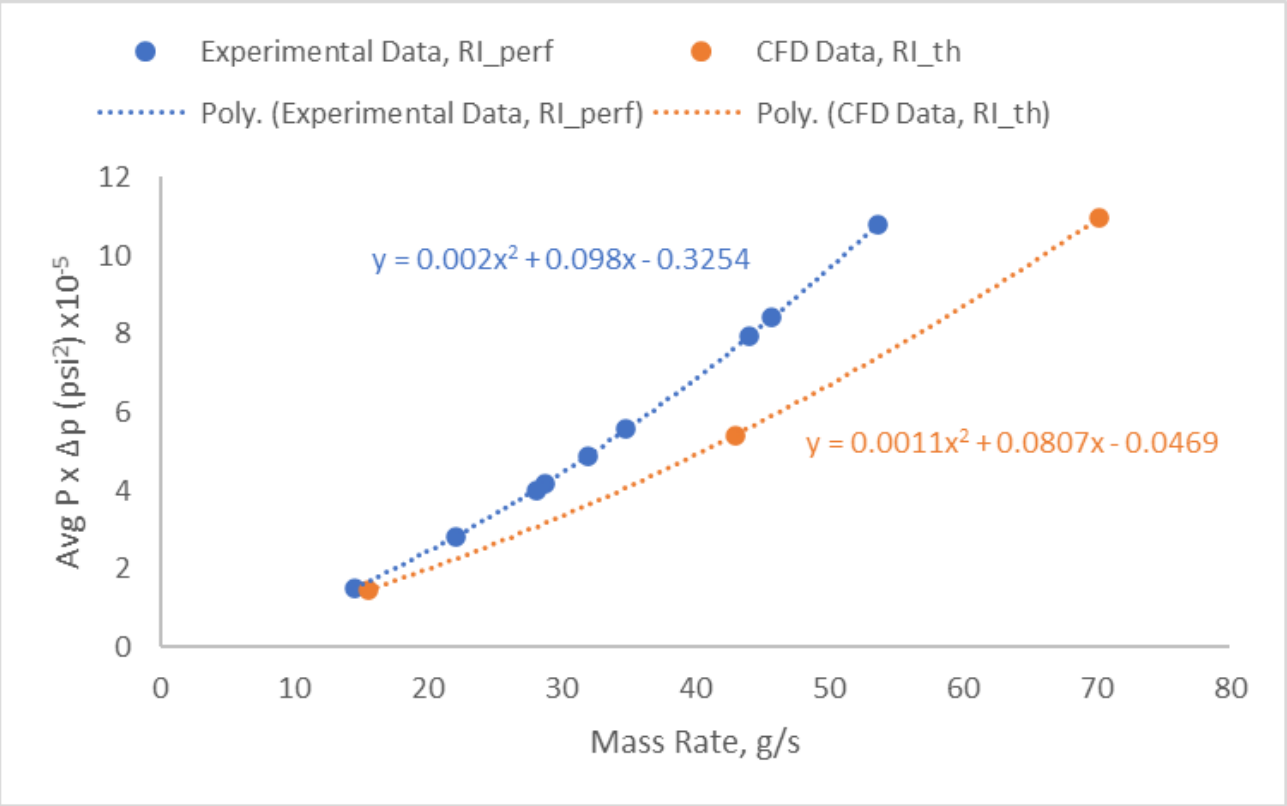
$$CFE(Q_m) = \frac{PI_{actual}}{PI_{ideal}} = 5.79 \times 10^6 \times \frac{\left(\frac{\mu}{2k_h\beta\pi D_{op}} \ln\left(\frac{R_{core}}{R_{tunnel}}\right) + \frac{c_f}{\sqrt{k_h}} \frac{Q_m}{\beta(2\pi L)^2 L_{eff}}\right)}{a_{1,actual} + a_{2,actual}\,Q_m}$$

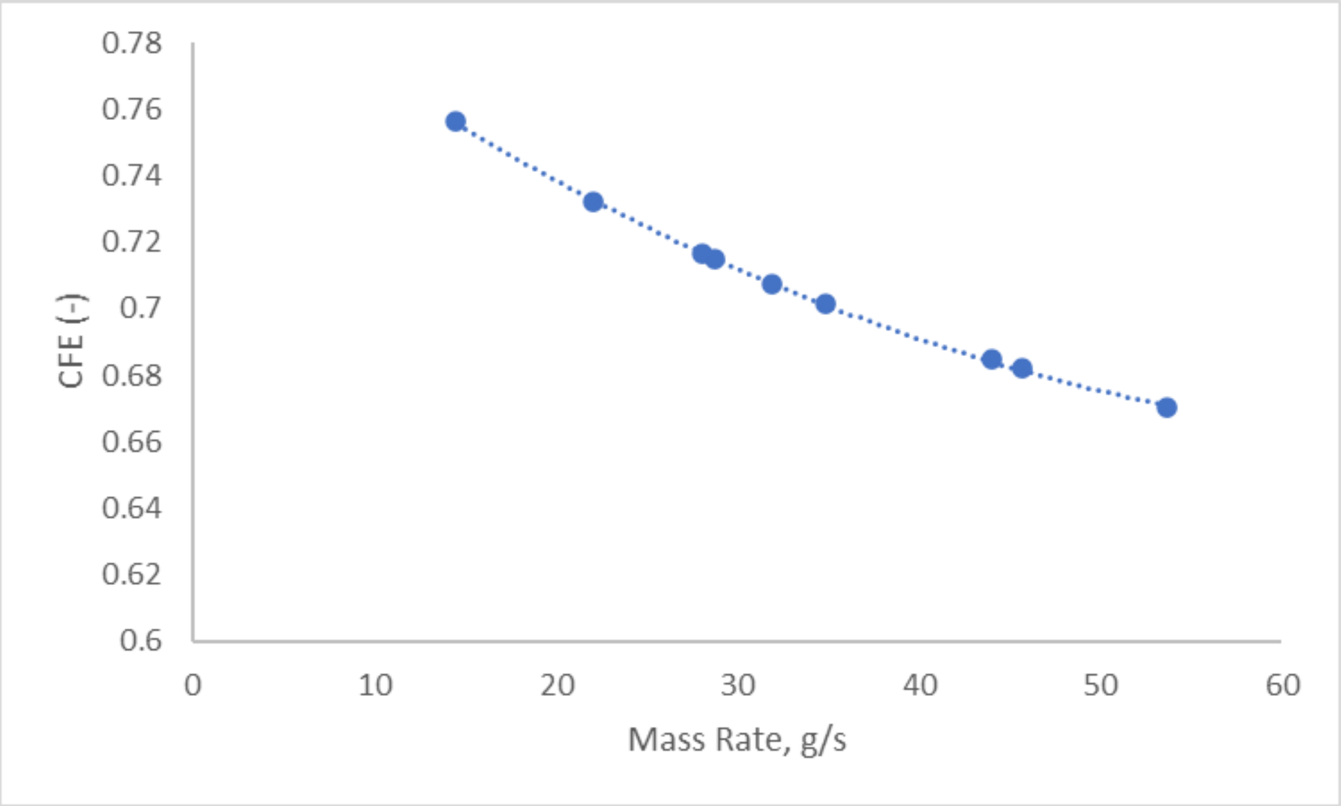
- $CFE(Q_m) = \frac{[a_1 + a_2 Q_m]_{ideal}}{[a_1 + a_2 Q_m + \not{c}]_{actual}}$

  - Regress a three-term 2nd-order polynomial to the data and use two of the three coefficients in a two-term 1st-order polynomial.

American Petroleum Institute. (2021). API RP 19B 3RD ED (2021) Evaluation of Well Perforators; Third Edition, July 2021.

Application of Data reduction approach given in API RP 19B





$$CFE(Q_m) = \frac{0.081 + 0.001Q_m}{0.098 + 0.002Q_m}$$

CFE ranges between 0.756 to 0.67 for the range of experimental flow rates tested (14.49 to 53.67 g/s).

Background: Axial Flow Test for Productivity Ratio

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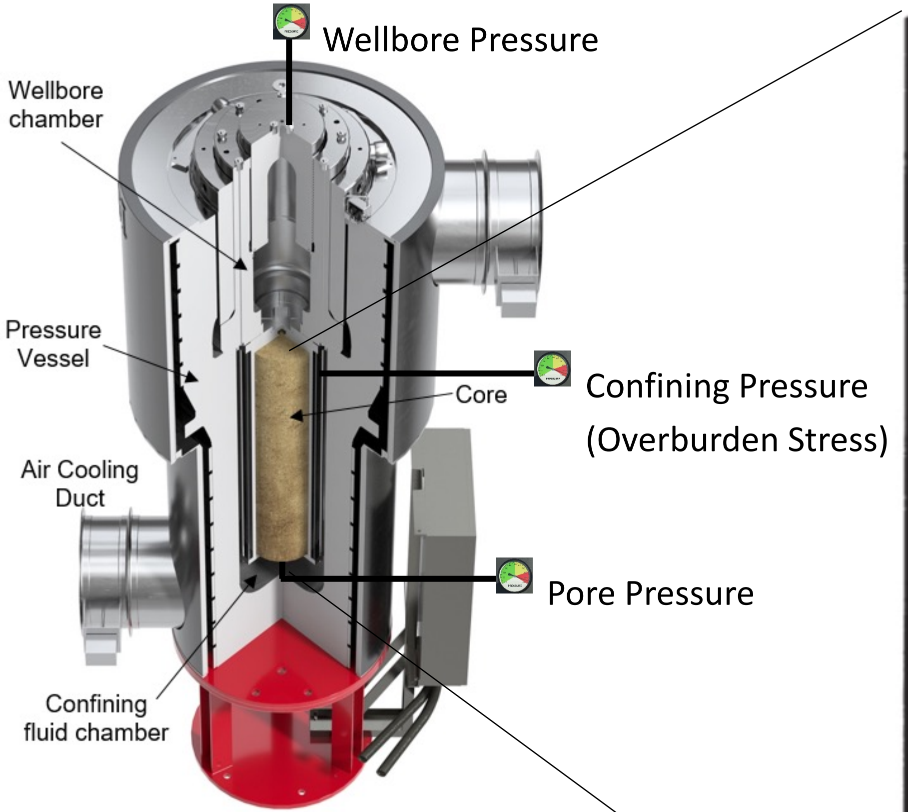
- Sandstone core conditioned to S_{wr}
- Deep penetrating charge
- Axial pressure/flow configuration
- Production-direction gas flow
- Pre-Shot Flow at 80 °F ($\bar{T}_f = 59$ °F)
- Post-Shot Flow at 347 °F ($\bar{T}_f = 224$ °F)
- Production Ratio metric (PR) used to evaluate flow performance



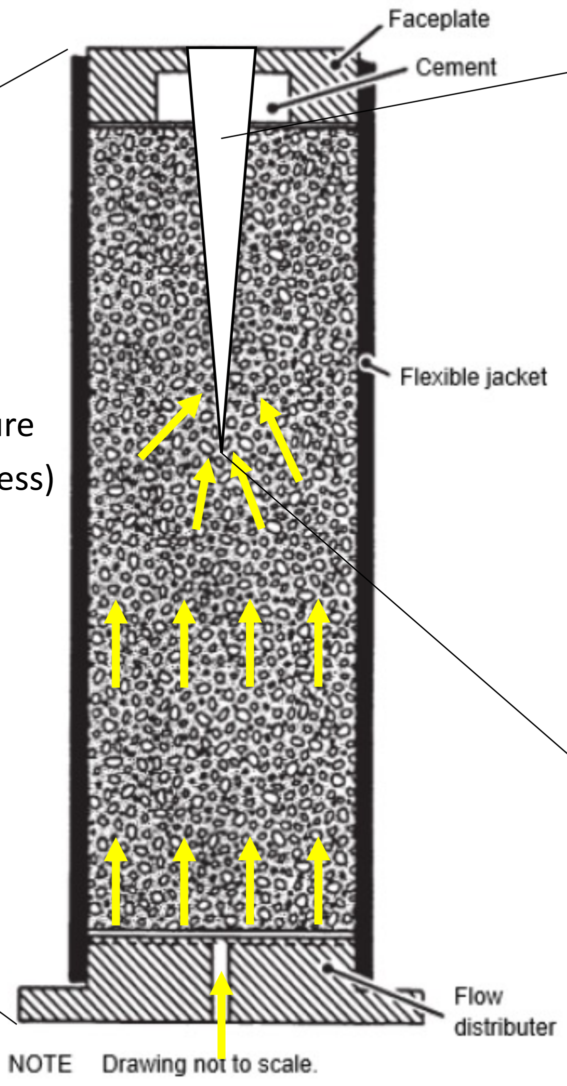
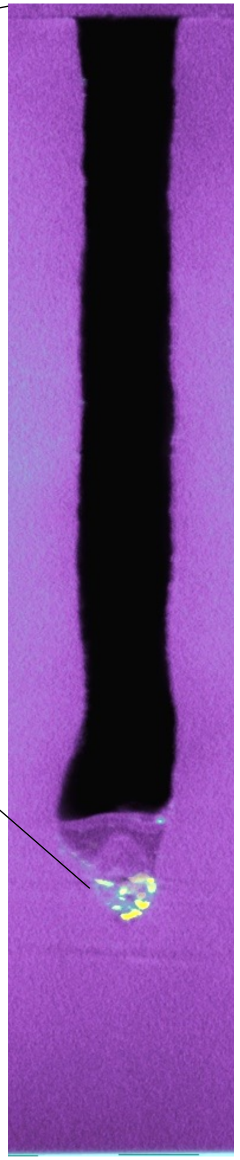


Figure 11—Typical Axial-flow Geometry



Data reduction approach given in API RP 19B

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Gas Flow Data Reduction (API 2021)

- 4.4.11.4 Production Ratio: Gas flow axial production ratio shall be defined as the ratio of the PI_{perf} to the pre-shot PI of the target, calculated according to Equation (15):

$$PR = \frac{PI_{perf}}{PI}$$

- The method for determining PI for axial flow is not explicitly given.
- What if we use the same methodology as is given for Core Flow Efficiency?

$$PR(Q_m) = \left(\frac{Q_m}{\bar{p}\Delta p}\right)_{perf} \cdot \left(\frac{\bar{p}\Delta p}{Q_m}\right)_{preshot}$$

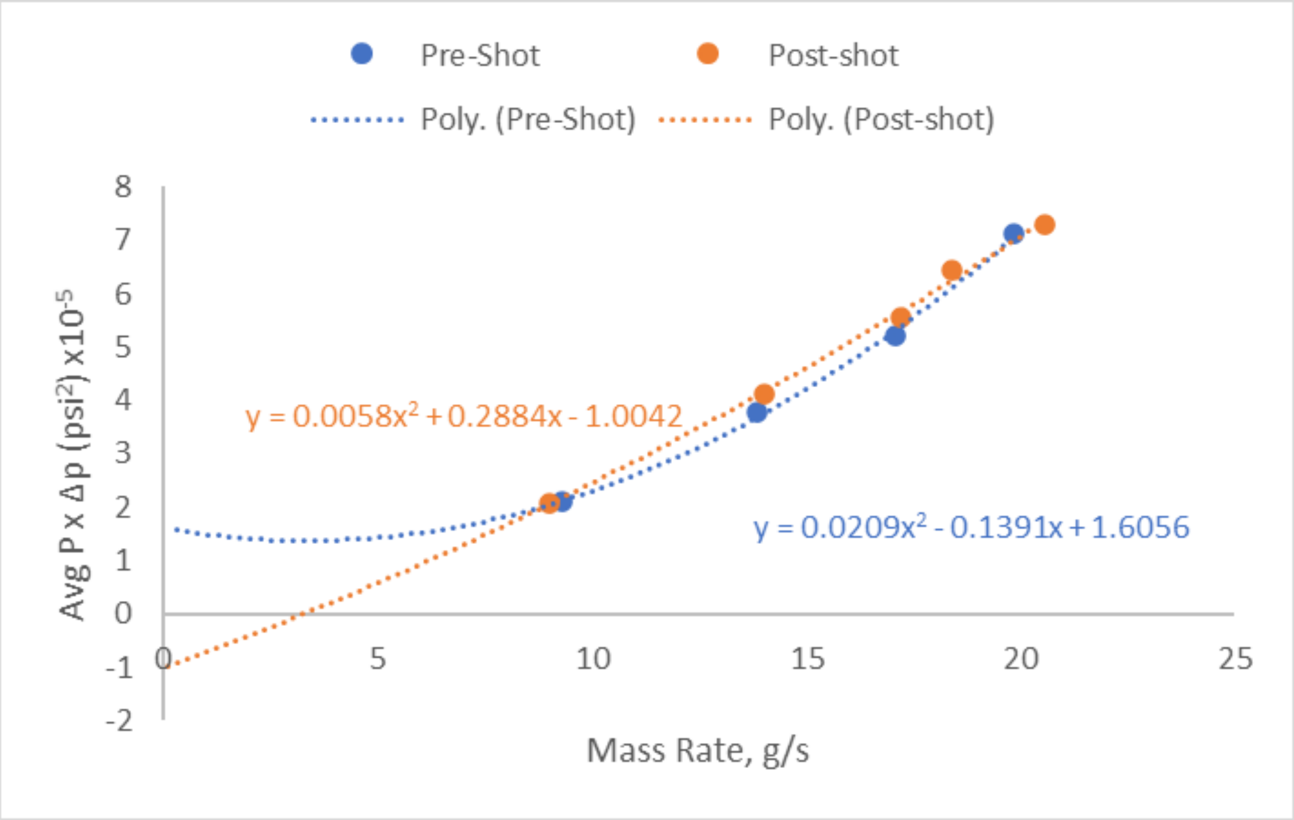
$$= \frac{(\bar{p}\Delta p)_{preshot}}{(\bar{p}\Delta p)_{perf}}\bigg|_{Q_m}$$

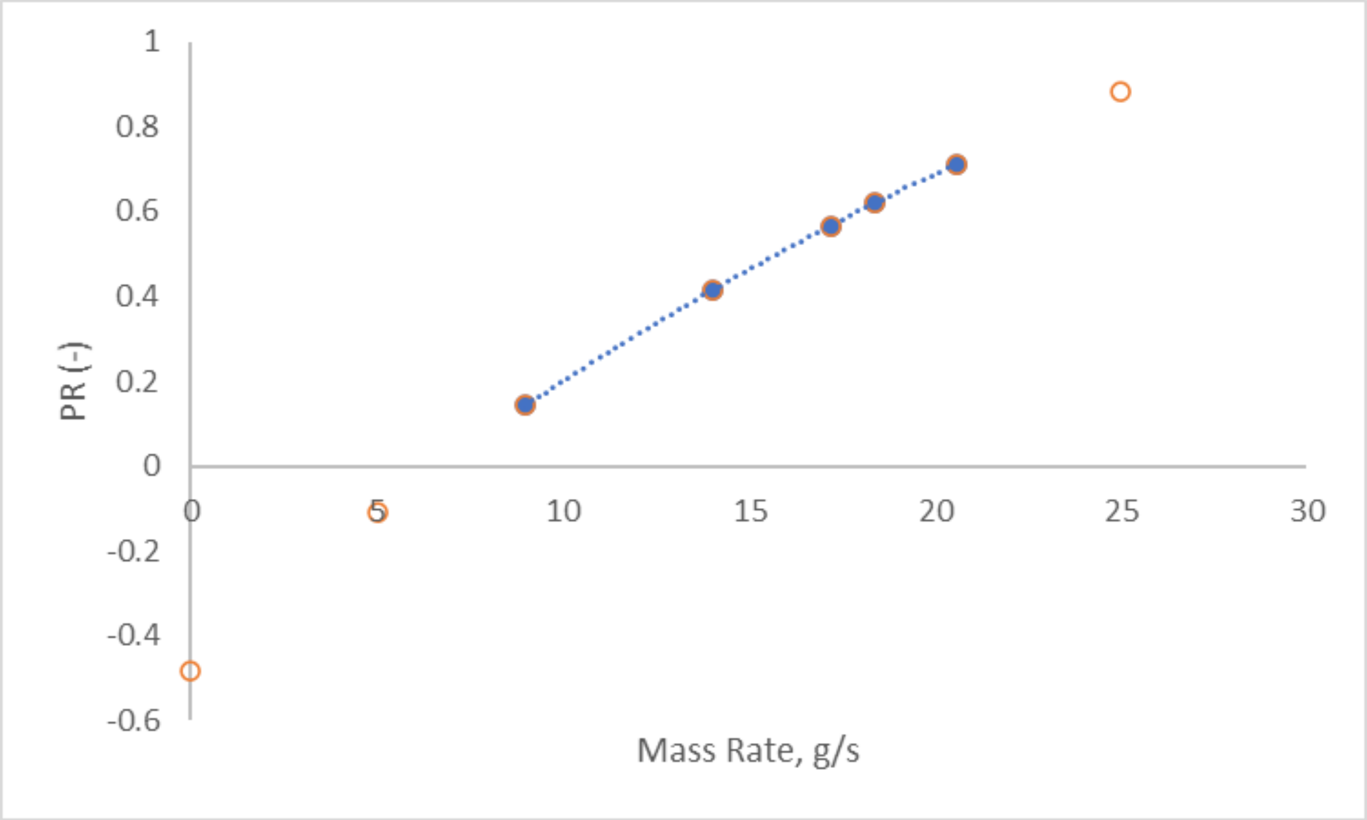
$$= \frac{[a_1 + a_2 Q_m + \not{c}]_{preshot}}{[a_1 + a_2 Q_m + \not{c}]_{perf}}$$

- No analytical expression for coefficients a_1 and a_2

American Petroleum Institute. (2021). API RP 19B 3RD ED (2021) Evaluation of Well Perforators; Third Edition, July 2021.

Application of Data reduction approach given in API RP 19B





$$PR(Q_m) = \frac{-0.1391 + 0.0209Q_m}{0.2884 + 0.0058Q_m}$$

PR ranges between 0.14 to 0.71 for the range of experimental flow rates tested (9.00 to 20.56 g/s).

Application of Data reduction approach given in API RP 19B

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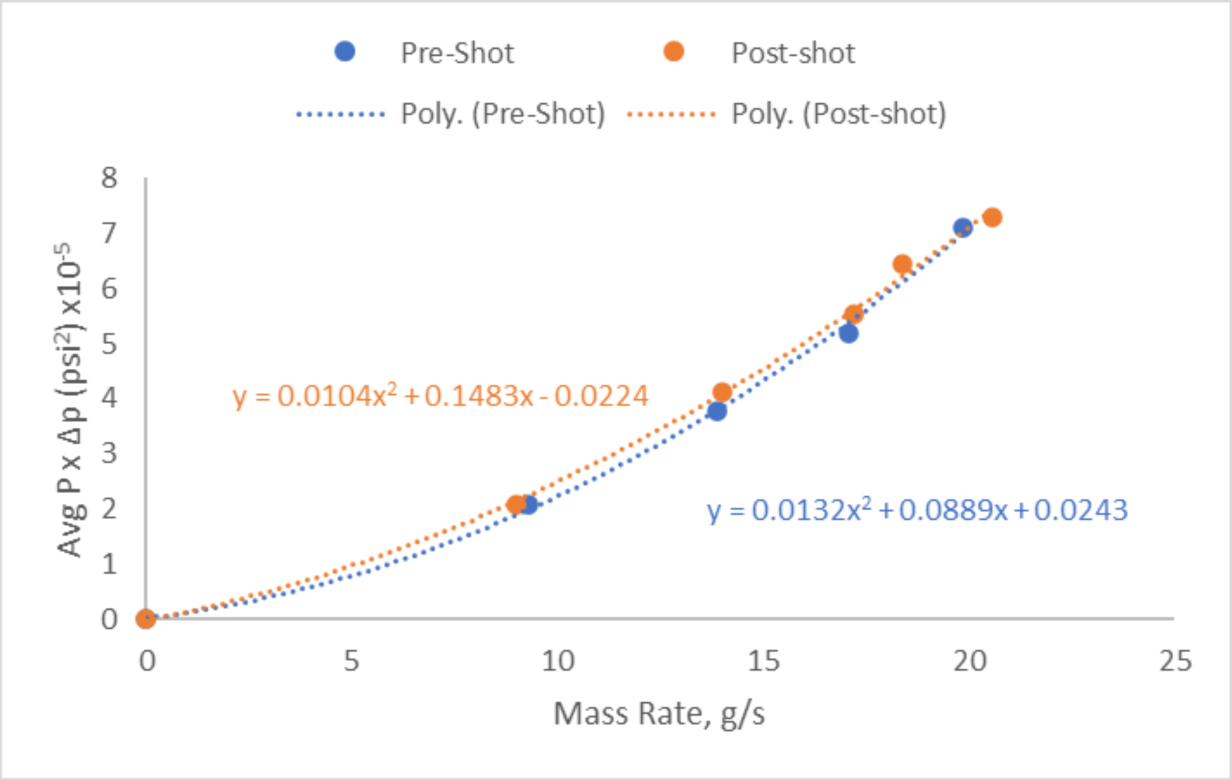
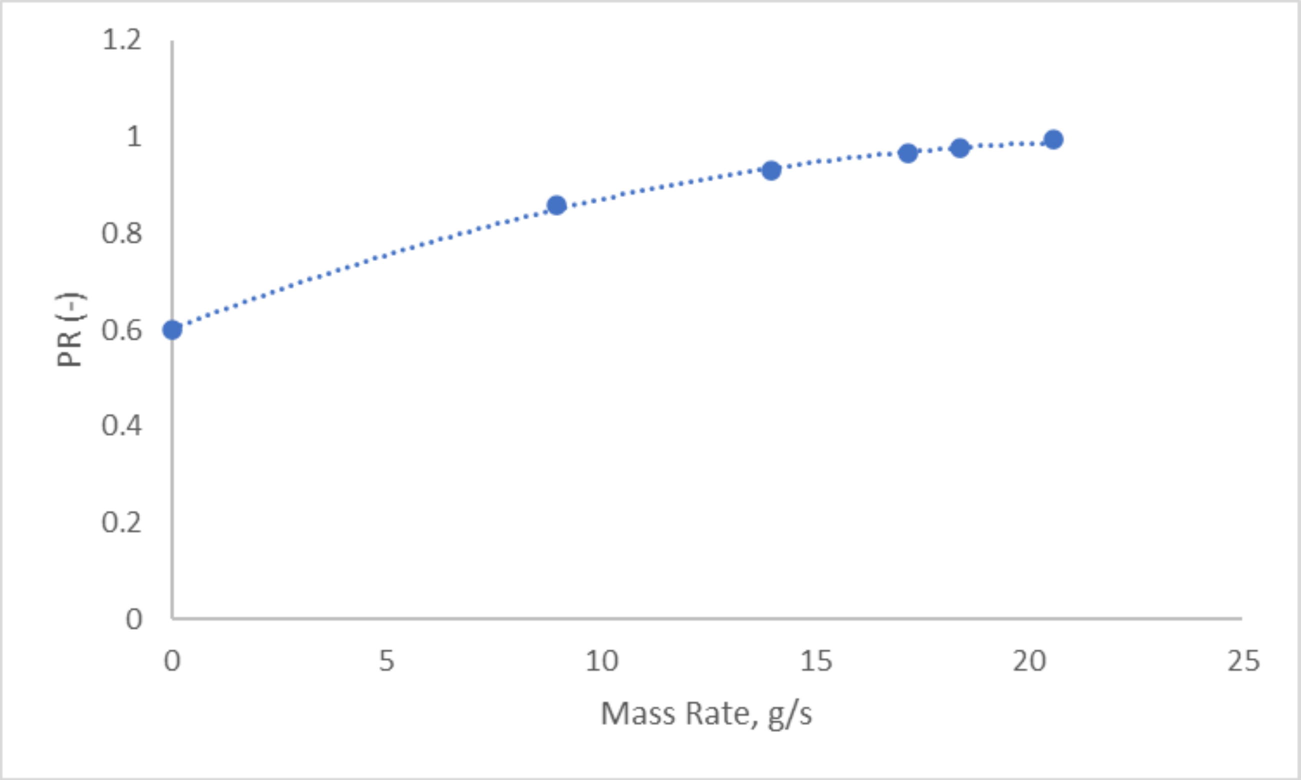
- Remedies:
  - Measure Q_m and $\bar{p}\Delta p$ at 'zero' (0), and include data in regression analysis

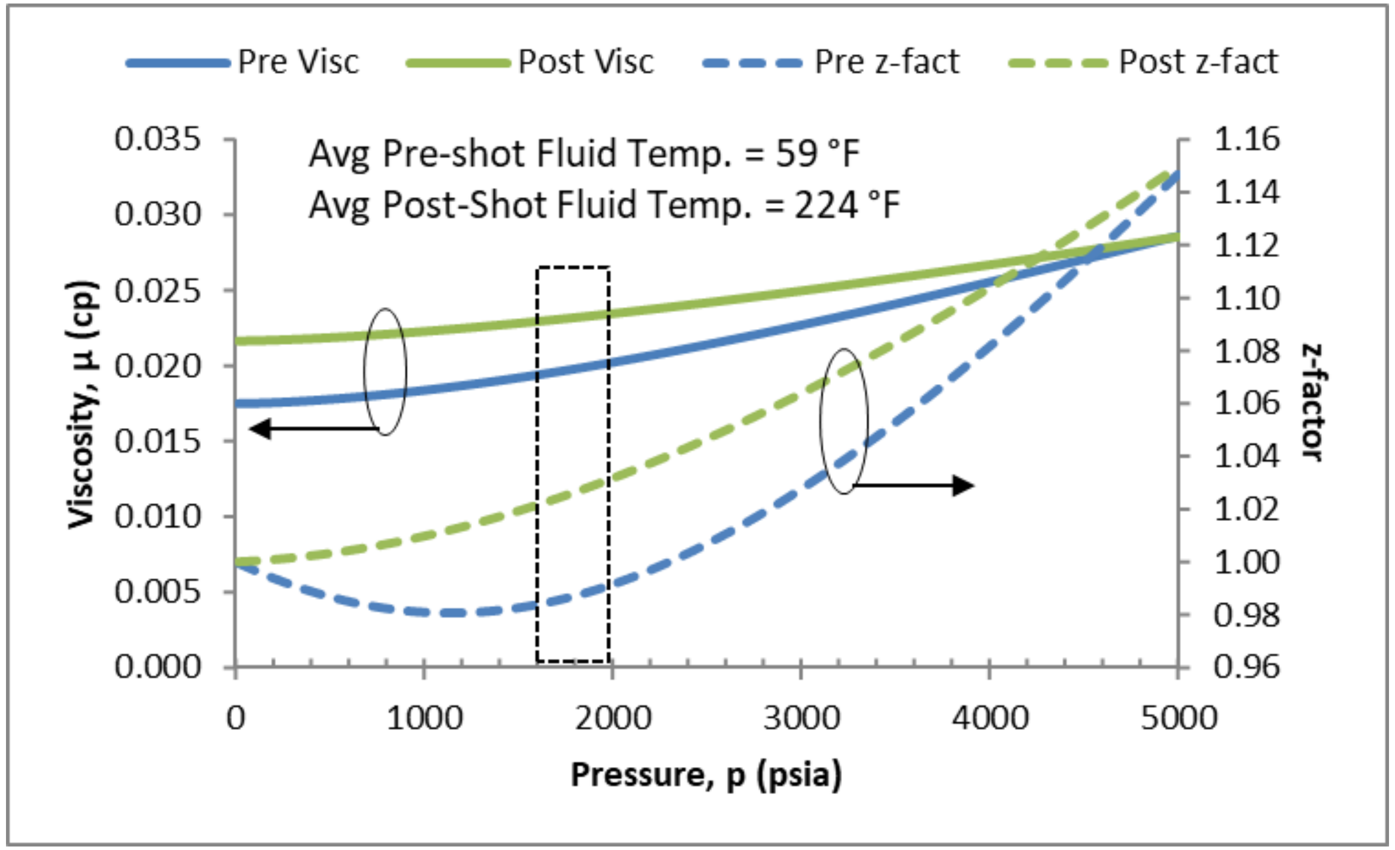
$$PR(Q_m) = \frac{0.0889 + 0.0132Q_m}{0.1483 + 0.0104Q_m}$$

PR ranges between 0.59 to 0.99 for the range of flow rates (0 to 20.56 g/s).





- Recall for this axial flow test,
  - Pre-Shot Flow at 80 °F ($\bar{T}_f = 59$ °F)
  - Post-Shot Flow at 347 °F ($\bar{T}_f = 224$ °F)
- Rate Ratio = $\dfrac{RI_{perf}(347\ °F)}{RI_{preshot}(80\ °F)}$
  - gas viscosity and density change due to temperature change; essentially two different fluids are being tested.



For Gas and Liquid Flow Data Reduction

- It would be nice to exclude fluid properties and non-Darcy flow effect from RI
  - Recall, a_2 & a_1 are functions of p & T since they include μ & $\beta(\rho)$
    - $\rho_g(p,T) = pM_w/(z(p,T)RT)$
- It would be nice to have a single value for $RI, RR, \& \ CFE$ just like we do for the liquid (Darcy) flow tests.

*Rate Index (RI) is generic term for productivity index (PI) and injectivity index (II).

The viscosity-corrected reciprocal rate index approach

- Use non-Darcy equation of the form*:

$$\frac{\Delta m(p)}{q_{sc}\mu_n B_n} = A_1 + A_2 Q_m;$$

$$m(p) = \mu_n B_n \int_{p_b}^{p} \frac{1}{\mu B}\, dp + p_b$$

$$B = \rho_{sc}/\rho$$

- When ρ and μ approximately constant,

$$\Delta m(p) \approx \Delta p$$

$$\frac{\Delta p}{q\mu} = A_1 + A_2 Q_m$$

- A_1 is only a function of permeability and flow path (length, area, & geometry); is equal to the reciprocal rate index (RRI).
- Analytical expressions for A_1 and A_2 can be derived (e.g., for full-face axial-, cylindrical-radial-, and hemispherical-flow).
- A_1 (the RRI value) is determined using a least-squares linear regression.

$$RRI \equiv \lim_{Q_m \to 0} \left(\frac{\Delta m(p)}{q_{sc}\mu_n B_n} \right) = A_1$$

- Viscosity-corrected rate index (RI) is then found as:

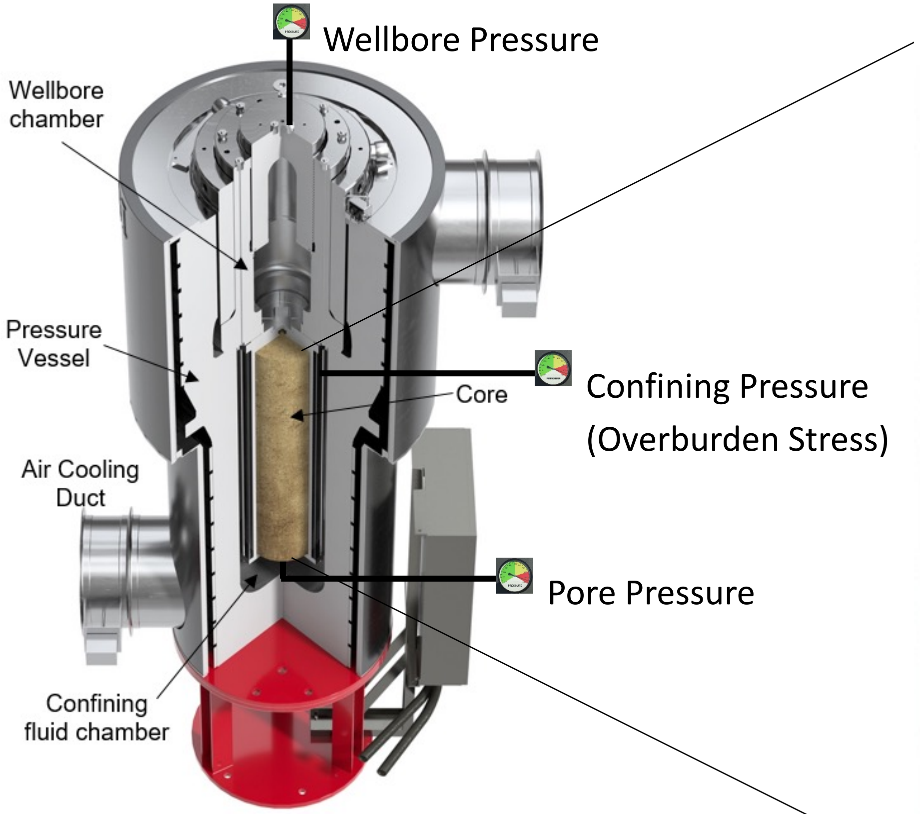
$$RI = A_1^{-1}$$

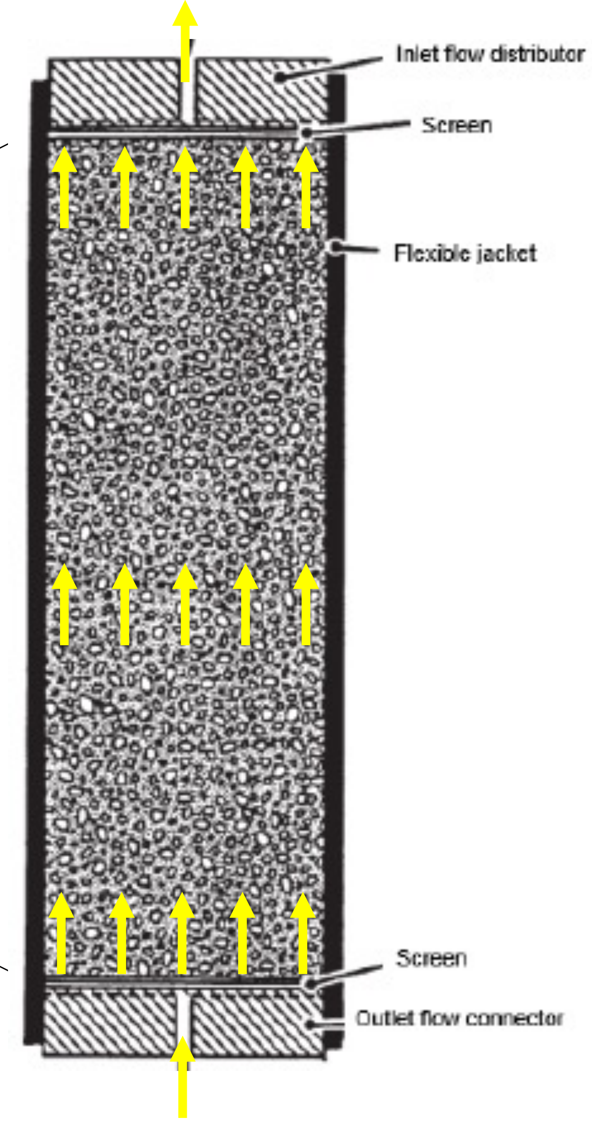
- Key Benefit: a systematic approach to determine a single Darcian fluid-independent rate index value.

*Jones, L. G., Blount, E. M., & Glaze, O. H. (1976). Use of Short Term Multiple Rate Flow Tests To Predict Performance of Wells Having Turbulence. doi:10.2118/6133-MS

Application & Assessment: Background

- Sandstone core
- Axial pressure/flow configuration
- Production-direction 100% gas flow and 100% liquid flow





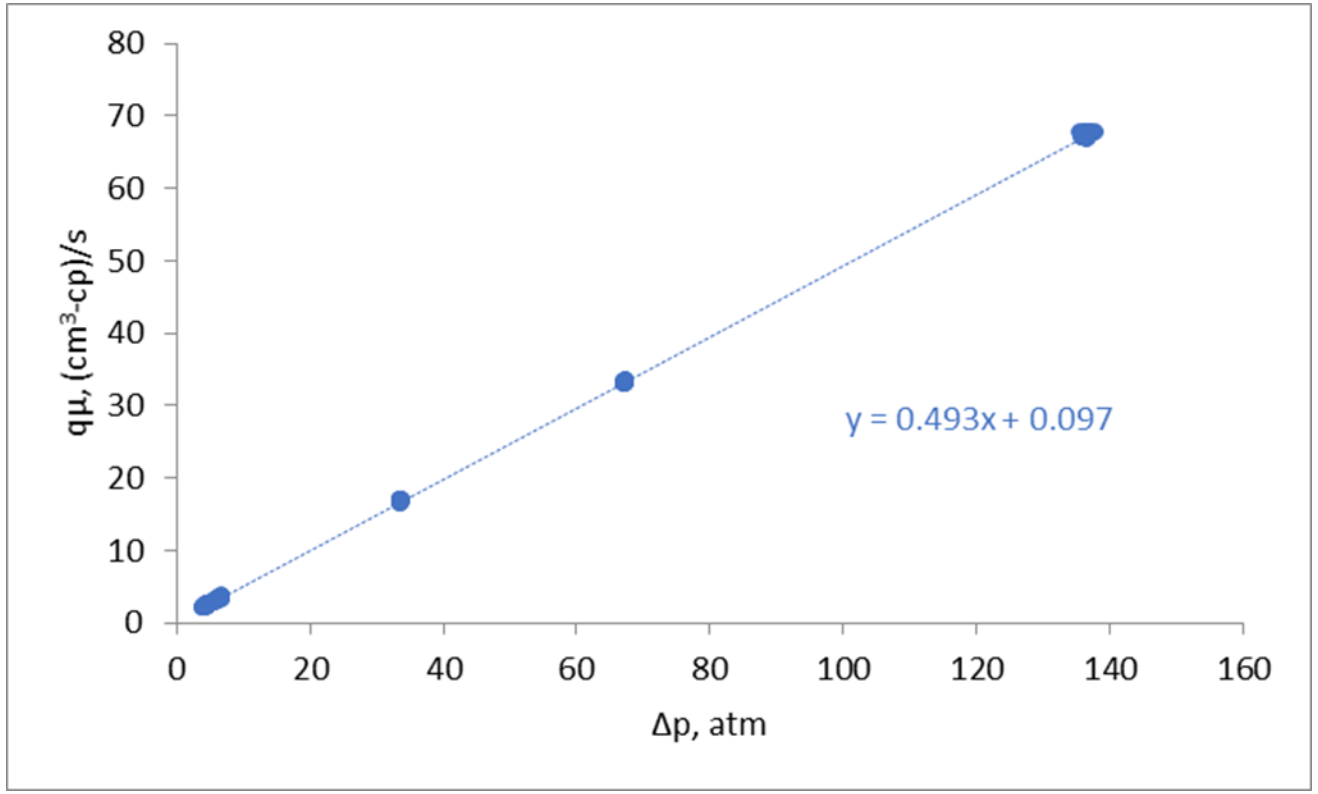
NOTE Not to scale.

Figure 7—Typical Axial-Flow Permeability Equipment

Application & Assessment

- Liquid Flow

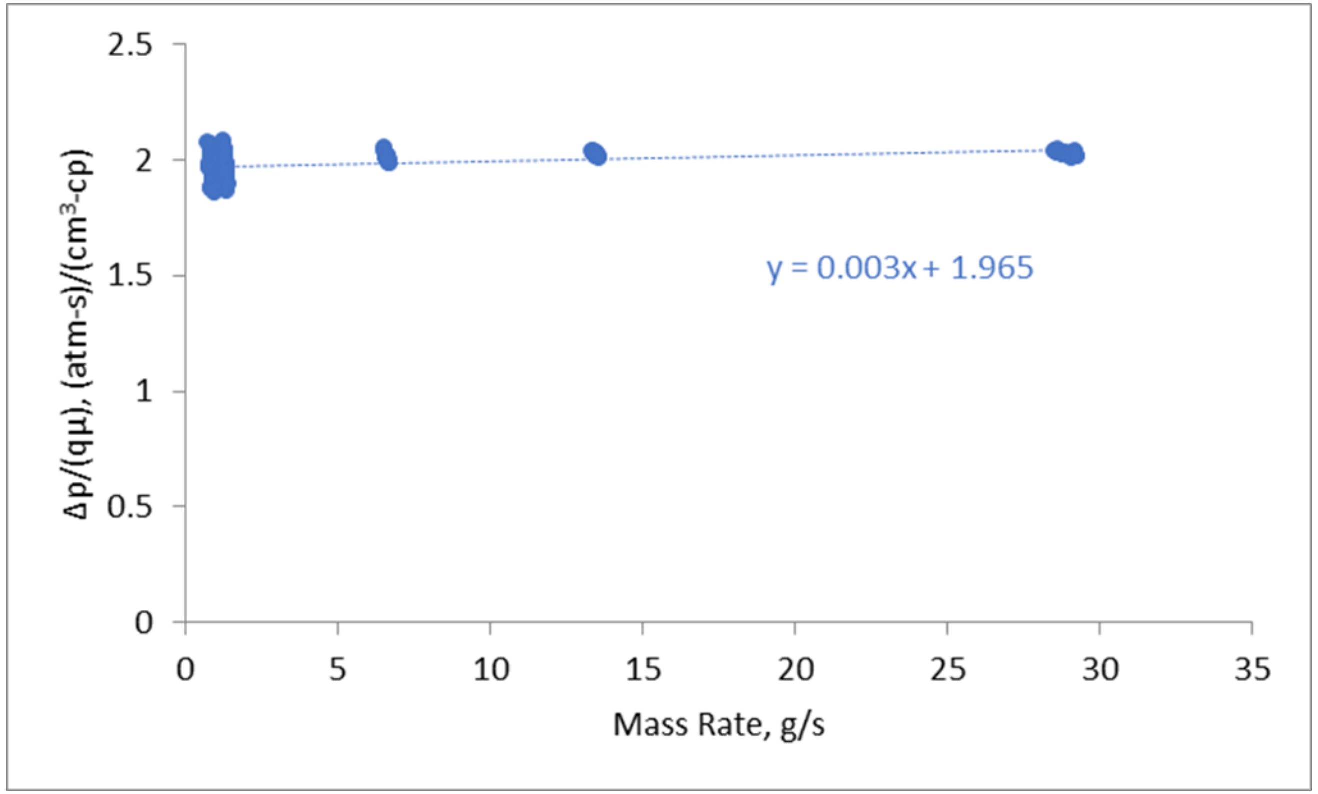
Conventional Darcy analysis approach



Liquid Flow
RI $\frac{(\mathrm{cm}^3 \cdot \mathrm{cp})}{(\mathrm{atm} \cdot \mathrm{s})}$
0.493

- Liquid Flow

Viscosity-corrected reciprocal rate index approach

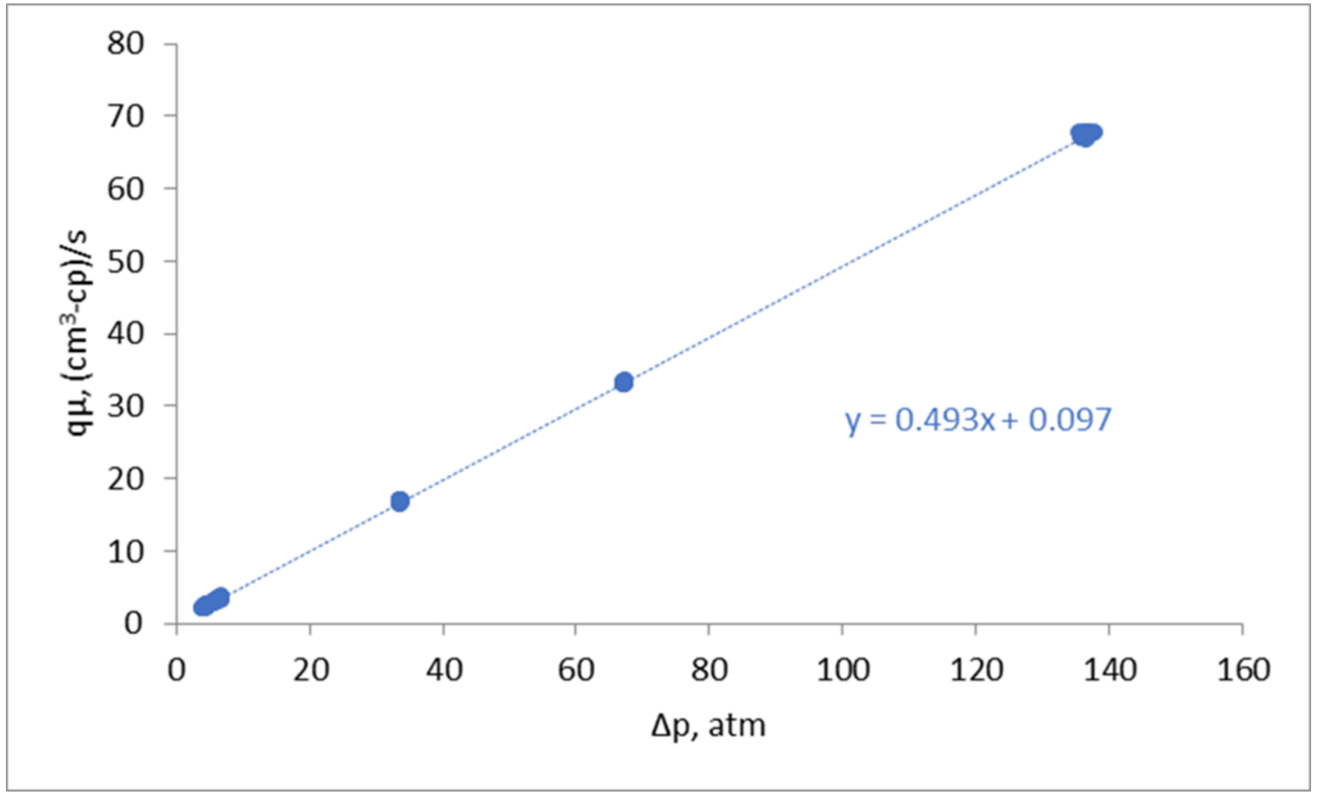


Liquid Flow	
A_1 $\frac{(\mathrm{atm} \cdot \mathrm{s})}{(\mathrm{cm}^3 \cdot \mathrm{cp})}$	RI $\frac{(\mathrm{cm}^3 \cdot \mathrm{cp})}{(\mathrm{atm} \cdot \mathrm{s})}$
1.965	0.509

Application & Assessment

- Liquid Flow

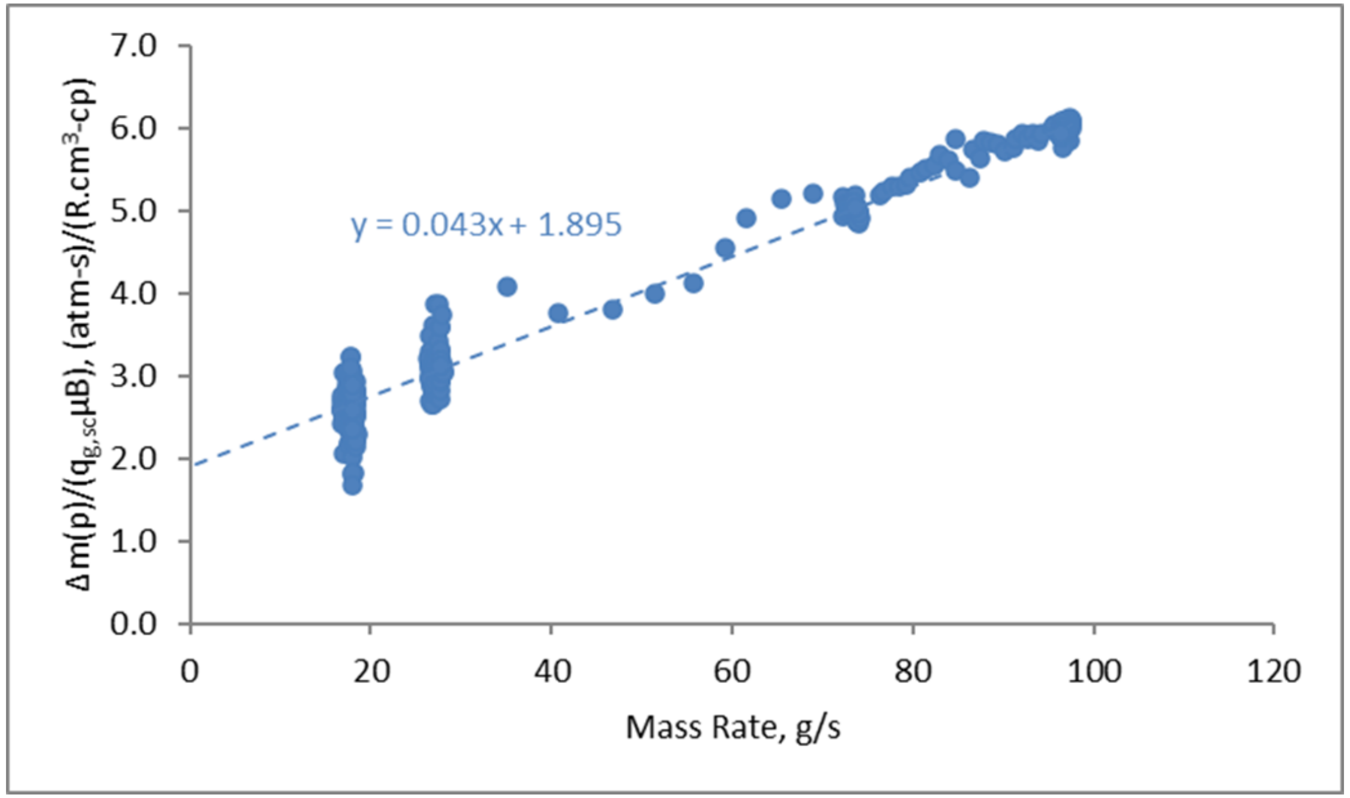
Conventional Darcy analysis approach



Liquid Flow
$\boldsymbol{RI}$ $\frac{(cm^3 \cdot cp)}{(atm \cdot s)}$
0.493

- Gas Flow

Viscosity-corrected reciprocal rate index approach



Gas Flow	
$\boldsymbol{A_1}$ $\frac{(atm \cdot s)}{(cm^3 \cdot cp)}$	$\boldsymbol{RI}$ $\frac{(cm^3 \cdot cp)}{(atm \cdot s)}$
1.895	0.528

Application & Assessment: Background

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- Sandstone core
- Deep penetrating charge
- Axi-radial pressure/flow configuration
- Production-direction 100% gas flow and 100% liquid flow

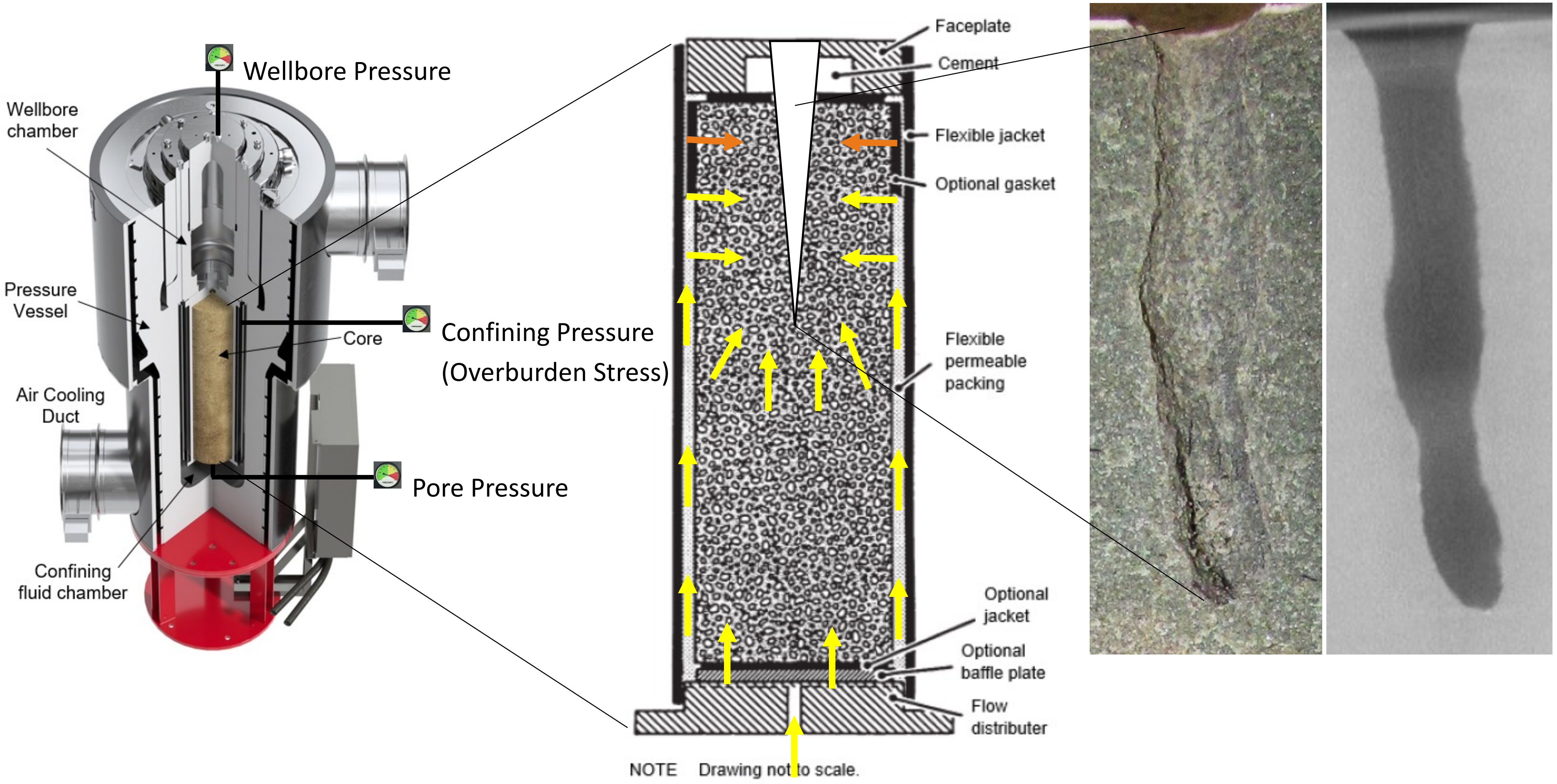
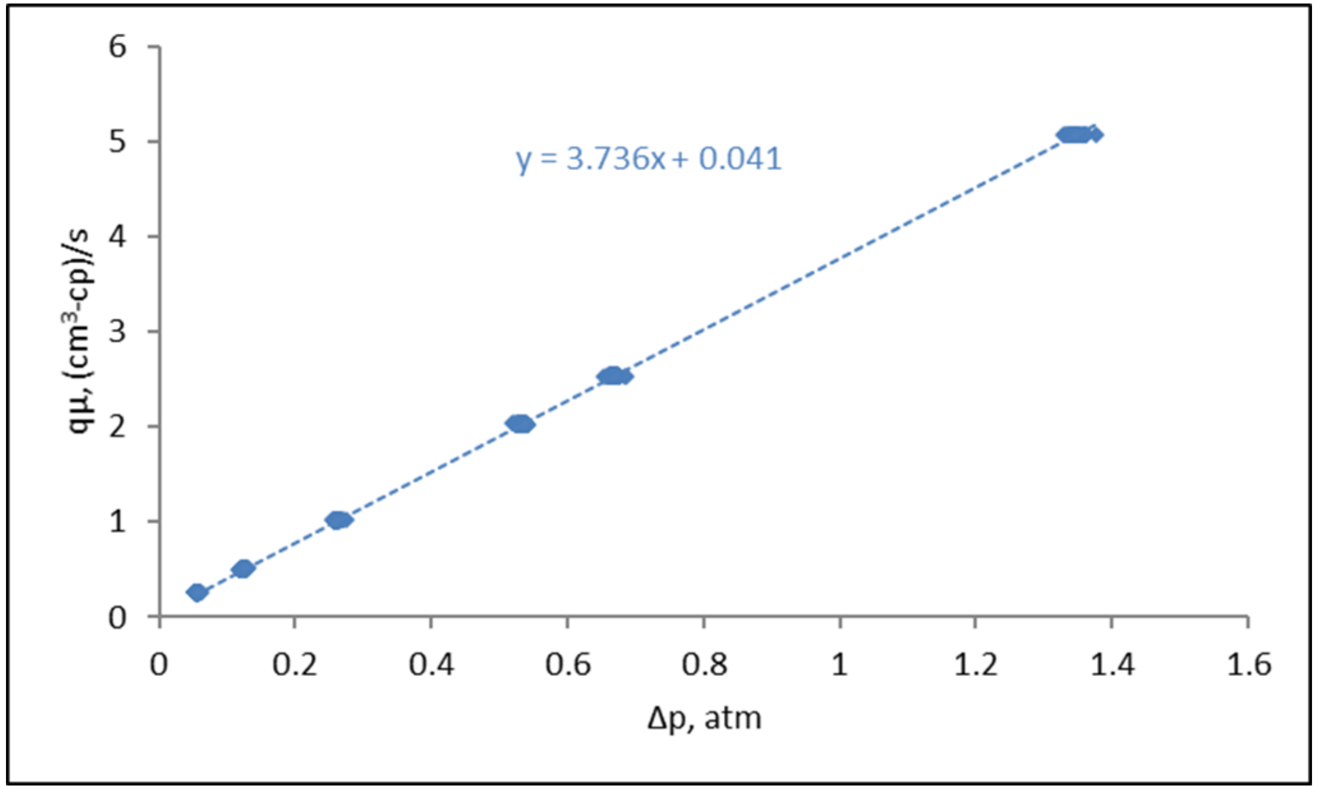


Figure 10—Typical Radial-flow Geometry

Application & Assessment

- Liquid Flow

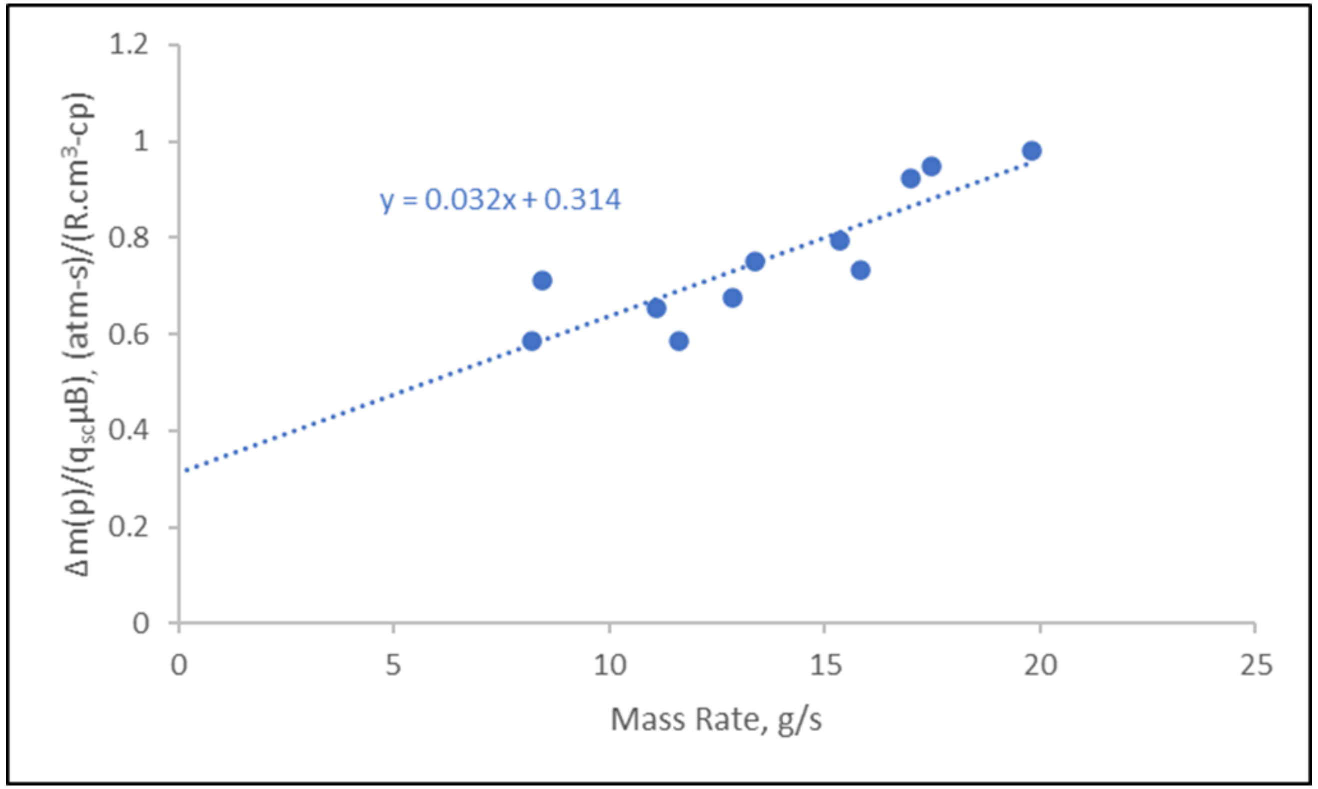
Conventional Darcy analysis approach



Liquid Flow
RI $\frac{(cm^3 \cdot cp)}{(atm \cdot s)}$
3.736

- Gas Flow

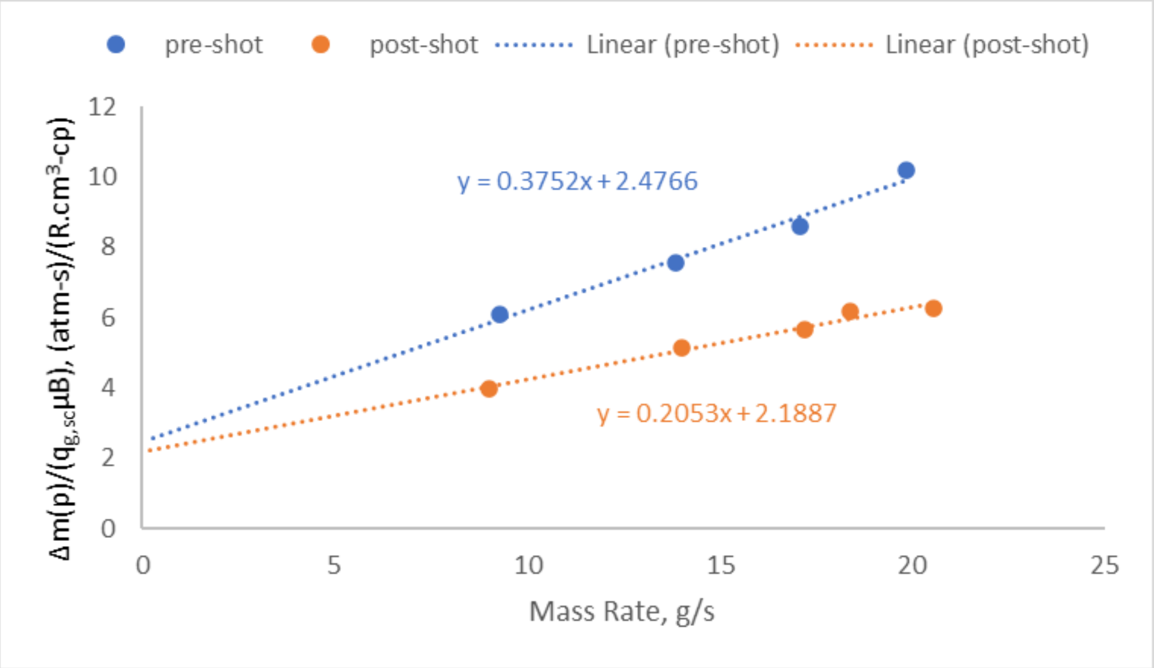
Viscosity-corrected reciprocal rate index approach

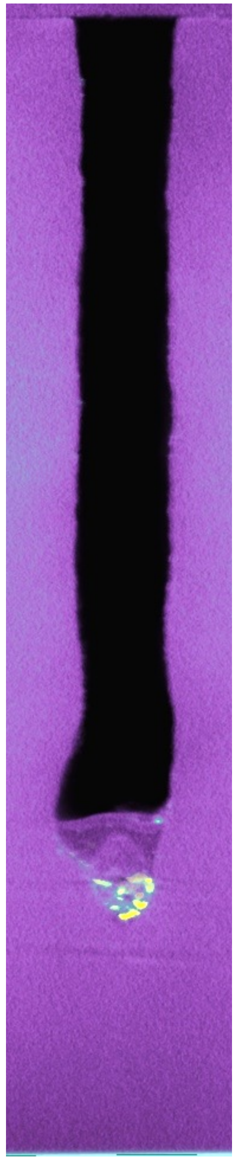


Gas Flow	
A_1 $\frac{(atm \cdot s)}{(cm^3 \cdot cp)}$	RI $\frac{(cm^3 \cdot cp)}{(atm \cdot s)}$
0.314	3.185

Applying the viscosity-corrected reciprocal rate index approach

- Axial configuration Test for RR:

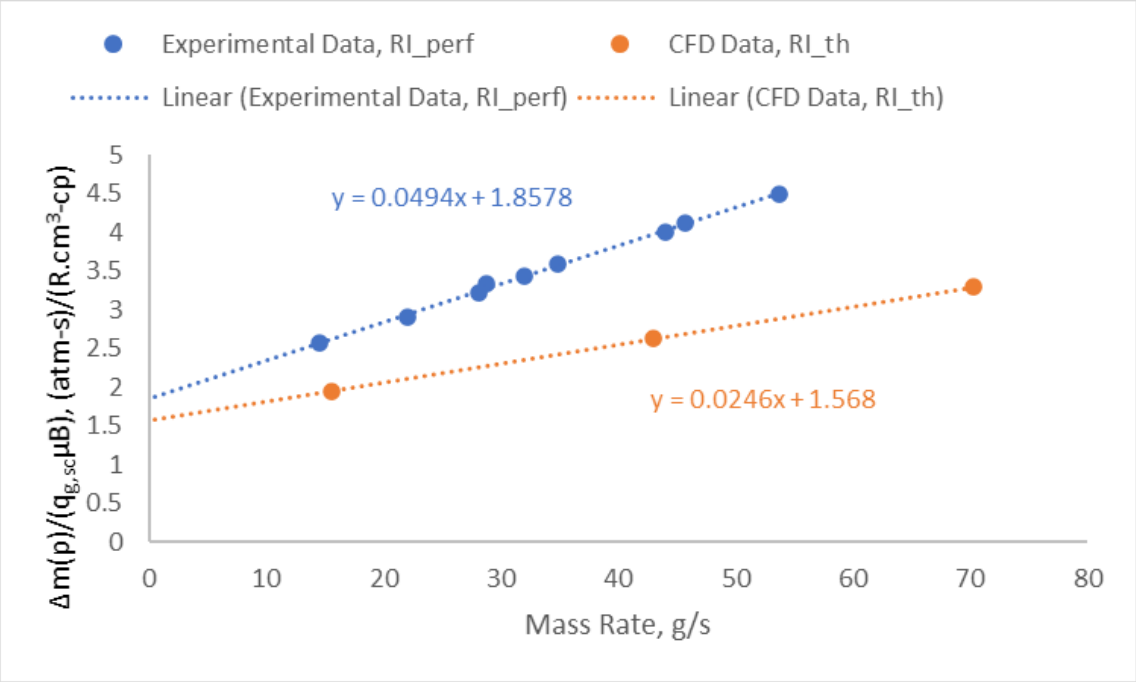


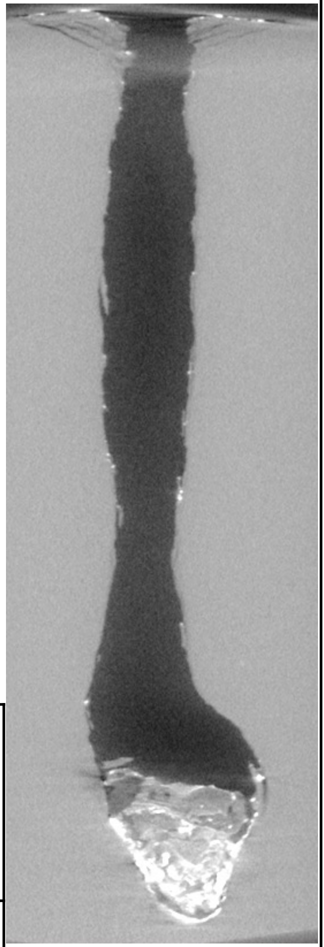


	A_1 $\frac{(\text{atm} \cdot \text{s})}{(\text{cm}^3 \cdot \text{cp})}$	RI $\frac{(\text{cm}^3 \cdot \text{cp})}{(\text{atm} \cdot \text{s})}$
Pre-shot	2.477	0.404
Post-shot	2.189	0.457

$$RR = \frac{RI_{postshot}}{RI_{preshot}} = \frac{0.457}{0.404} = 1.132$$

- Axi-radial Configuration Test for CFE:





	A_1 $\frac{(\text{atm} \cdot \text{s})}{(\text{cm}^3 \cdot \text{cp})}$	RI $\frac{(\text{cm}^3 \cdot \text{cp})}{(\text{atm} \cdot \text{s})}$
Actual	1.858	0.538
Ideal	1.568	0.638

$$CFE = \frac{RI_{actual}}{RI_{ideal}} = \frac{0.538}{0.638} = 0.844$$

So what?

- This alternative method provides:
  - A systematic approach to determine a single Darcian, fluid- and rate-independent, rate index value. As defined, this rate index is only a function of permeability and flow path (length, area, & geometry).
    - Helpful for when more than one fluid is tested (e.g., liquid injection followed by gas production), when the same fluid is tested but at different temperatures, when different flow rates or differential pressures are tested.
    - Important when determining CFE → single-shot skin → crushed zone permeability.
  - A different perspective of the flow data, which can be helpful in the analysis process of determining the flowing properties of the perforation.

Q&A