IPS 2022

INTERNATIONAL PERFORATING SYMPOSIUM

SEPTEMBER 26-28

On the measurement of flow resistance and erosion of perforations

IPS-1.3-22

AUTHORS: Davood M. Yosefnejad, Bernd Fricke, Jörn Löhken, Liam McNelis, Denis will and Rudolf Reimer

Intro

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Coefficient of Discharge and Perforation erosion is a large industry topic in recent years

Effects of Perforation-Entry Friction on Bottomhole Treating Analysis
J.B. Crump, Halliburton Services
M.W. Conway,* SPE, Halliburton Services

SPE 16189
The Application of Limited-Entry Techniques in Massive Hydraulic Fracturing Treatments
D.D. Cramer, BJ-Titan Services Co.
SPE Member

New Perforation Pressure-Loss Correlations for Limited-Entry Fracturing Treatments
A.M. El-Rabba,* SPE, S.N. Shah, SPE, U. of Oklahoma, and D.L. Lord, SPE, Halliburton Energy Services

SPE-200612-
The Role of Back Pressure and Perforation Hole Erosion on the Magnitude of the Coefficient of Discharge in Hydraulic Fracturing Stimulation
Davood M. Yosefnejad, Bernd Fricke, Joern Loehken, and Liam McNelis, DynaEnergetics Europe GmbH
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SPE-204178-MS
An Experimental Study of Coefficient of Discharge for Consistent Hole Perforating and the Effect on Limited Entry Designs
Scott Thiessen and Oliver Han, Hunting Energy Services - Titan Division; Ramadan Ahmed and Rida Elgaddafi, University of Oklahoma
Copyright 2021, Society of Petroleum Engineers

SPE-209178-MS
Modeling Proppant Transport in Casing and Perforations Based on Proppant Transport Surface Tests
Jack Kolle, Oil States Energy Services; Alan Mueller, ACMS, LLC; Steve Baumgartner and David Cuthill, Geodynamics Inc.

SPE-209141-MS
Execution and Learnings from the First Two Surface Tests Replicating Unconventional Fracturing and Proppant Transport
Phil Snider and Steve Baumgartner, GEODynamics Inc.; Mike Mayerhofer, Liberty Oilfield Services; Matt W
PDC Energy
Copyright 2022, Society of Petroleum Engineers DOI 10.2118/209141-MS

SPE-209156-MS
Determination of the Perforation Hole Erosion Characteristics on Single and Dual Casing for Hydraulic Fracturing, in a Laboratory Test Setup Under Realistic Downhole Conditions
Joern Loehken, Bernd Fricke, Liam McNelis, and Davood Yosefnejad, Dynaenergetics Europe GmbH

Content

Why is the Hole Size and the Coefficient of Discharge important?

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- Perforation pressure drop is given by the difference between bottom hole treating pressure and the fluid pressure in the fracture:

$$p_r = p_{BHTP} - p_f - p_{NB}$$

- It can be calculated according to:

$$p_r = \frac{8\rho}{\pi^2 C_D^2 D^4}\left(\frac{Q}{n}\right)^2 = \frac{\rho}{2(AC_D)^2}\left(\frac{Q}{n}\right)^2$$

- A high perforation pressure drop is essential for a successful limited entry fracking strategy!
- Accurate perforation hole sizes and coefficient of discharge knowledge is crucial due to a high sensitivity to these values!

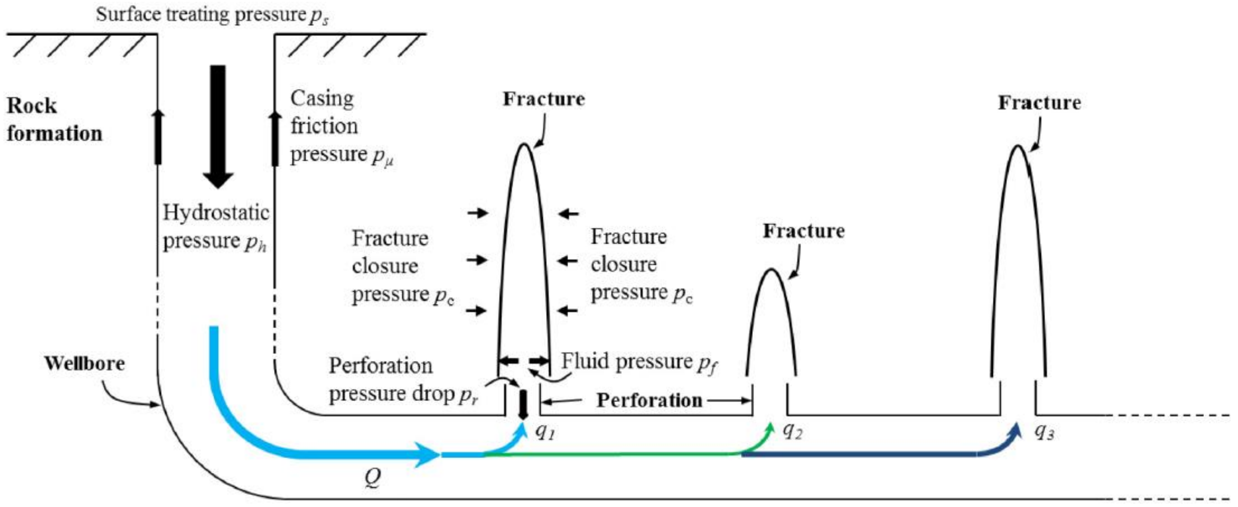
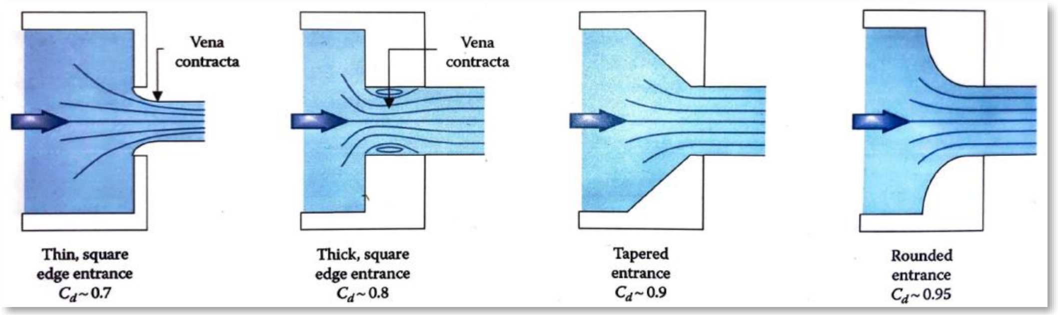
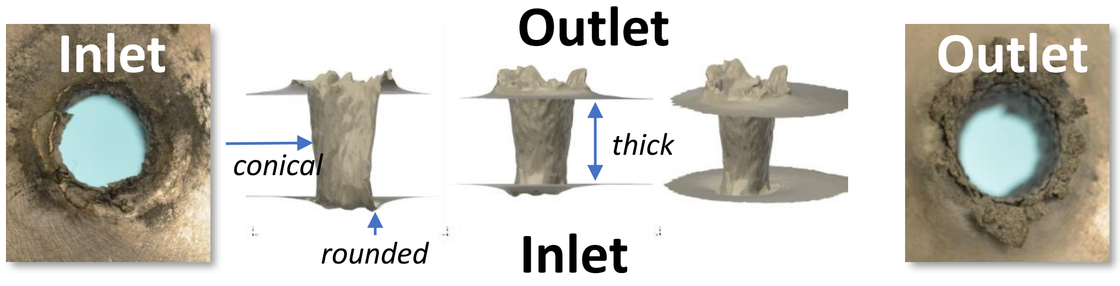


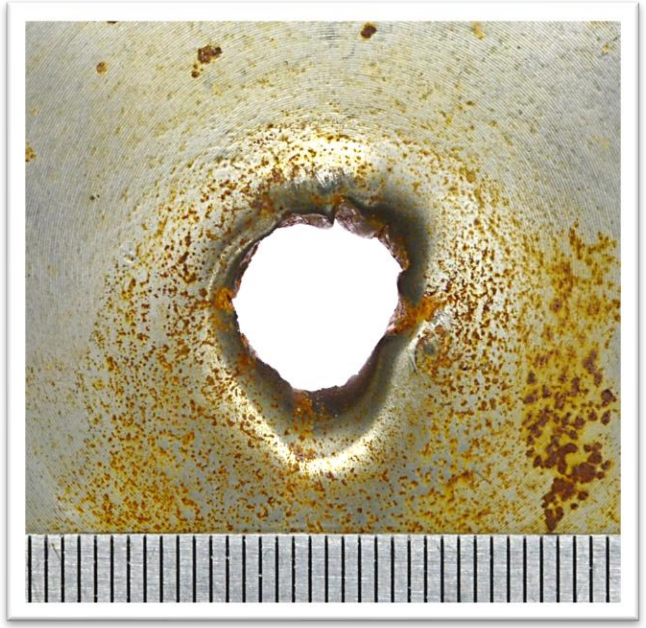
Figure 1—Schematic view of the pressure and fluid distribution during a hydraulic fracturing treatment

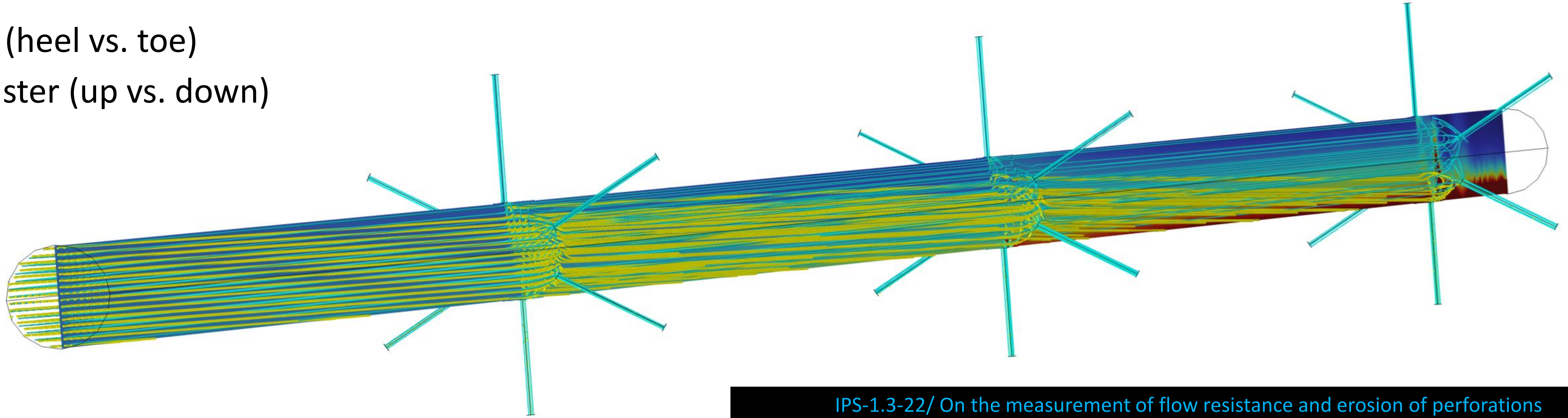




Erosion

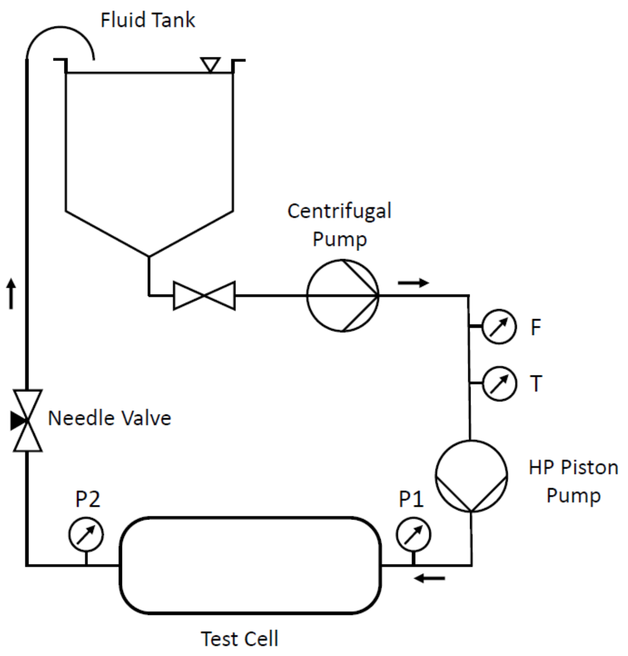
- But Hole Size and C_D change!
- During the frac treatment the proppant in the fluid causes an abrasive growth of the perforation hole and change of the geometry
- An uncontrolled increase of the holes may lead to a non uniform frac treatment
- Many factors influence the erosion
  - Proppant size & Concentration
  - Flow velocity
  - Position of the cluster (heel vs. toe)
  - Position within the cluster (up vs. down)
  - Type of Steel
  - …….

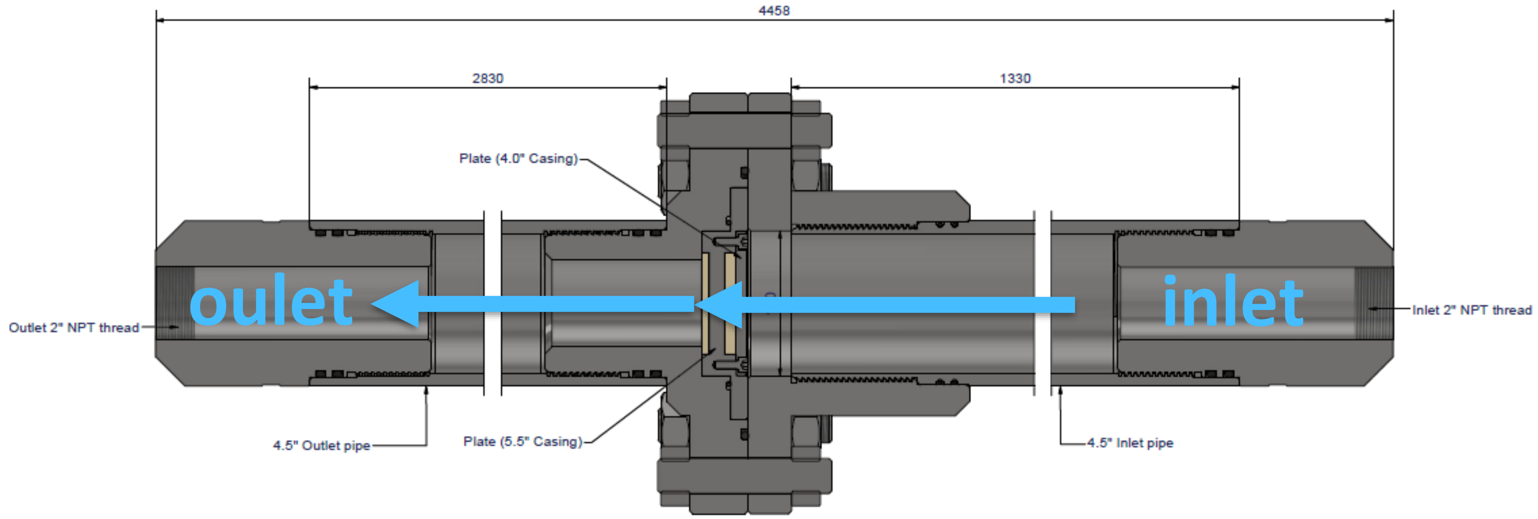




Laboratory flow test setup A – Flow through Single & Dual Casing

- High pressure test cell
  - flow rates of up to 3-4 bbl/min per hole
  - Pressure rating 5Kpsi
- Flat casing plates from API Section 4 tests
  - Effect of the cement and wellbore pressure on the hole is considered
- Benefit:
  - Backpressure can be applied
  - Long chamber to host sand jet (no abrasive destruction)
- Drawback:
  - flow direction not perpendicular to the perforation as in a well.

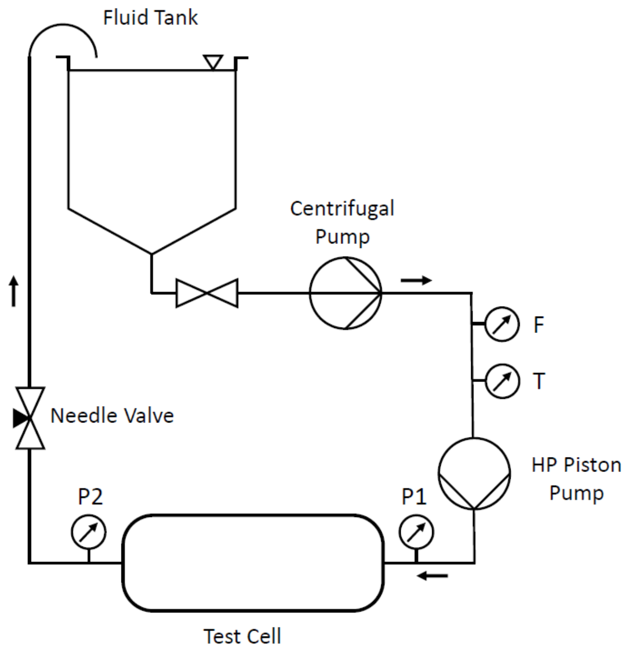


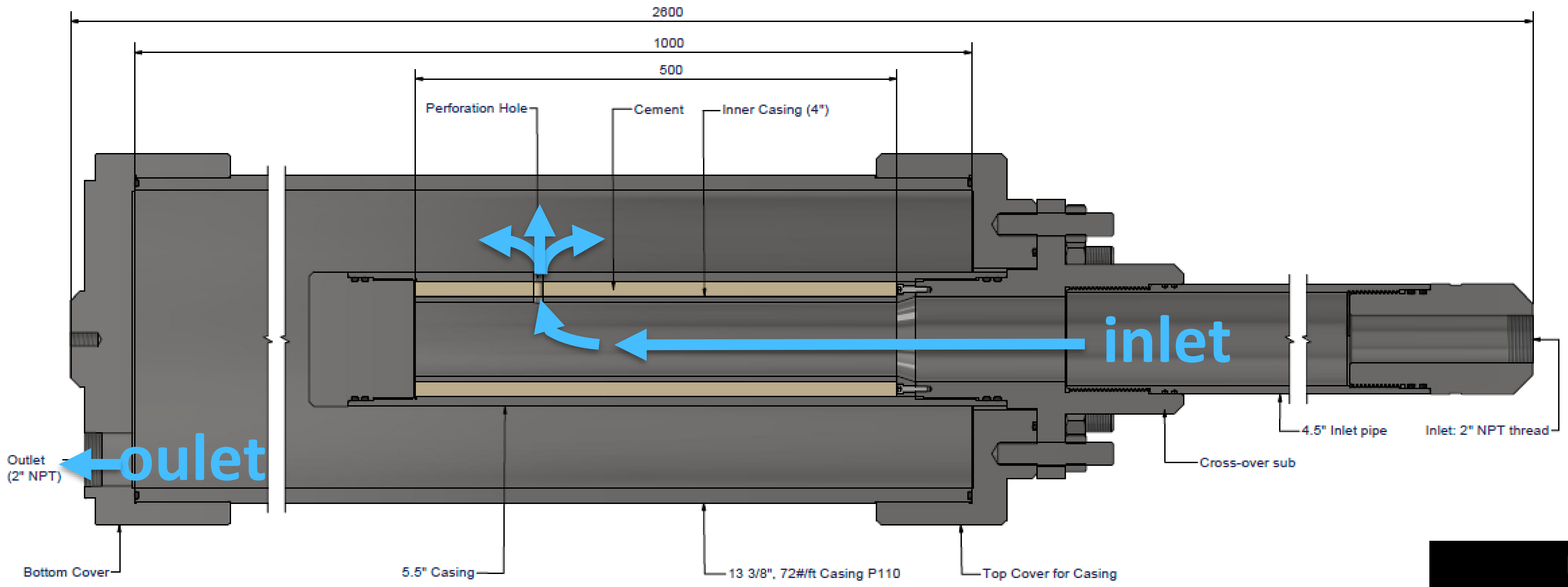


Laboratory flow test setup B – Flow through Single & Dual Casing

- 2K pressure test cell for casing pipes
- Benefits:
  - Original Casing can be used
  - Flow direction mimics well bore
  - Multi-shot guns can be tested

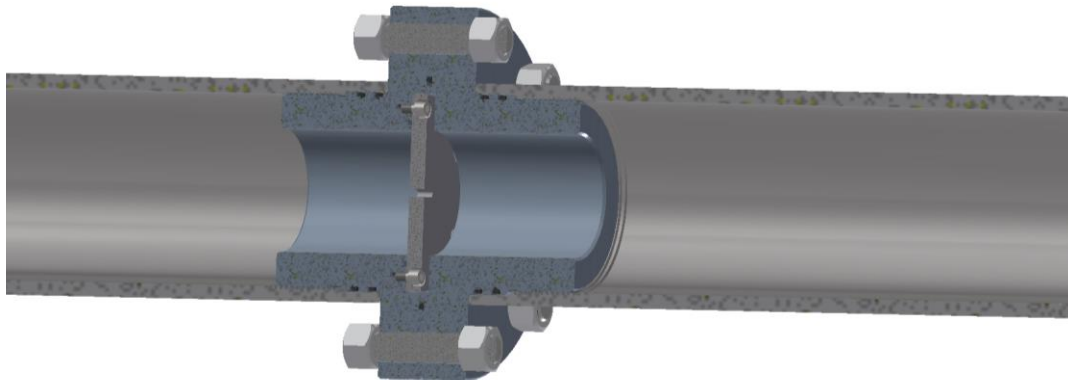
- Drawback:
  - Perforation not shot under realistic pressure conditions
  - Lower pressure rating of the test cell
  - Outer cell wall is close to the perforation:
    - Additional backpressure?
    - Sand jetting?



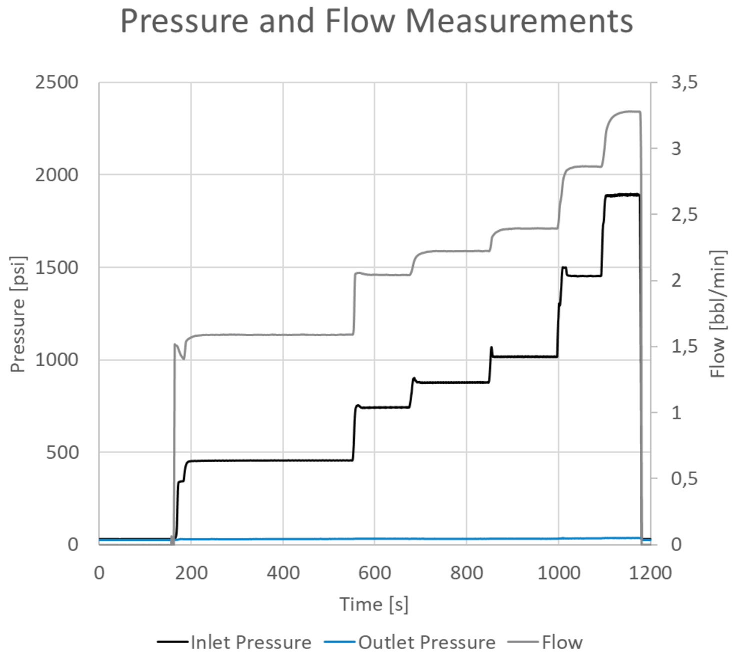


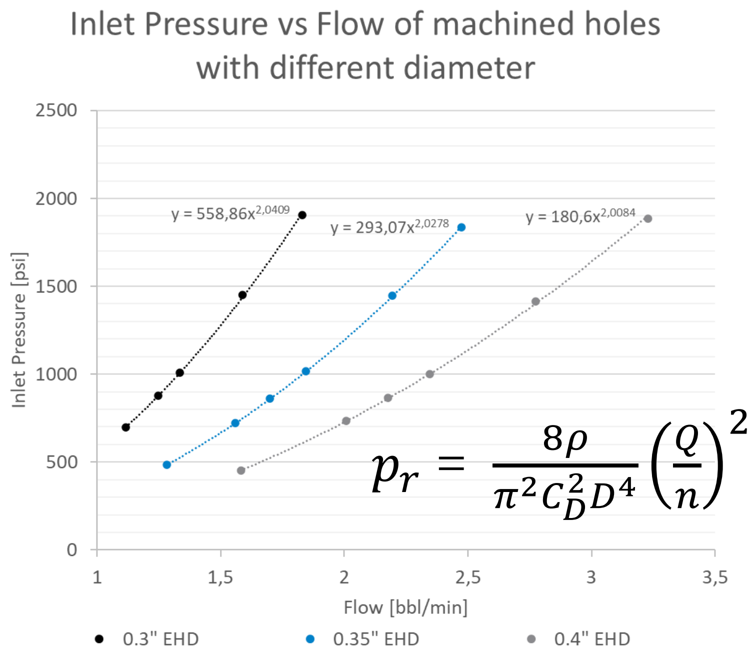
Test program

- 10 Machined plates were tested to see the influence of:
  - Holes Size
  - Casing thickness
  - Conical shapes
  - Tapered inlets
  - Slots



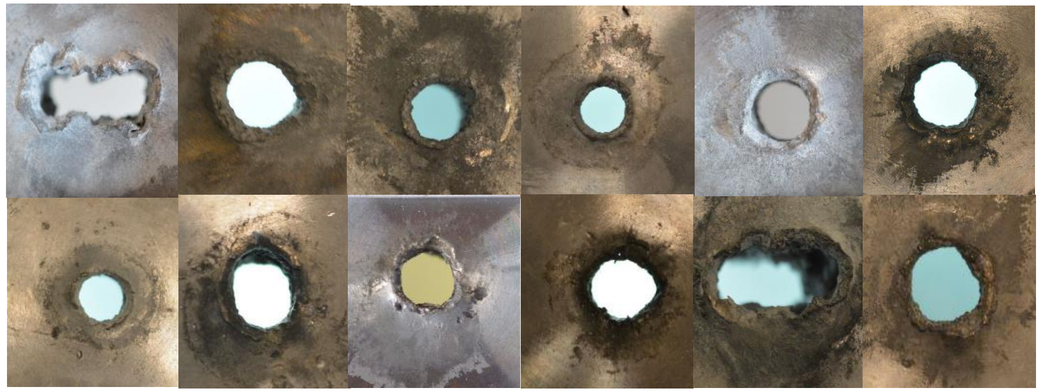
- 12 Perforated plates were taken from API 19 B Section IV tests
  - EEH charge, DP, Slotted, ….
  - 8 gram up to 39 gram





$$p_r = \frac{8\rho}{\pi^2 C_D^2 D^4}\left(\frac{Q}{n}\right)^2$$

- Real Casing were tested in Setup B

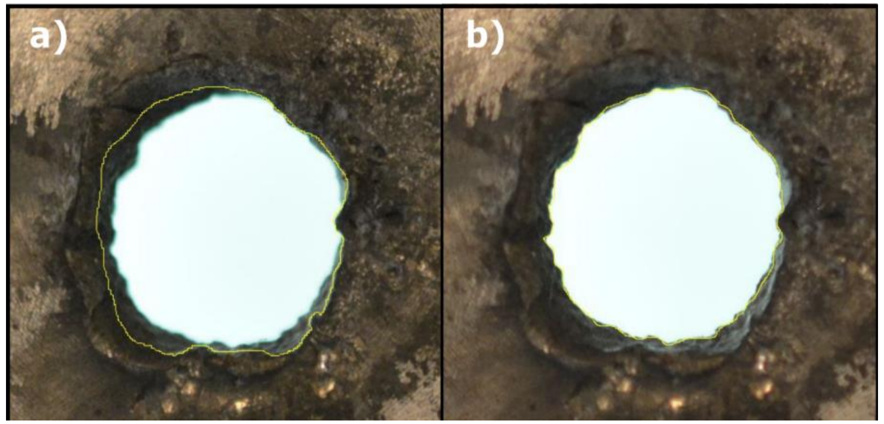


1. Importance of hole size measurements

Caliper measurements

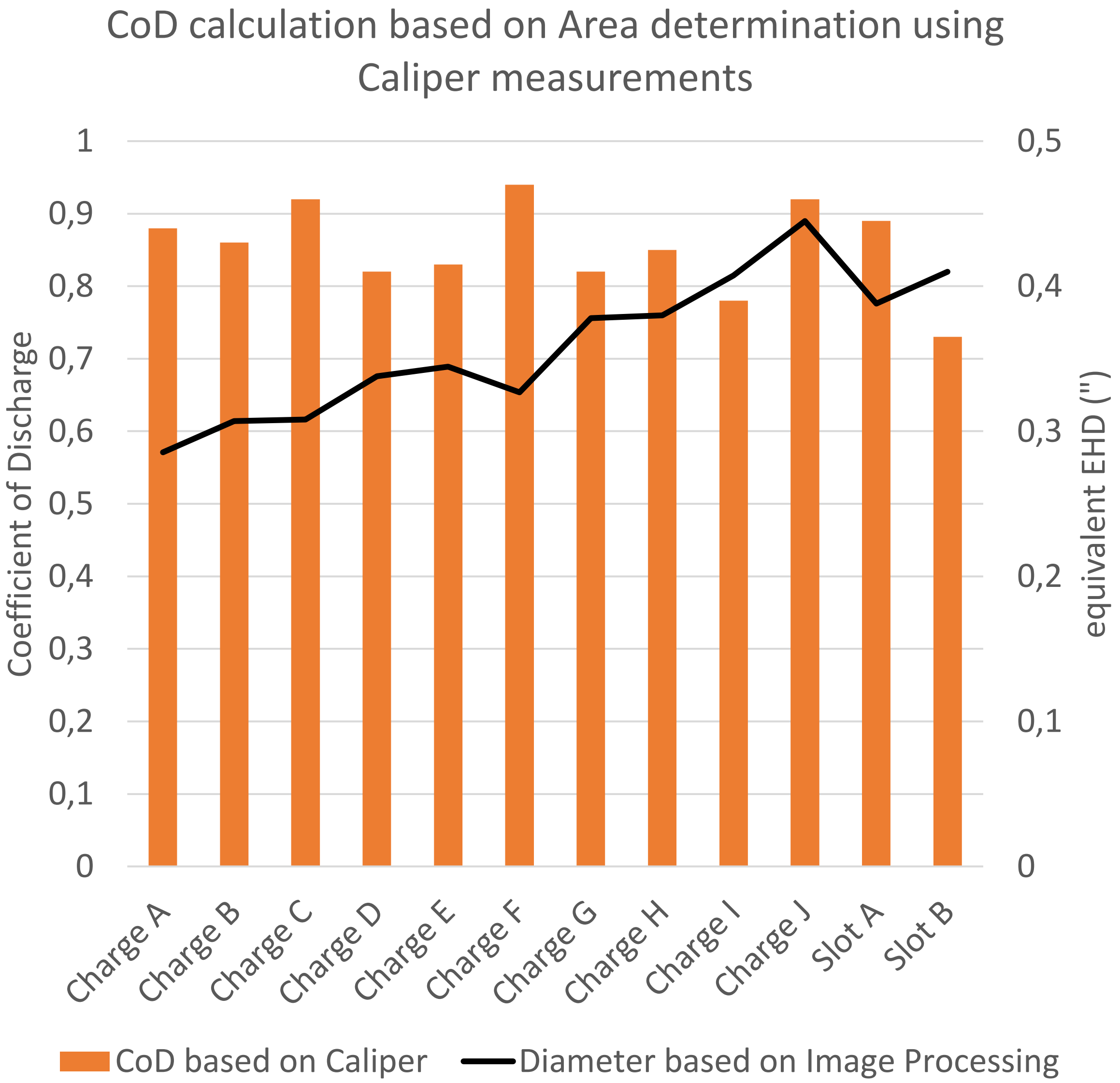
0.29“

Optical measurements



manual 0.32“

automatic 0.30“



1. Importance of hole size measurements

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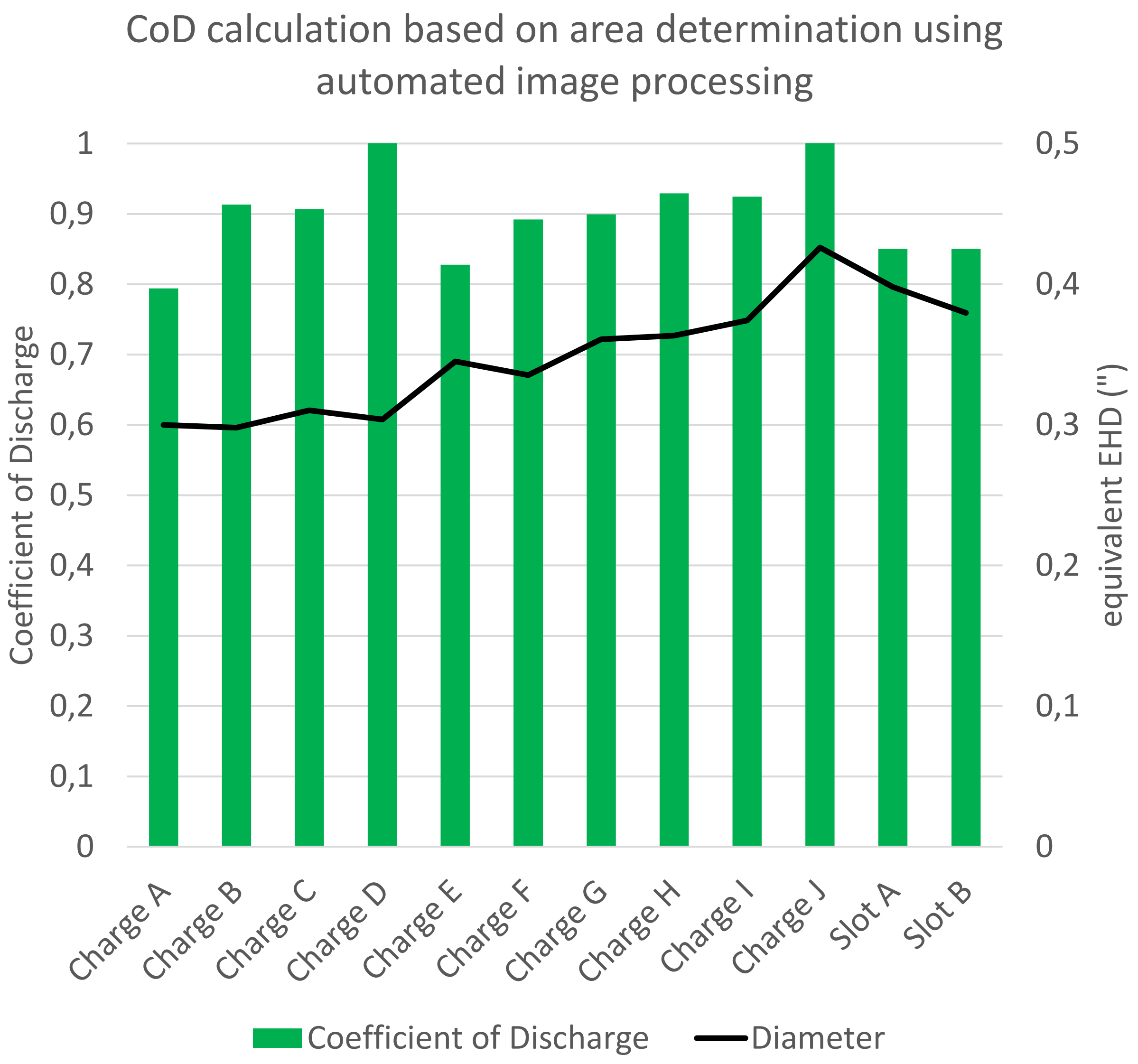
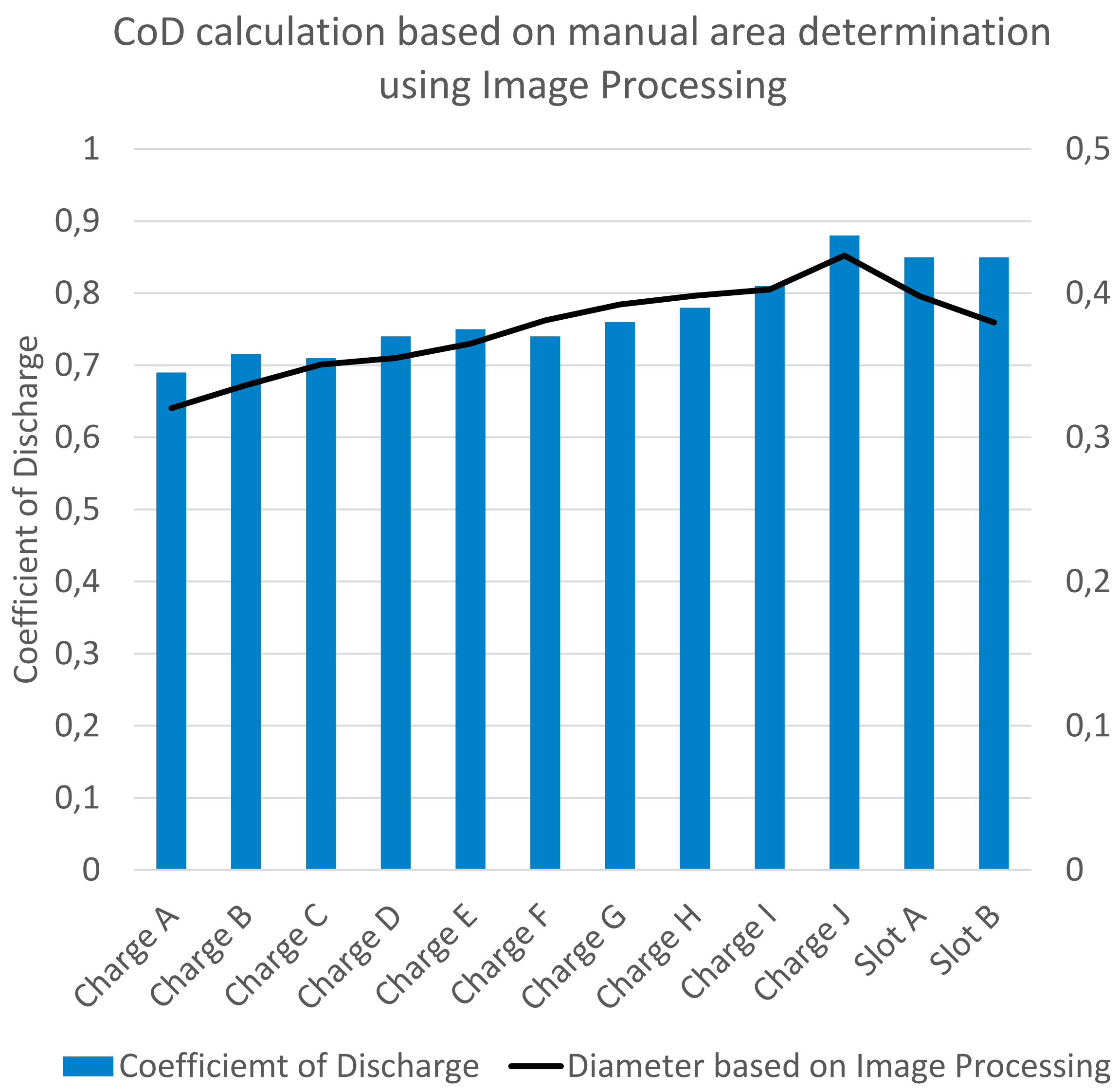
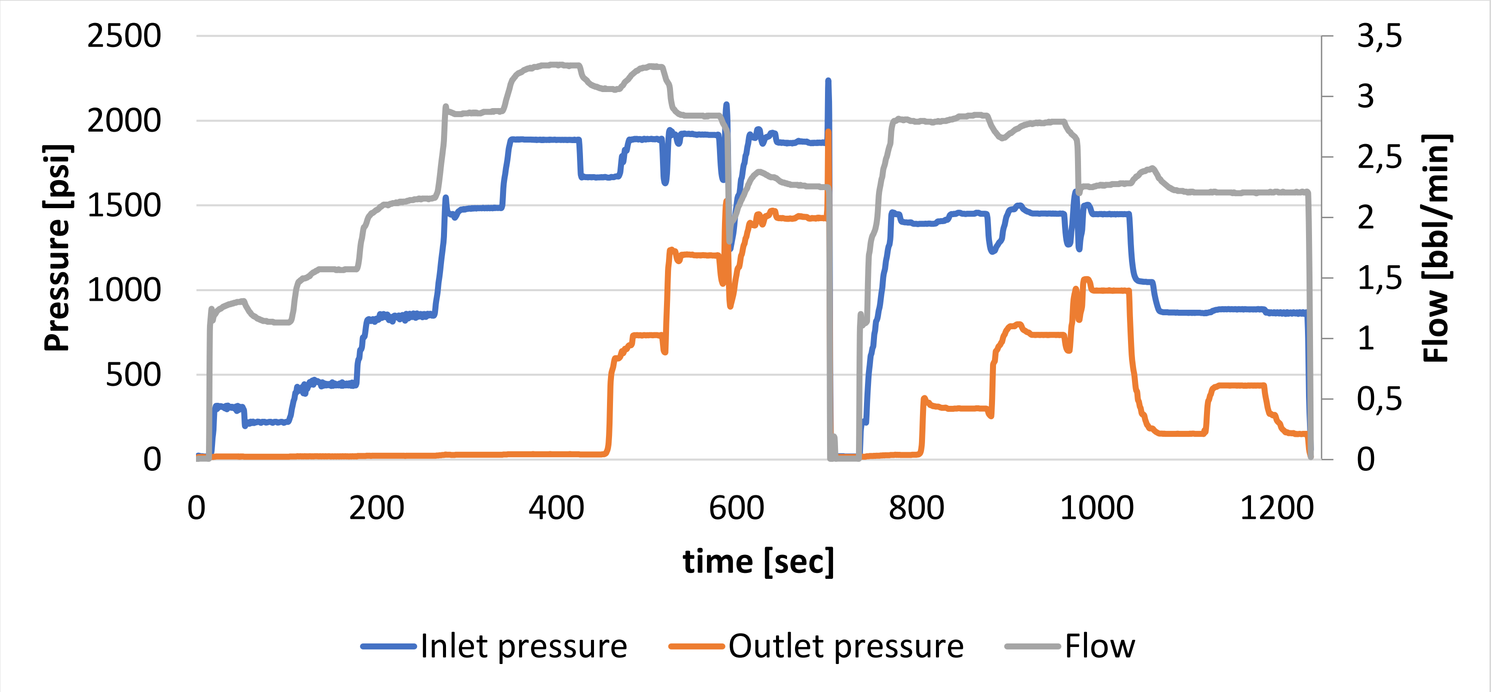




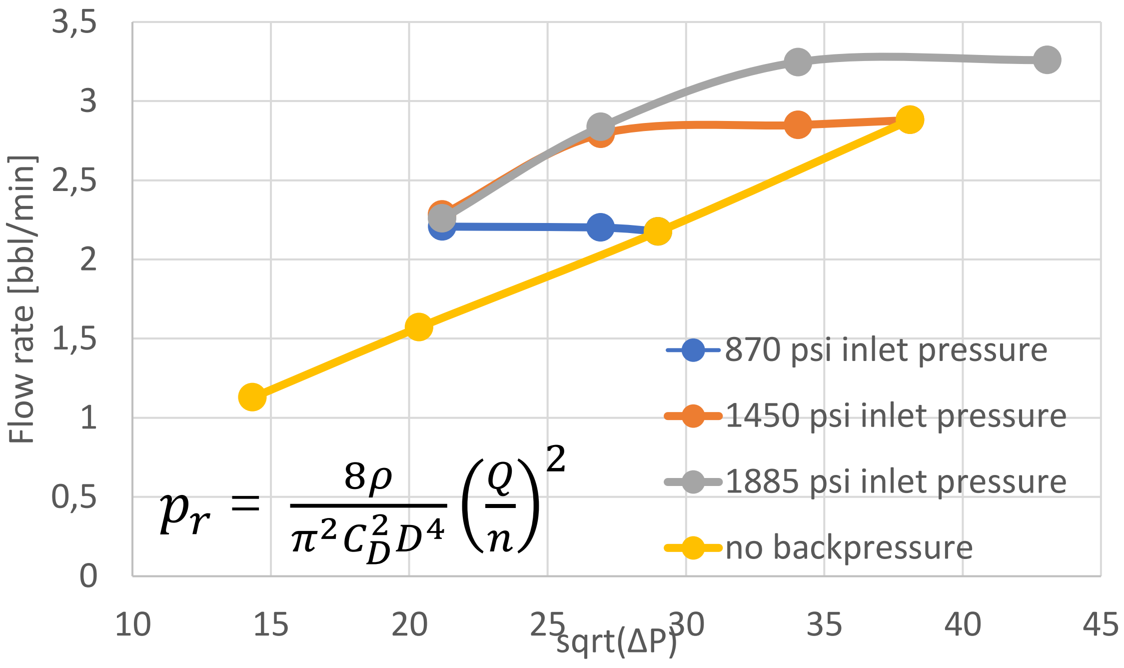
Increasing CoD with hole size also observed e.g. by Lord et al., 1994 and decreasing by Crump and Conway!

2. Influence of the Backpressure

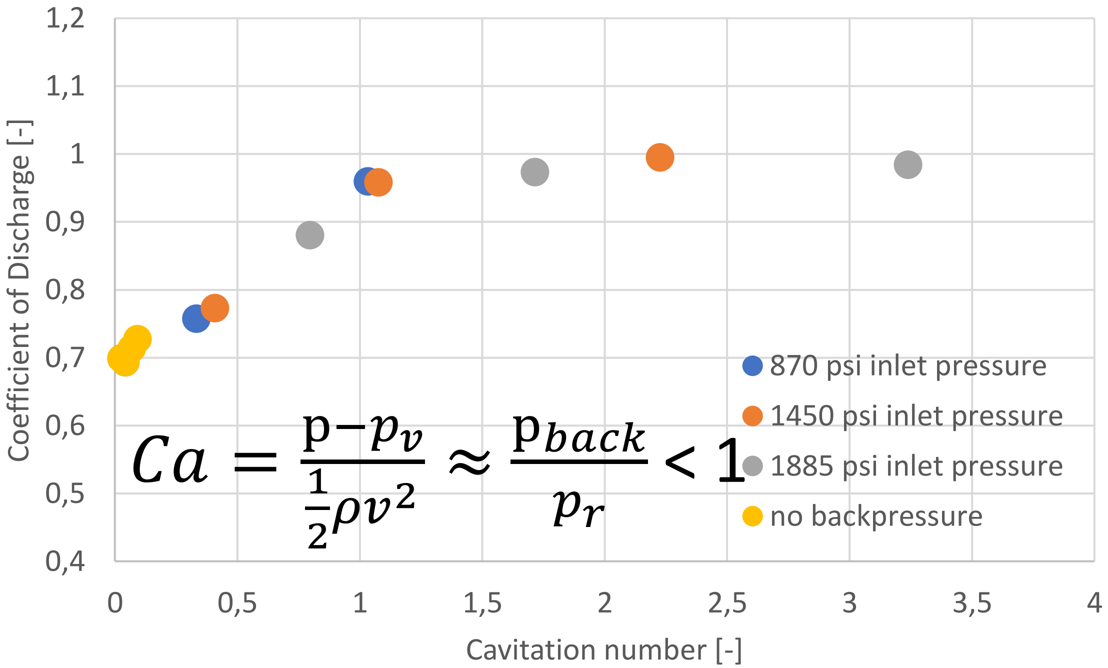
- Measurements also with backpressure, where the backpressure was increased at constant inlet pressure
- C_D is influenced by cavitation
- Backpressure increased the C_D significantly from 0.7 to value of approx. 0.95-1



See also: Kolle et. al. SPE-209178



$$p_r = \frac{8\rho}{\pi^2 C_D^2 D^4}\left(\frac{Q}{n}\right)^2$$



$$Ca = \frac{p - p_v}{\frac{1}{2}\rho v^2} \approx \frac{p_{back}}{p_r} < 1$$

3. Influence of the flow direction

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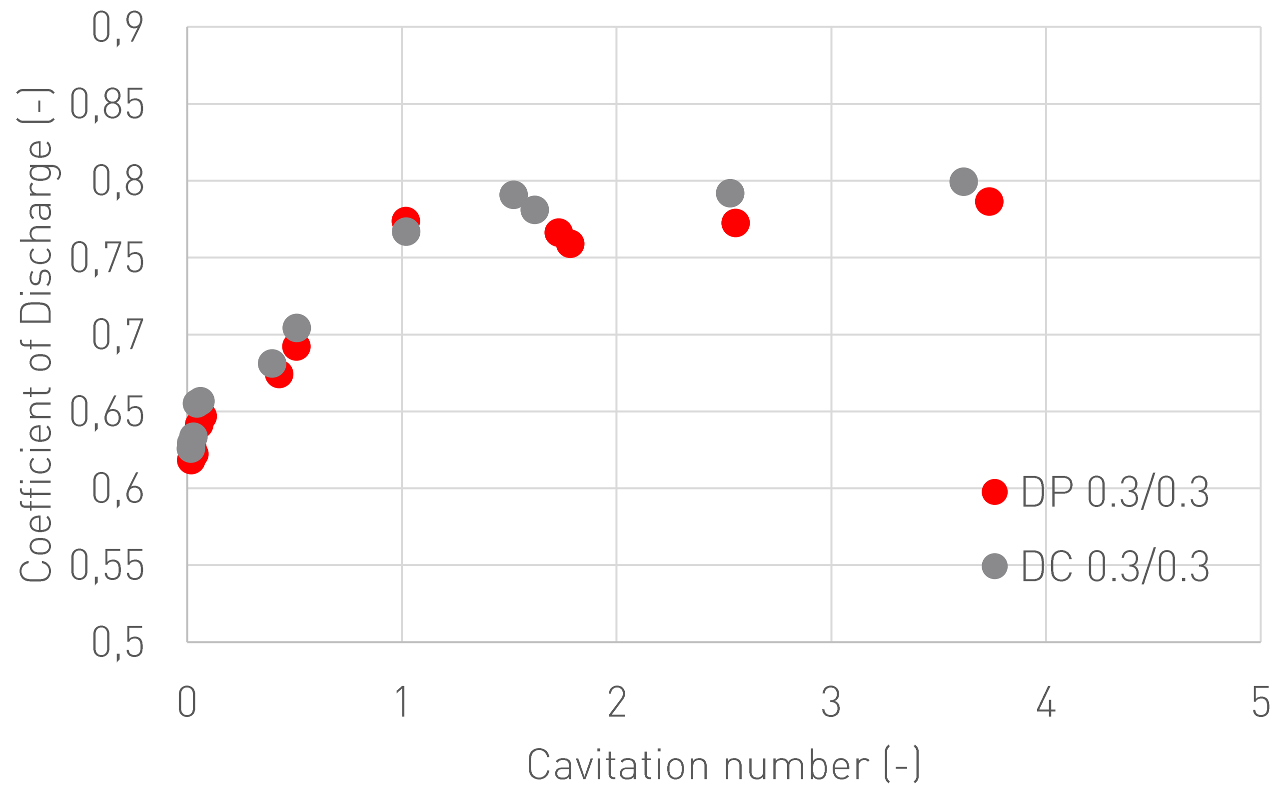
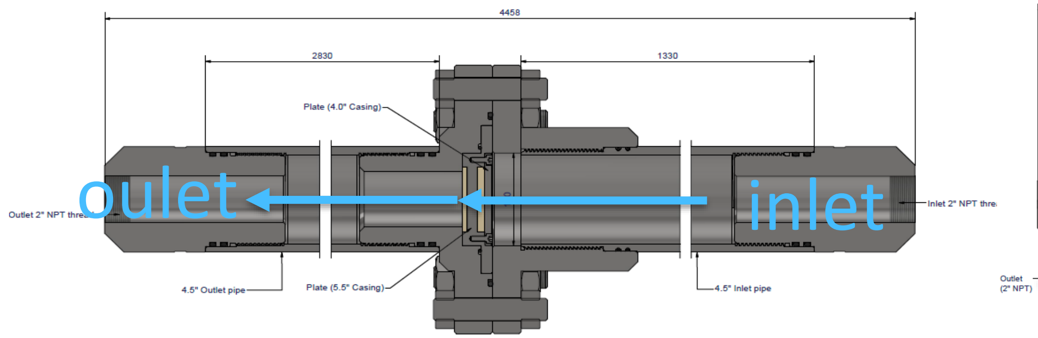
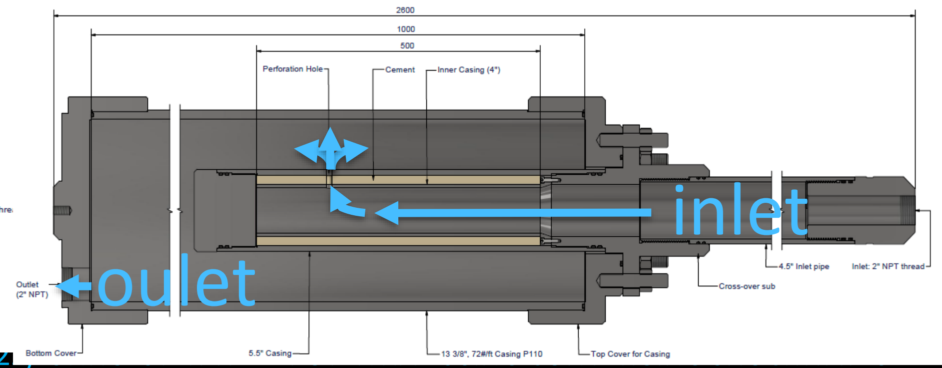
- No difference observed in C_D measurements between the two setups:
  - No flow direction effect for setup A
  - No additional local backpressure effect for Setup B
- Also, for shaped charge perforated casings the results are comparable
- Multi-shot guns were also tested in setup B. The flow scales with number of holes



Setup A

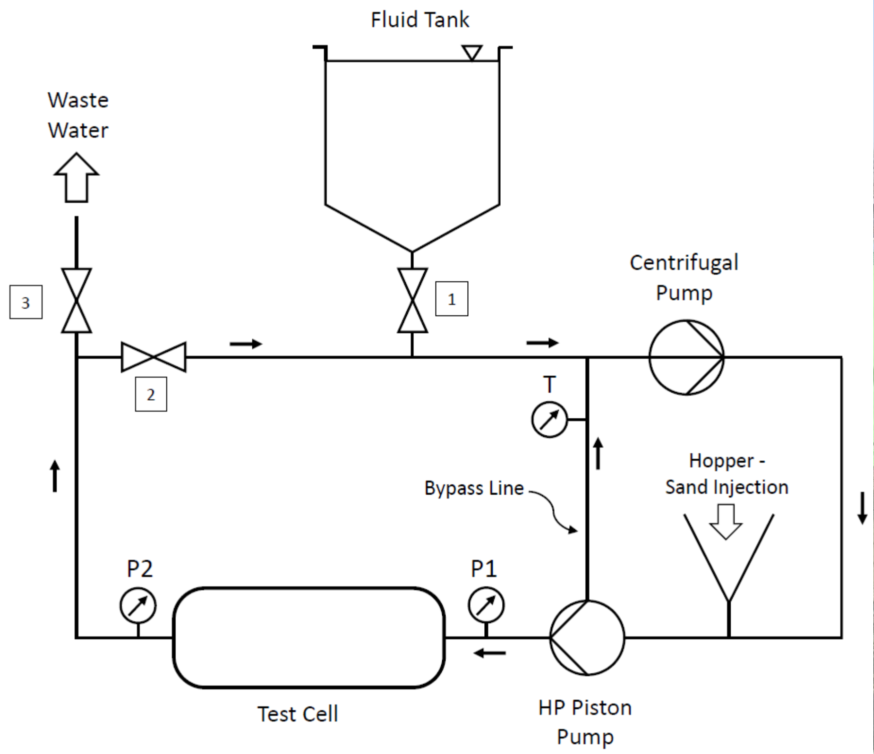


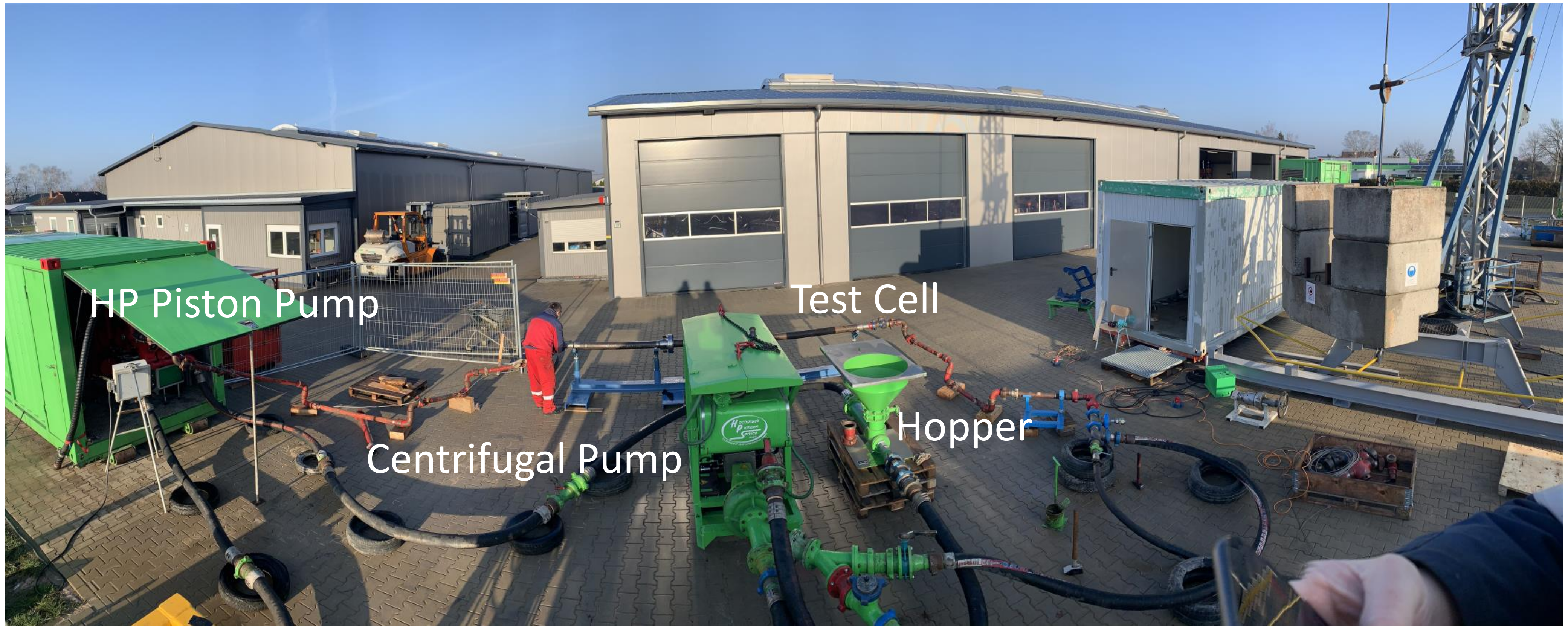
Setup B



4. Test setup real casing vs. closed loop setup for erosion measurements

- 2 h treating time, 1ppg, 3bbl/min per hole – 15120lbs (7.5tons) of sand per hole & test
- In 16 min 1 ton per hole and test
  - What about test programs with multiple clusters and parameter studies?
  - Logistics & Disposal
  - Costs & Time
- In a closed loop the amount of sand reduces to 150lbs & 1.5h per test, but there are also disadvantages…..





5. Limitations of the closed loop setup - temperature

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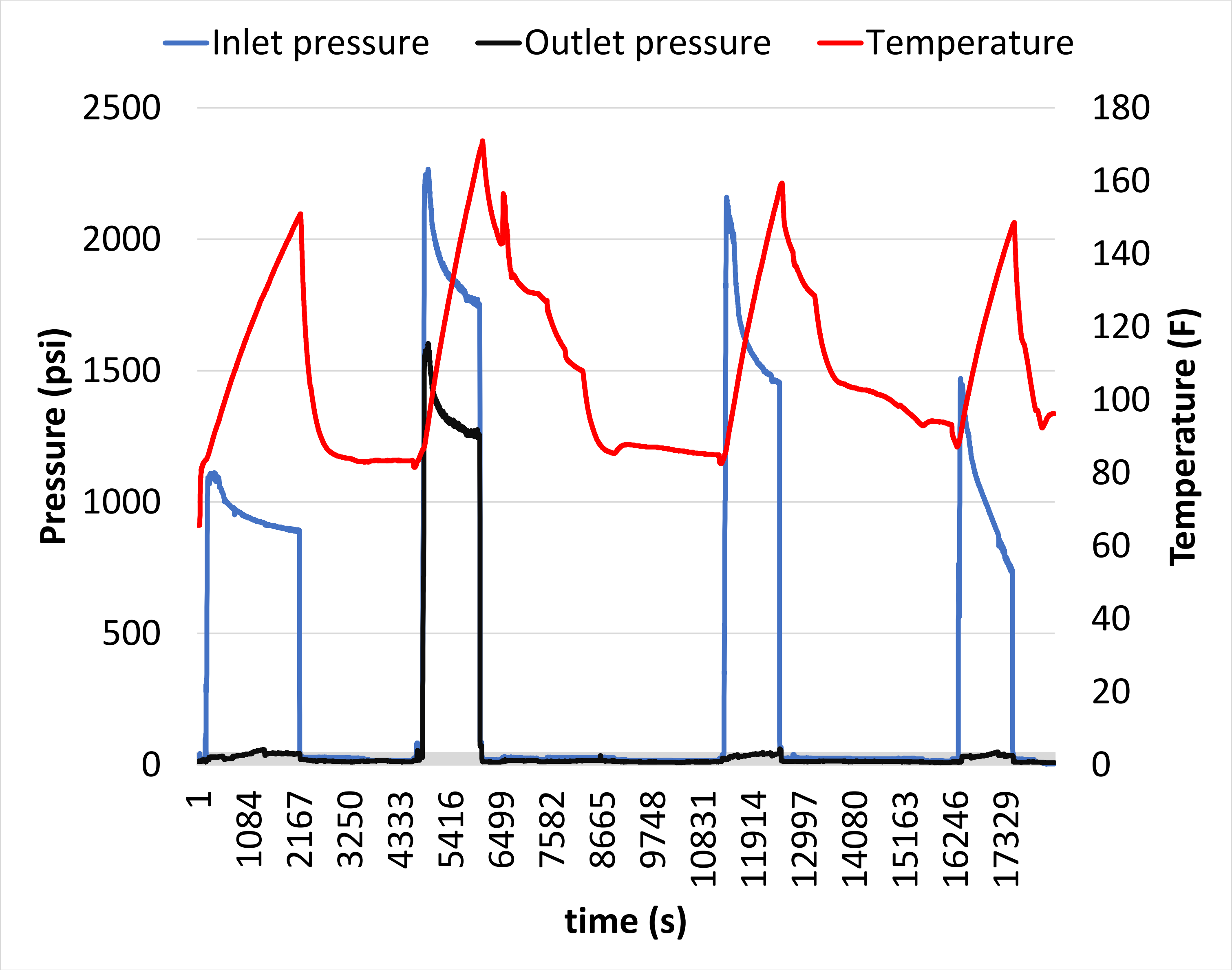
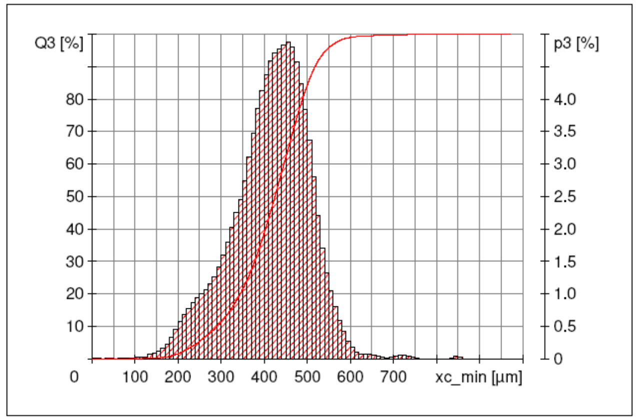
- Temperature increases due to the kinetic energy of the sand grains impacting the casing
- Temperature raises from 30 °C to 70°C within 10-15 min
- Risk that rubber hoses burst
- Test duration limited
- Effect not observed with pure water



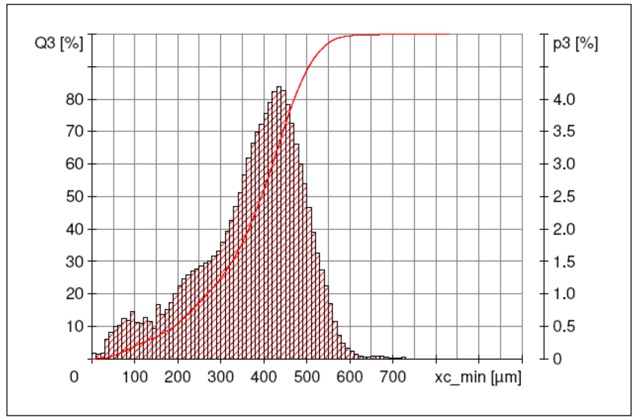
6. Limitations of the closed loop setup - sand

- Sand is crushed by the impact
- Sand grain size distrubution changes during the test
    - Total mass of sand is identical
    - Better transport of fine grains, but
    - Less “high energetic” coarse sand grains
- Better Logistics & Cost for closed loop setup
- But after approx. 10 min data might be influenced by sand grain crushing

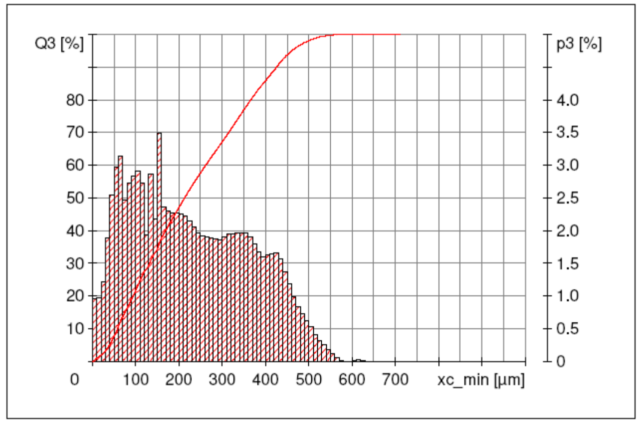
Before the test



After 10 min

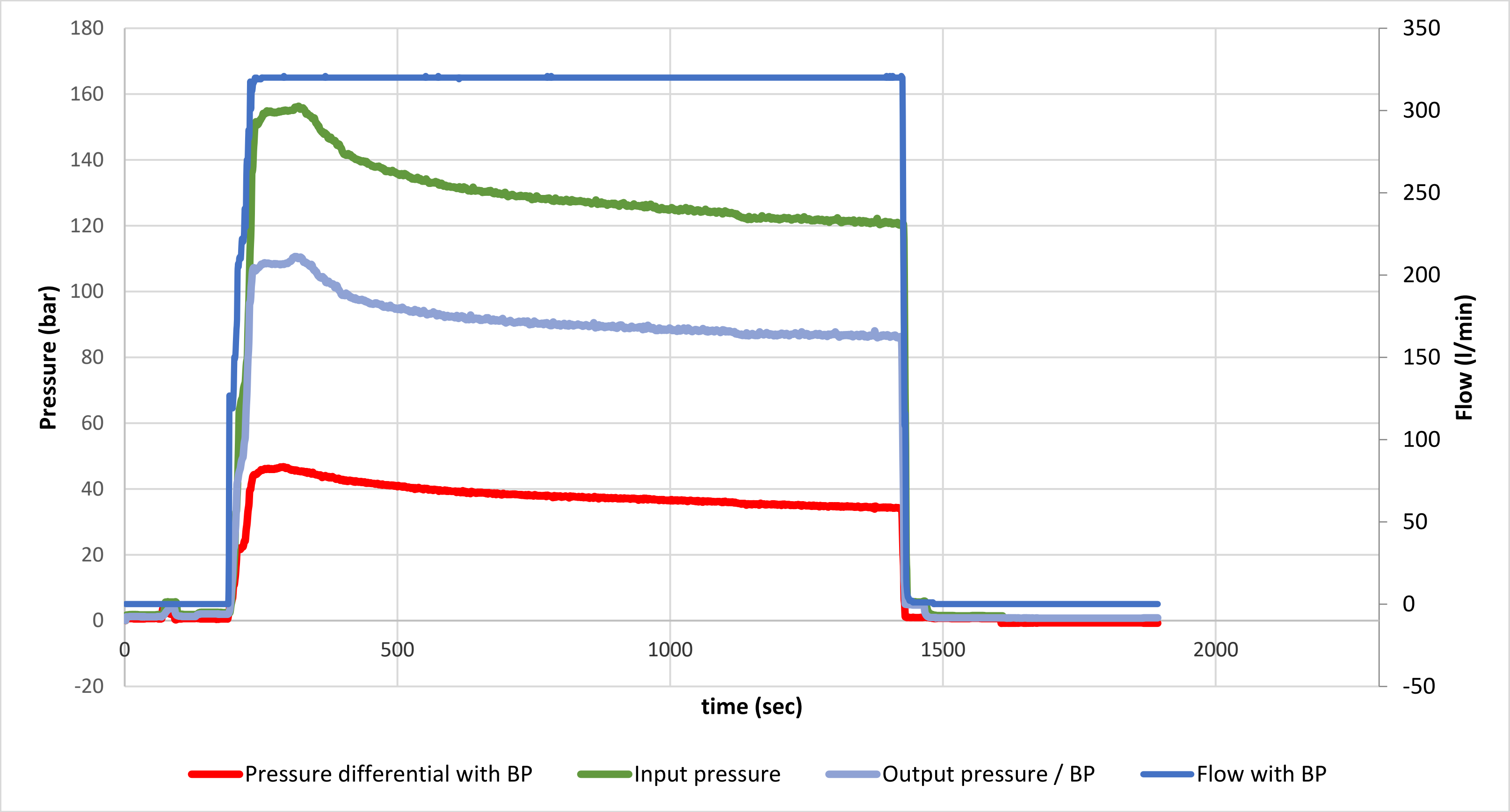


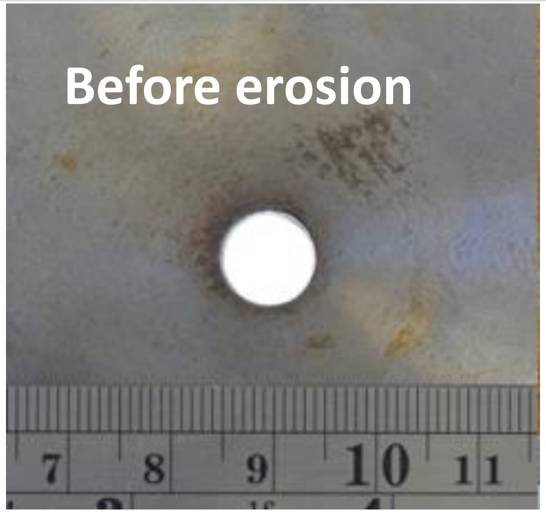
After the test (approx. 20 min)

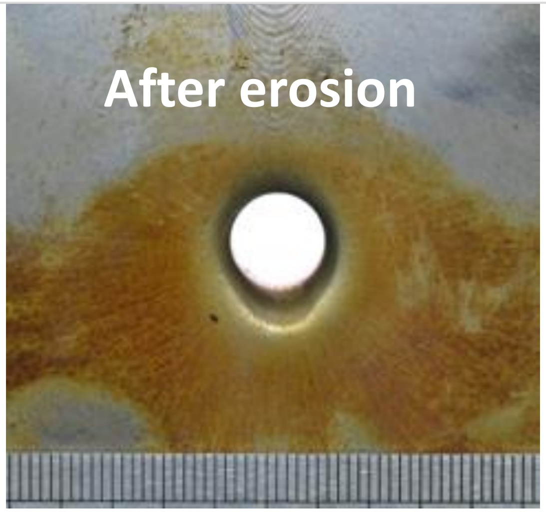


7. Influence of the back pressure on the erosion

- In a frac well the formation pressure creates a backpressure behind the casing
- How does it influence the erosion?
- Nozzle was used to create a back pressure
- Erosion of the nozzle led to a decreasing back pressure

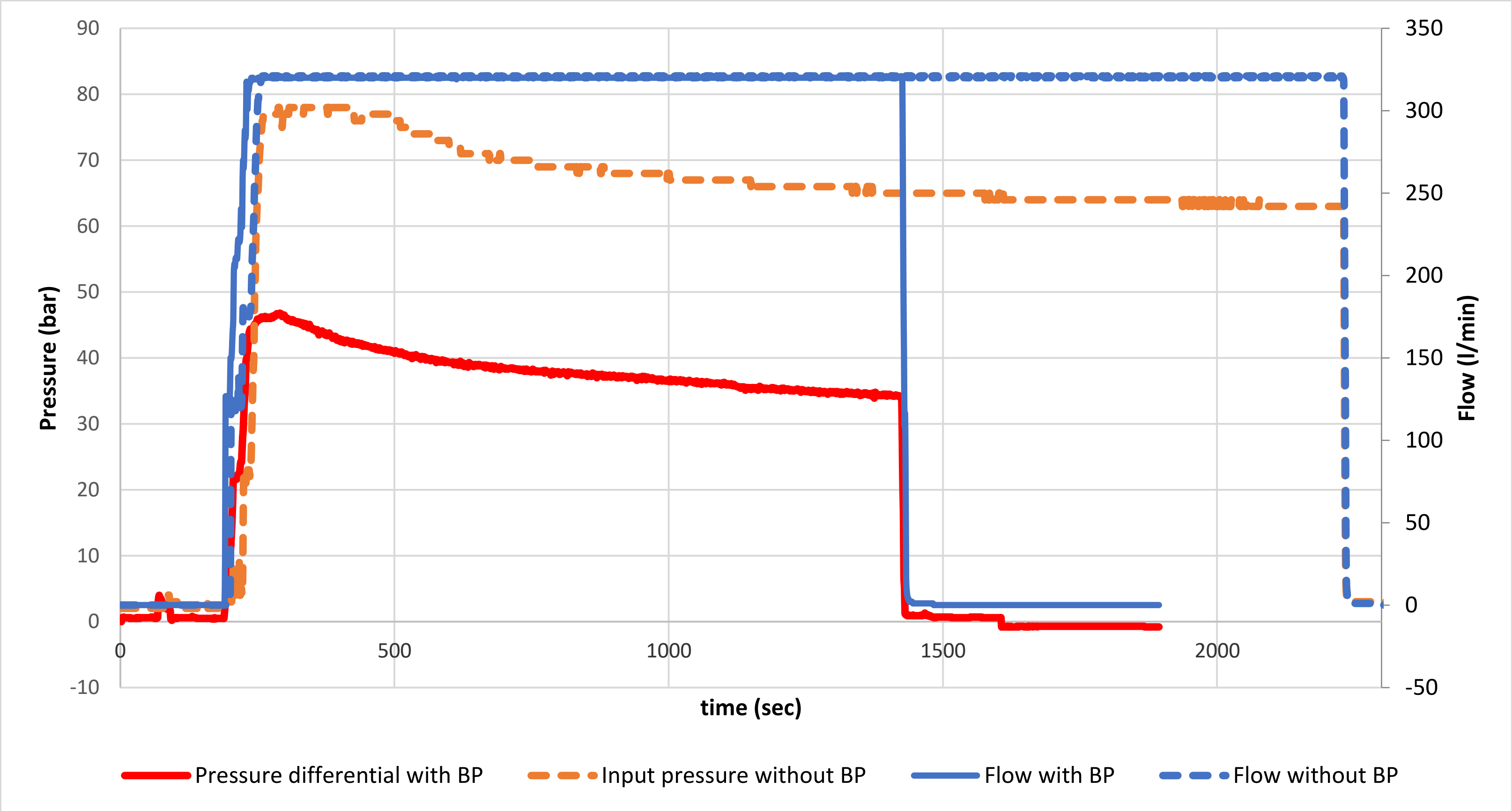


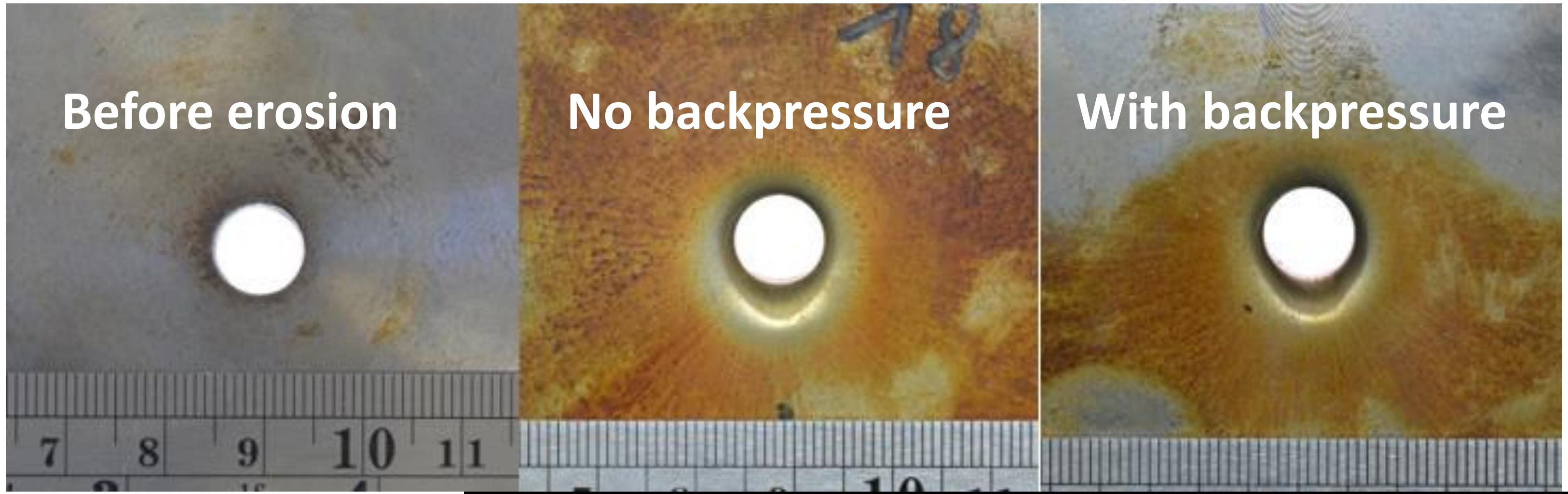




7. Influence of the back pressure on the erosion

- Test was repeated without back pressure
- Due to cavitation more pressure differential is required during the test for the same flow rate
- Hole erosion looks very similar in both tests
- Measured Coefficient of Discharge (C_D) values after the tests are nearly identical
- But pressure vs. C_D or pressure vs. D correlations as being sometimes used for simulations are different for both scenarios





7. Can we convert ambient Data into Backpressure data?

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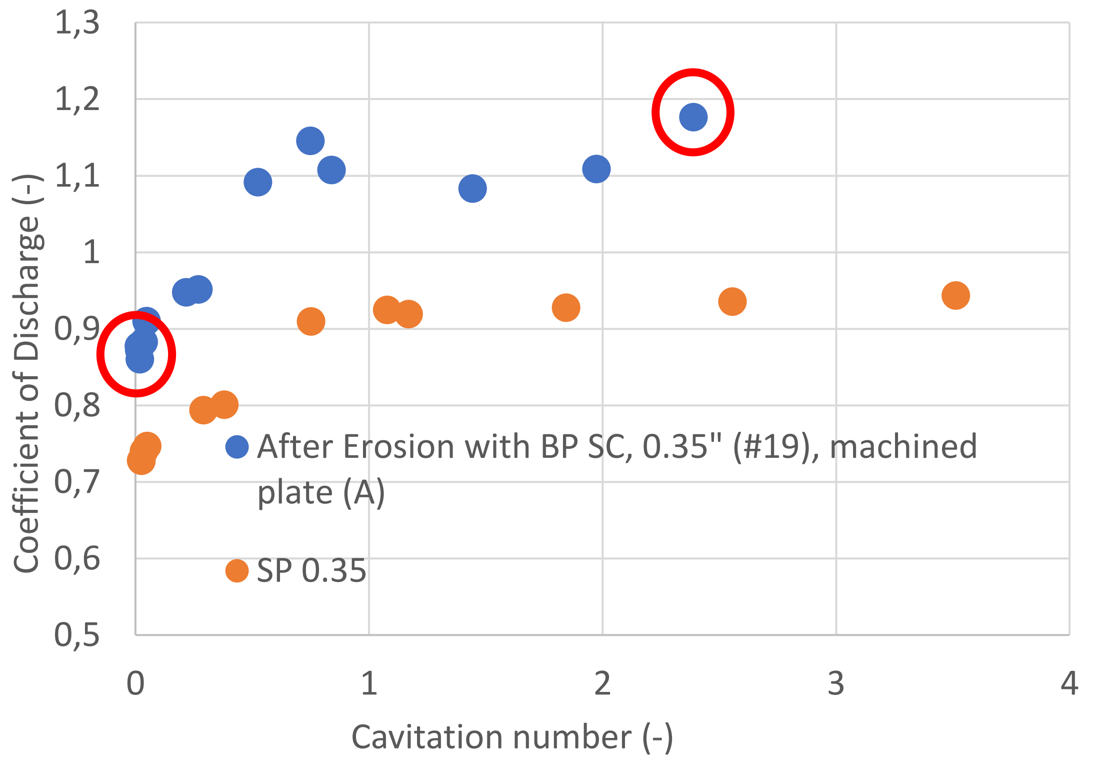
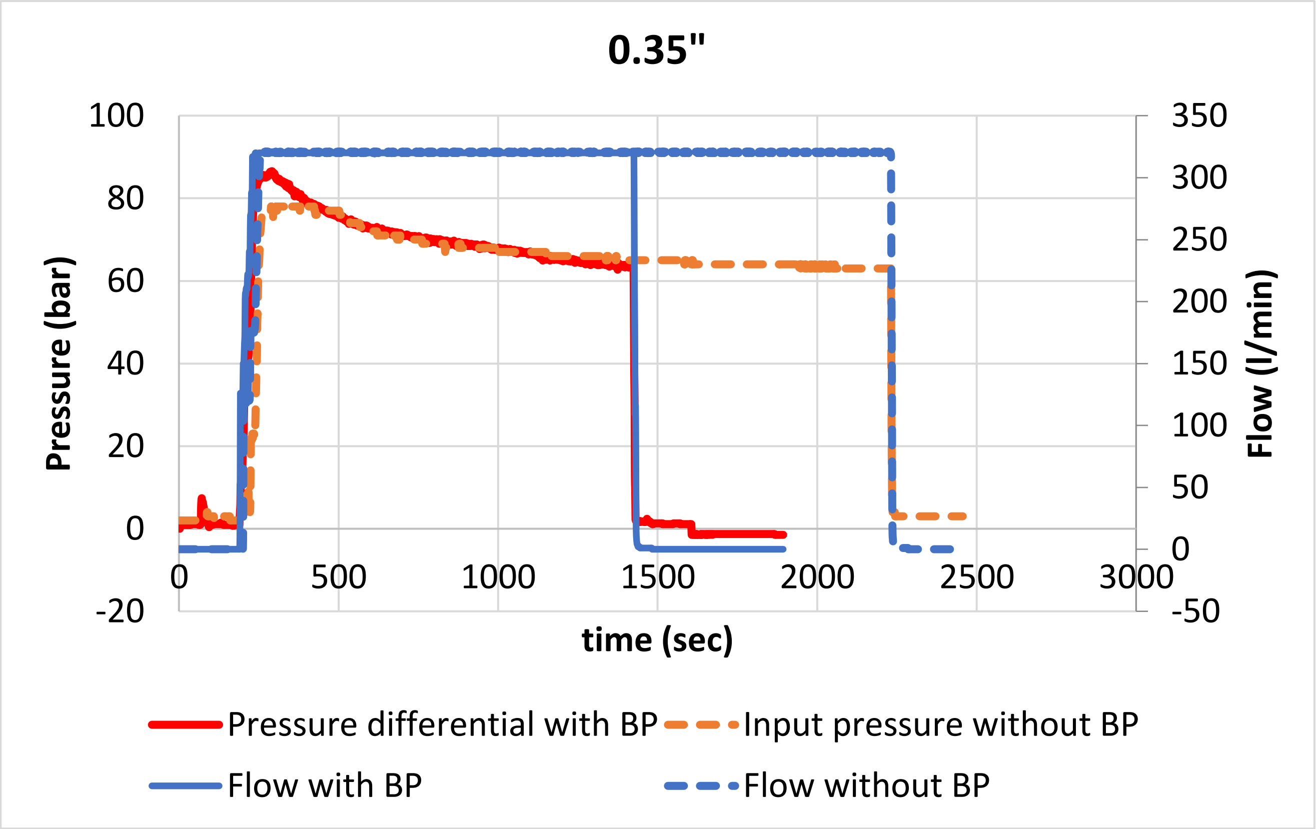
- Correction of pressue using the C_D at Ambient and the C_D with Backpressure, measured after erosion:

$$p_{corrected} = p_{ambient} * \left(\frac{C_D^{ambient}}{C_D^{CN\gg1}}\right)^2$$

- Correction only applicable after the “rounding phase”

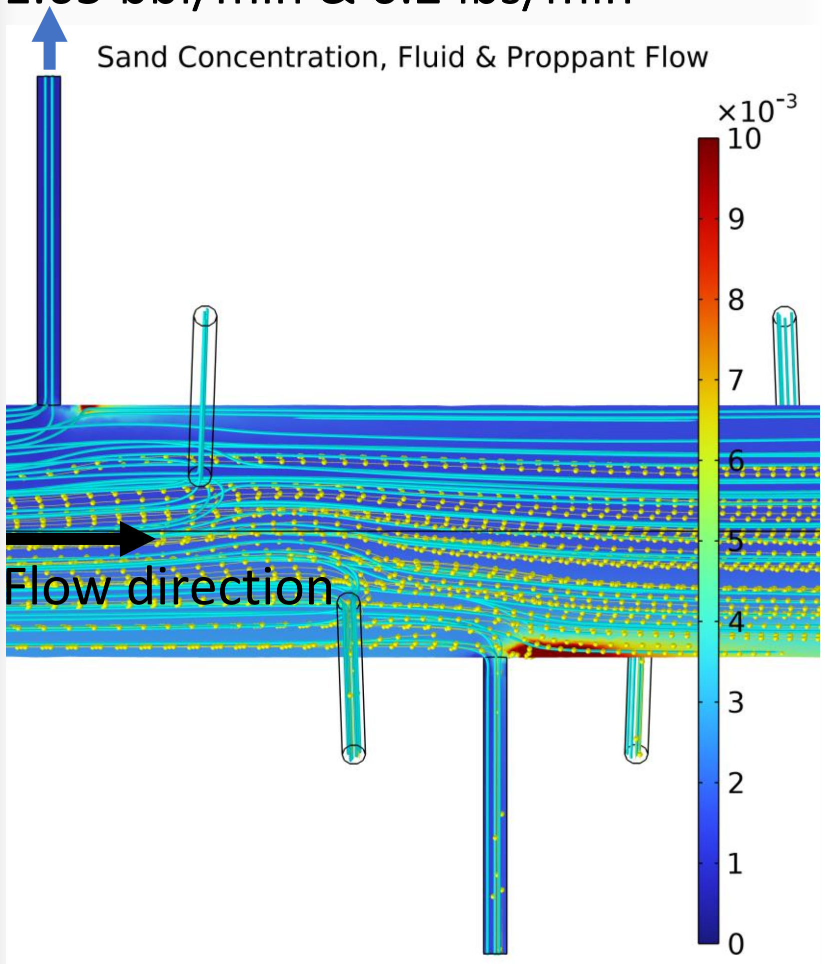




8. Influence of gravity and concentration gradients

- Sand concentration gradient influences **hole shape** & **sand distribution**
- Orientation/Phasing of the hole crucial for a realistic result

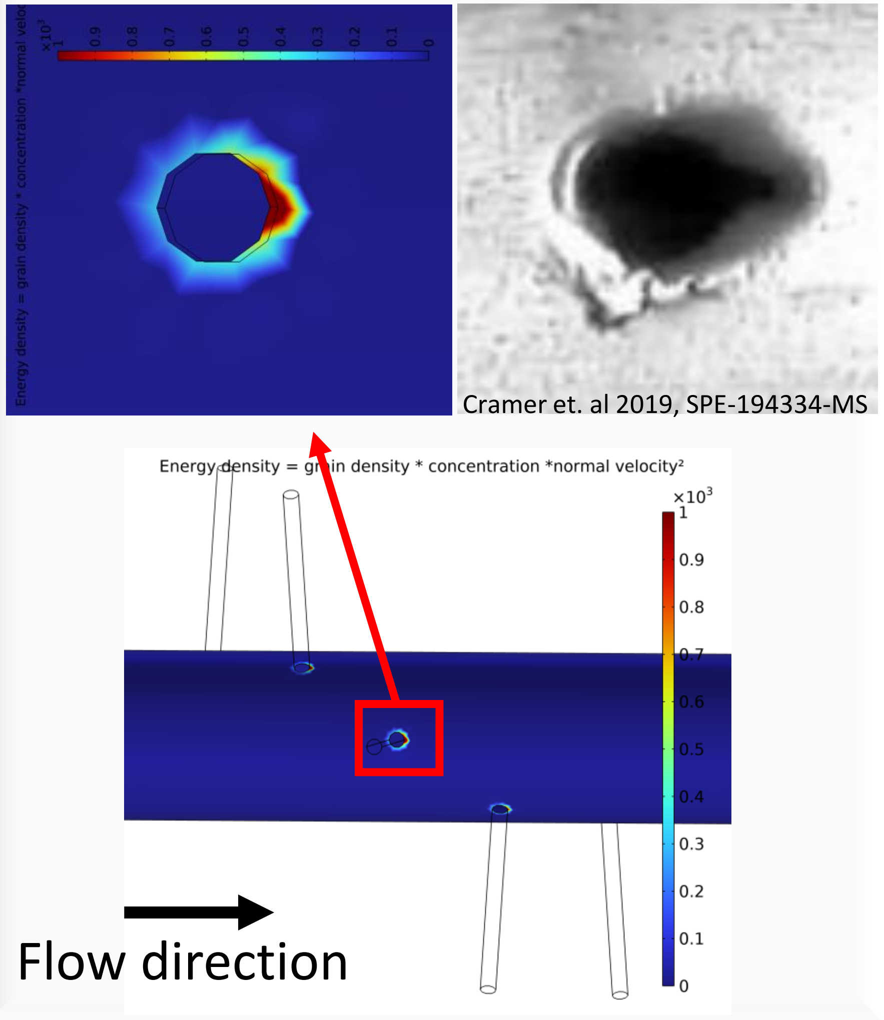
1.65 bbl/min & 6.2 lbs/min

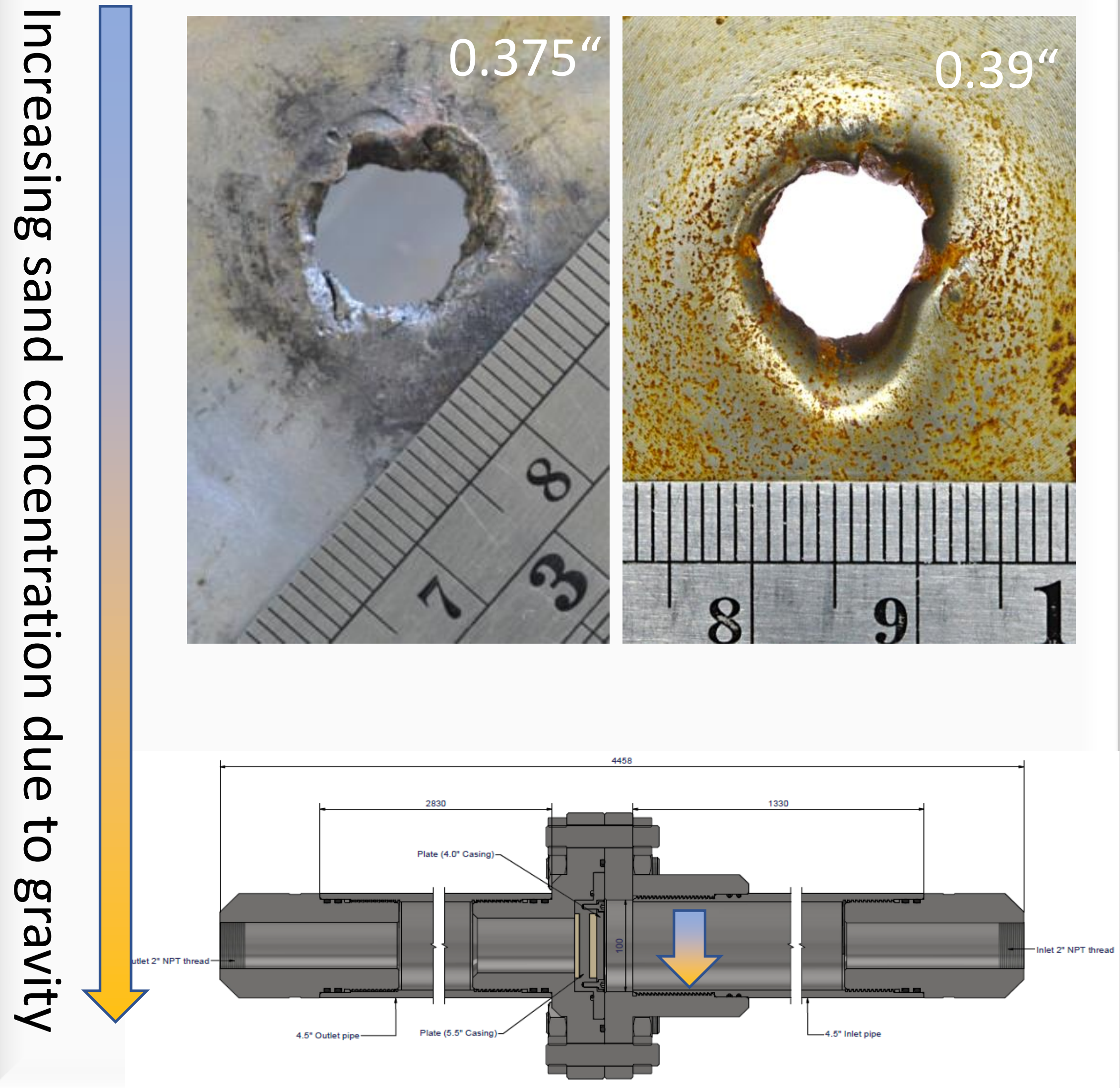


1.65 bll/min & 18.3 lbs/min

See also Almulhim et. al 2020, Liu et al, 2021, Kolle et al. 2022 for further reading

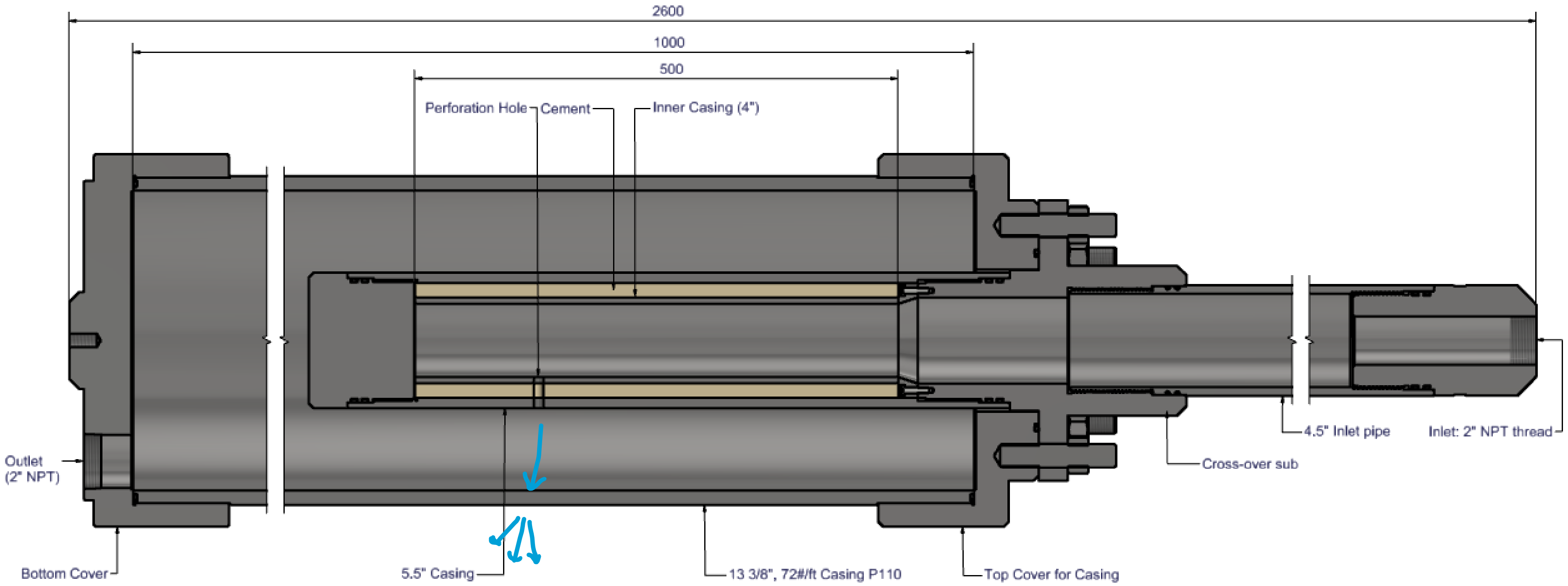
Energy of the proppant & Erosion





9. Measurements in Setup B - sand jetting

- Tests like those presented from Setup A were planned to be conducted in Setup B
- However, the test cell was destroyed by the slurry jet within minutes
- Similar effect on near well bore tortuosity can be expected
- Installation of Sacrificial Shield to allow completion of tests without destroying test cell



10. Position of the cluster - Improvements to Setup B

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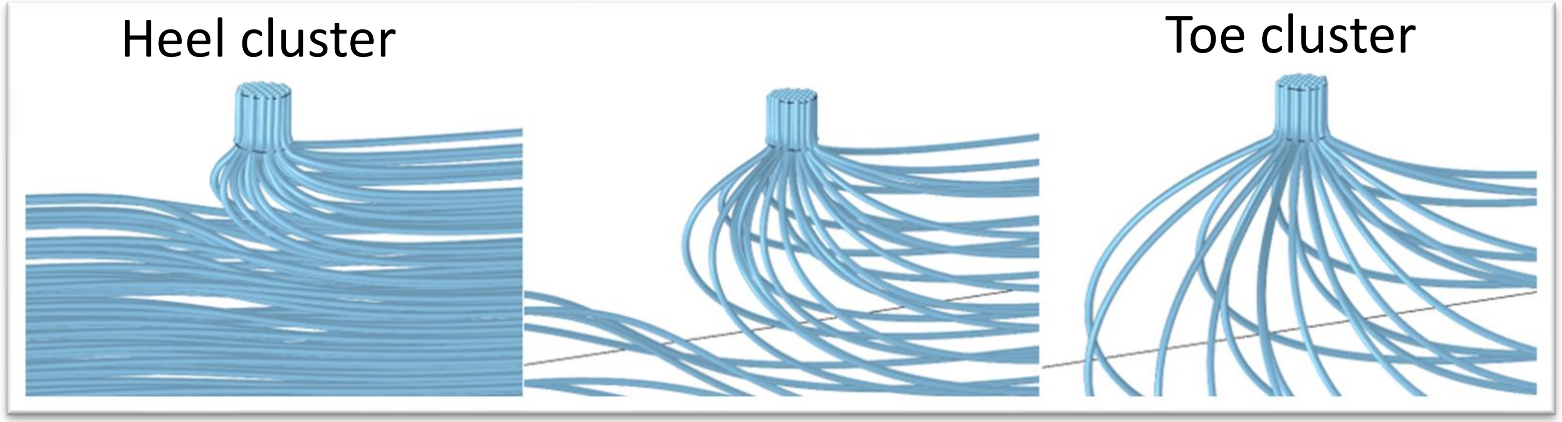
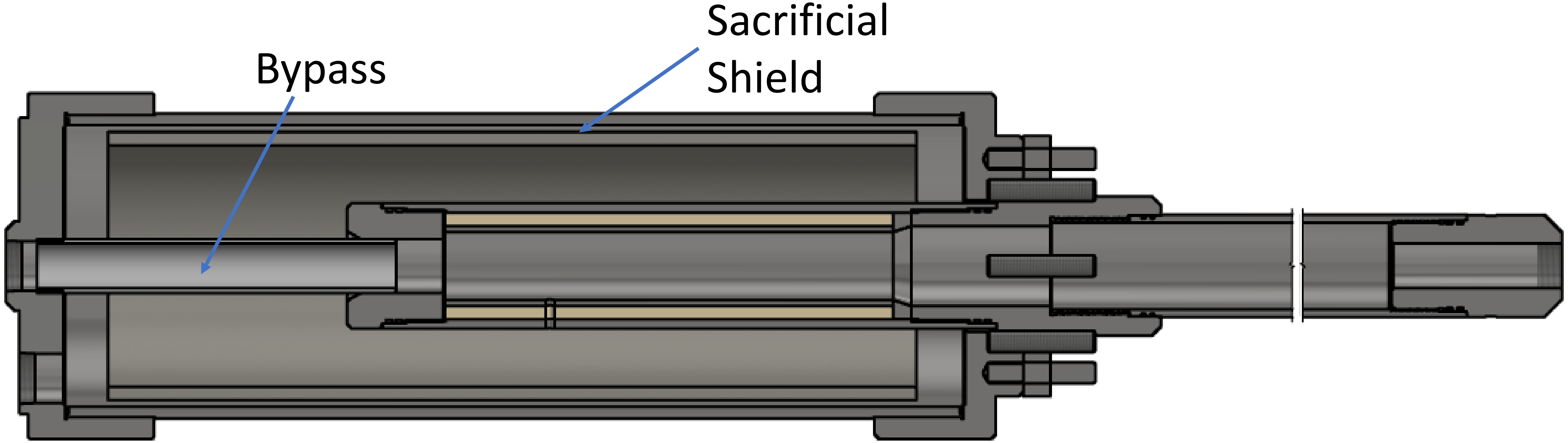
- Sacrificial Shield
- Installation of Bypass to allow more accurate heel side and mid interval flow patterns and test results
- Outlook: Erosion tests for the PEER Consortium planned





Summary

- Hole Size measurements have a tremendous influence on the CD, even if taken very accurate and carefully.
- Flow measurements should be made with backpressure, for erosion tests this might not be required, if CD values for non cavitating flow are available.
- For flow measurements the directions seem to have no influence, but for erosion tests a realistic orientation of the perforations and the setup relative to gravity must be considered.
- A closed loop setup has logistical and cost advantages, but heating and sand grain crushing limits the possible duration of each test.
- Improvements to test setup required to mitigate sand jetting and to account for the cluster position

Q&A

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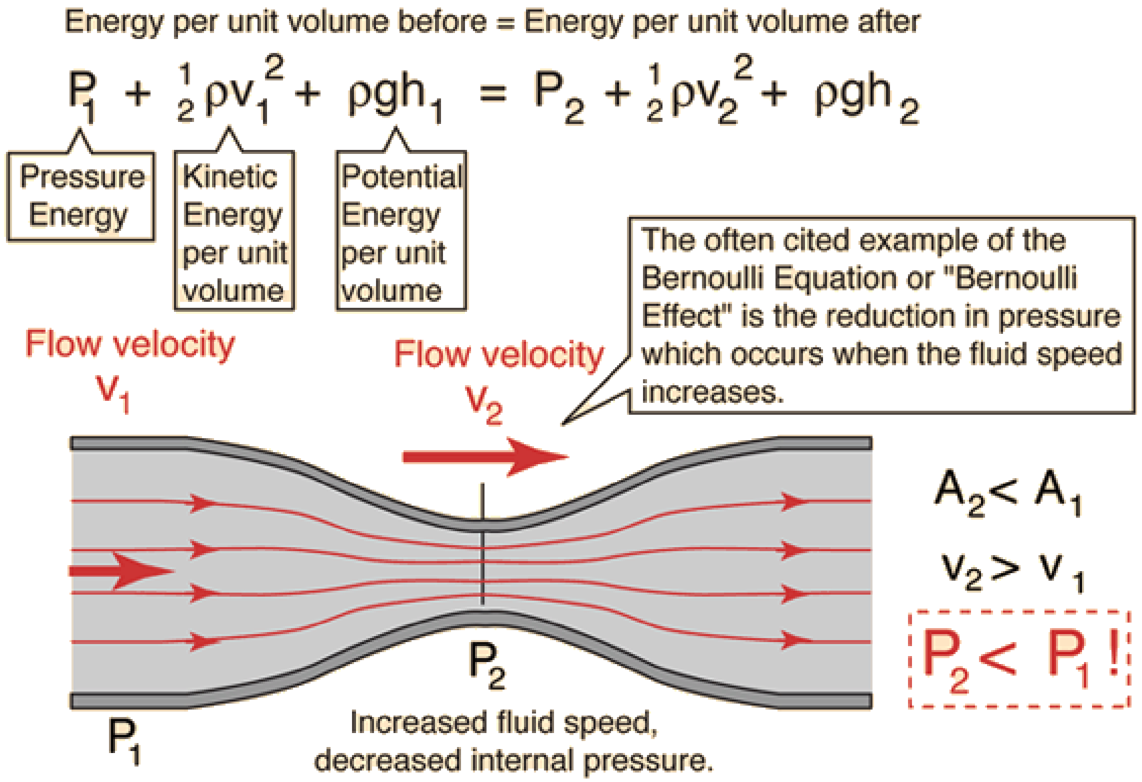
- **Observation:** During the test it was acoustically observed that a loud noise was created by the flow, which vanished as soon as the backpressure was raised over a certain level
- **Cavitation** occurs if the static pressure drops below the vapor pressure
  - Fluid vaporizes, bubbles are built and collapse at higher pressures again

Cavitation number $Ca = \frac{p - p_v}{\frac{1}{2}\rho v^2} < 1$

Bernoulli Equation:

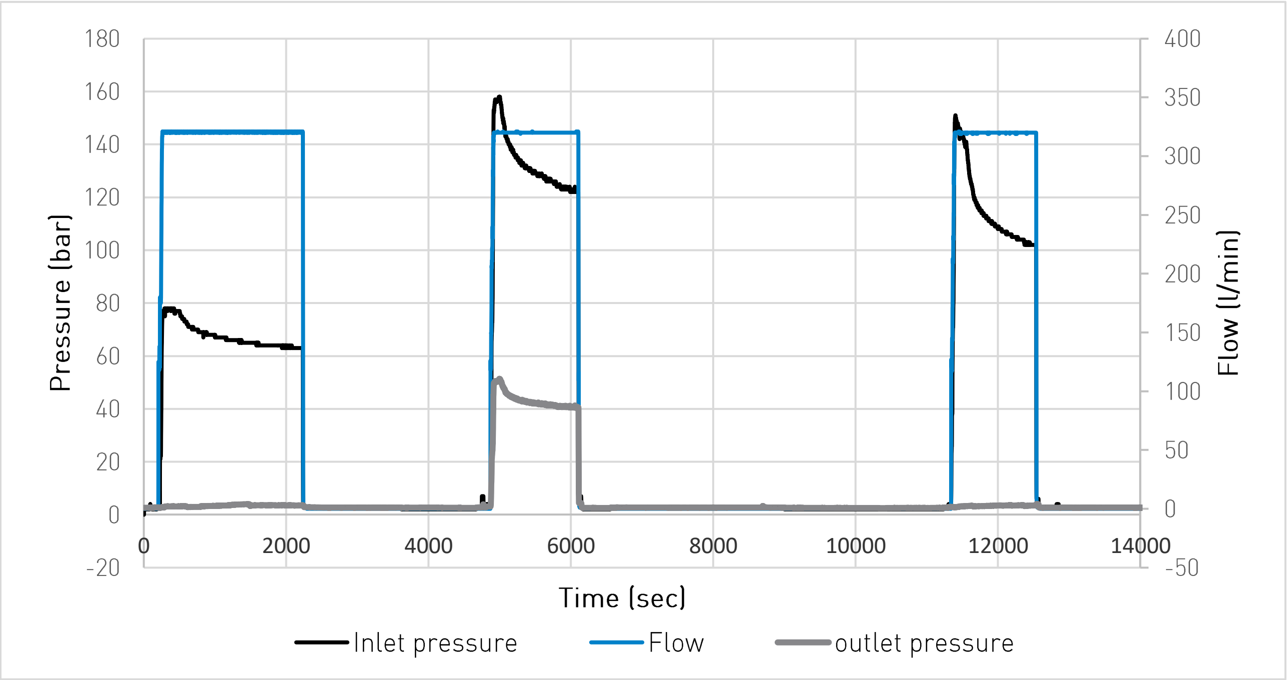


http://hyperphysics.phy-astr.gsu.edu/hbase/pber.html

See also Ebrahimi et al., 2017

Testing Parameters

- Erosion tests with 2bbl/min and 3 bbl/min per perforation
- Flow rate was kept constant
- Inlet, outlet pressures, flow rate and fluid temperature were recorded
- Test with backpressure on machined holes for better comparability
- 35/70 mesh sand was used in all erosion tests
- Sand concentration was approx. 1 ppg
- Flow duration 10-20 min
- Total Sand 840 lbs. - 1680 lbs.
- No viscosifiers or friction reducers were used



Energy, Velocity or Concentration?

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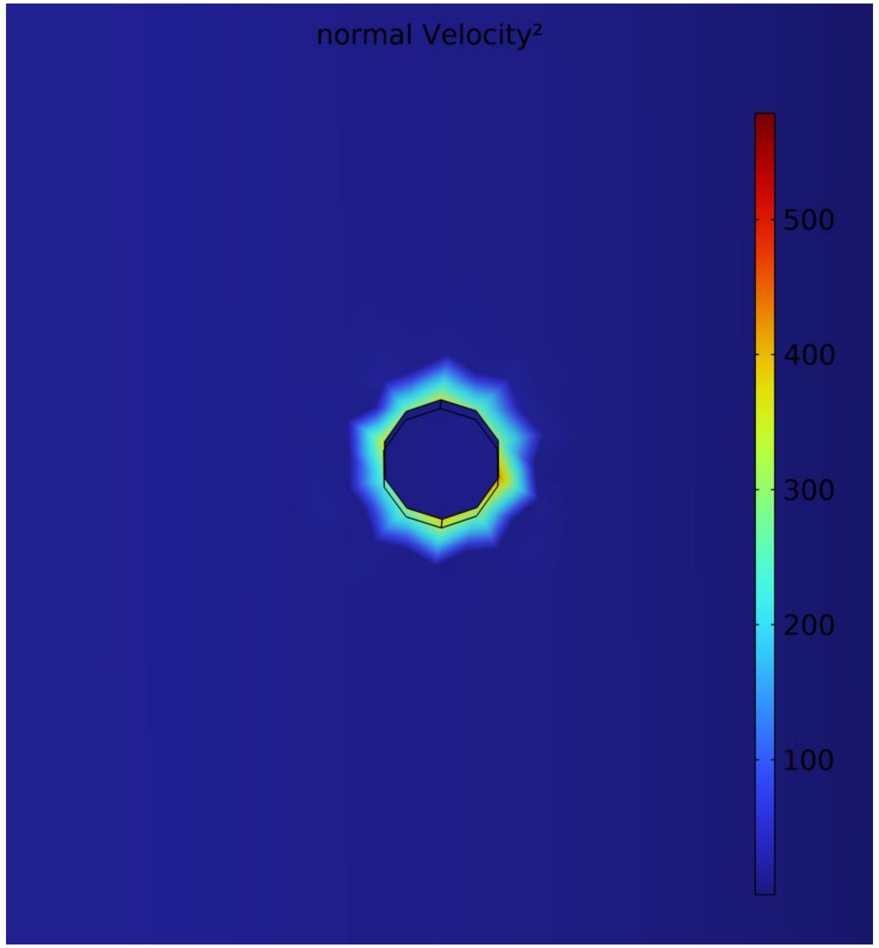
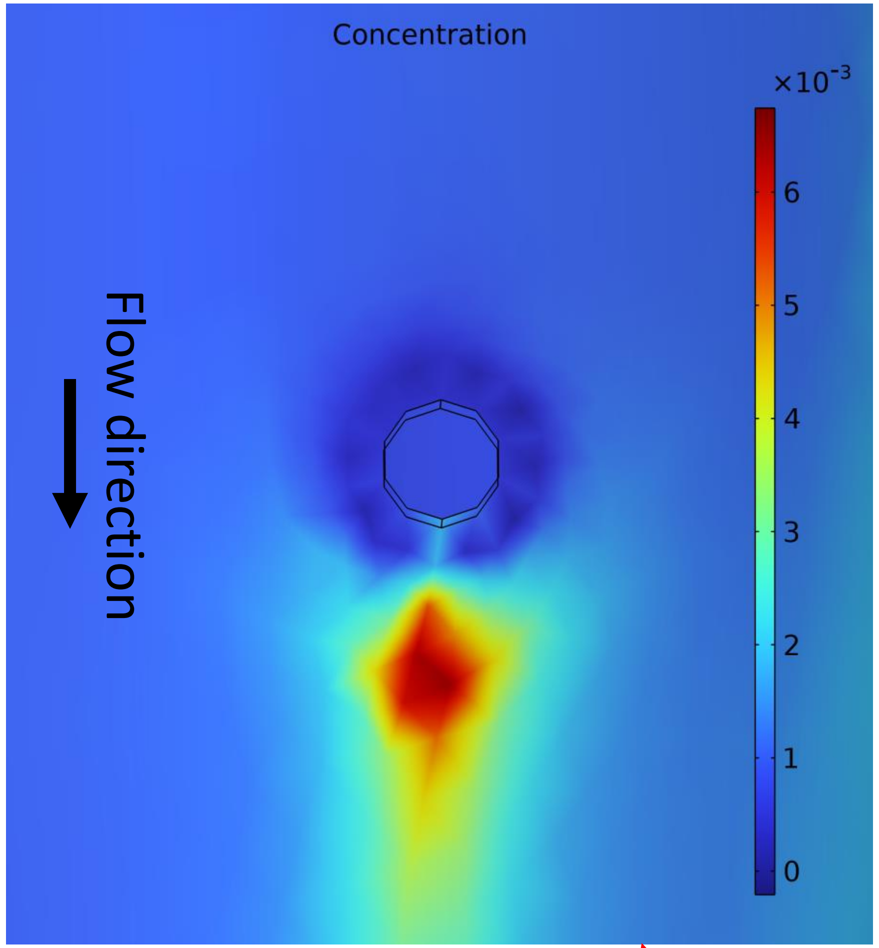
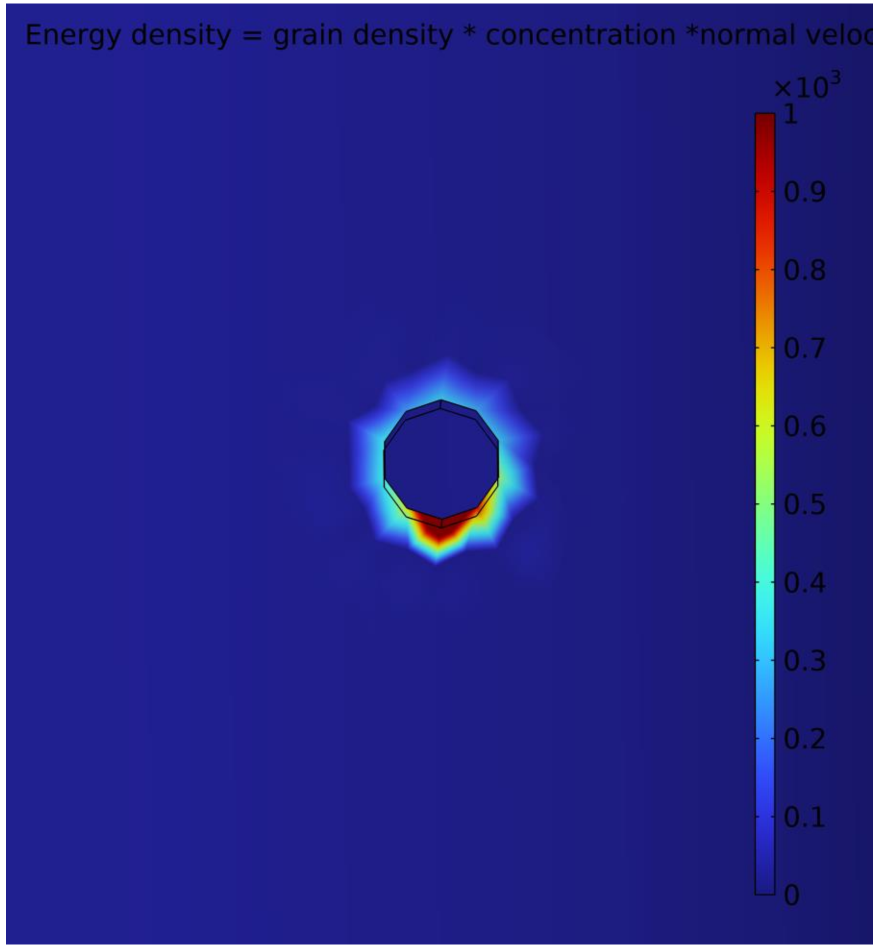
Velocity² normal to the surface

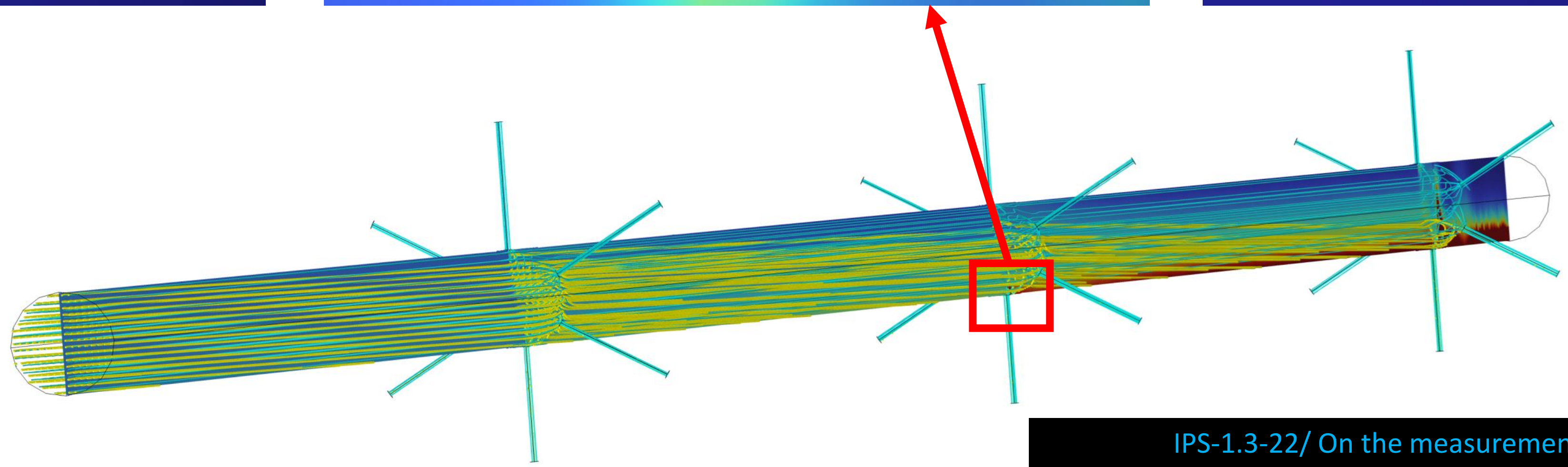


Concentration



Energy density:
Velocity² * concentration*grain density





Analysis of the data

- Both charges show a linear $p^{-1.25}$ vs t behavior
- This supports the correlation between the pumped energy and the erosion rate
- The calculated erosion parameter α is nearly identical (4.95e-13 and 4.98e-13)
- Machined holes had a smaller erosion rate (1.06e-13) because conical holes need less material removal to grow than cylindrical holes
- Pressure loss vs cumulative energy shows only at later times a linear trend
- This trend seems to be different for the two charges and might be related to hole size