Nozzle Geometry and Needle Motion Session

Group Leader: Alan Kastengren (Argonne National Laboratory)
Contributors: Christopher Powell (Argonne National Laboratory), Lyle Pickett and Peter Lillo (Sandia National Laboratory), Raul Payri (CMT), Tim Bazyn (Caterpillar)

Experimental Techniques

It is well-known that the detailed nozzle geometry in spray nozzles can profoundly impact the spray behavior. To better understand the ECN spray behavior, four different measurement techniques have been used to measure the nozzle geometry. Caterpillar has performed static x-ray tomography with a laboratory x-ray source. Argonne has performed phase-contrast imaging of nozzles using a synchrotron undulator source. Sandia has performed optical and SEM microscopy of the nozzle exit region. Finally, CMT has performed silicone molding to characterize the internal geometry. Argonne has also performed time-resolved phase-contrast x-ray imaging of the injector needle motion to characterize the three-dimensional motion of the needle during the injection event.

Findings

- X-ray tomography measurements provide the best base dataset for the nozzle geometry, as the data are quantitative, three-dimensional, and cover the entire nozzle tip region.
- X-ray tomography results suffer from some artifacts and drawbacks, which can be corrected using the other measurement techniques.
    - The spatial resolution of the tomographic reconstructions (3 µm transverse, 8 µm axially) is insufficient to precisely define the nozzle exit diameter.
    - Tomographic reconstruction shows oscillations in the nozzle wall that are not seen in the phase-contrast images.
- Optical microscopy provides the best measure of the nozzle exit shape and size.
- SEM looking into the nozzle hole provides perhaps the only feasible non-destructive method to determine the nozzle surface roughness, but requires dismounting the nozzle from the injector.
- Silicone molding has the best potential to determine the nozzle inlet diameter, but requires dismounting the nozzle from the injector.
- Nozzle K-factors vary, but tend to be around 2 – 2.5. The exit diameter of all nozzles seems to be less than 90 µm, which has important implications regarding the determination of nozzle flow coefficients.
- Tomography and phase-contrast imaging both show a significant narrowing of the nozzles for about 50 µm near the nozzle exit. This seems consistent for the various nozzles.
- The needle motion for each injector is highly repeatable from injection to injection. The needle motion is complex and three-dimensional, with significant oscillatory off-axis motions.
- The axial needle motions are quite similar between all injectors tested. The lateral motions of the needle are unique to each injector.

Recommendations & Future Investigation

- There is a lack of cross comparisons between the different techniques to measure nozzle geometry. Efforts are ongoing to complete a more comprehensive set of measurements with each of the techniques.
- Given the significant asymmetries seen in the nozzle geometry, all ECN experimenters should carefully record the injector orientation for their measurements. The recommended reference is the injector fuel inlet (which also aligns with the flats on the injector).

- A consistent methodology must be developed to create a reference geometry (preferably in STL format) for use in CFD modeling of internal nozzle flow.

Measurements of ECN Injector Geometry and Needle Motion

Alan Kastengren, Christopher Powell; Argonne National Laboratory
Tim Bazyn; Caterpillar
Raul Payri; CMT
Lyle Pickett, Peter Lillo; Sandia National Laboratories

DOE Vehicle Technologies Program

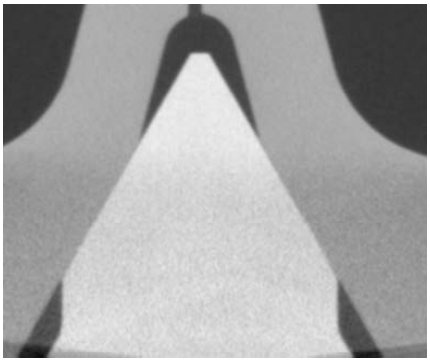
Team Leader: Gurpreet Singh

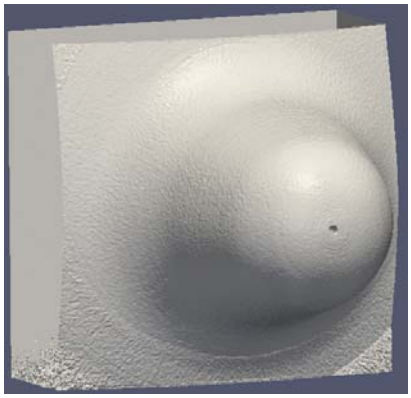
Need for Injector Geometry Data

- It is well-known that imperfections in nozzle geometry have a profound impact on spray behavior
- ECN nozzles are 90 µm in diameter; difficult to precisely make holes this small
- What do we want to know for modeling and experiment interpretation?
  - Hole diameter and length
  - K-factor
  - Inlet radius
  - Exit condition
  - Surface roughness
  - Imperfections in geometry: misalignment of hole, defects in machining
- Give an overview of several related efforts to measure injector geometry
  - Comparison of different techniques
  - Recommendations for interpretation of data
- Present results of nozzle geometry measurements

X-Ray Tomography: Caterpillar

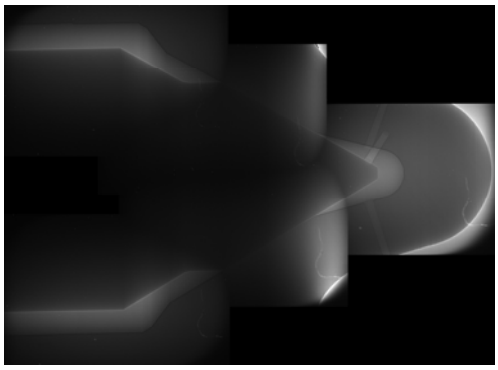
- Use x-ray tube source to view injector from multiple angles to reconstruct 3-D geometry
- Provides quantitative, 3-D geometry data throughout nozzle and upstream flow passage
- **Best way to get baseline geometry, but not perfect**
- Reconstruction can be complex, but a great deal of work has been done in this area: medical CT scans
- Static measurements only
- Resolution: original voxels 8 µm, interpolated in reconstruction to 3 µm





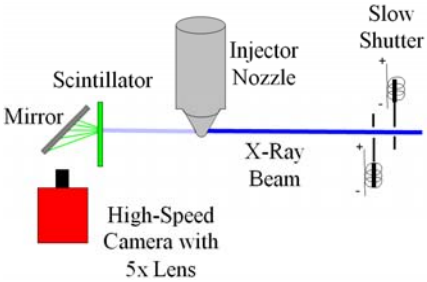
X-Ray Phase-Contrast Imaging: Argonne

- 2-D imaging with synchrotron source
- Phase effects accentuate boundaries
  - Biases in interface position?
  - In tomography measurements as well?
- Can perform measurements fast to see injector motion
- Very limited access; less than 2 weeks/year
- Resolution: 4-5 µm per pixel, perhaps blurred



Compilation of Phase Contrast Images Injector #211201

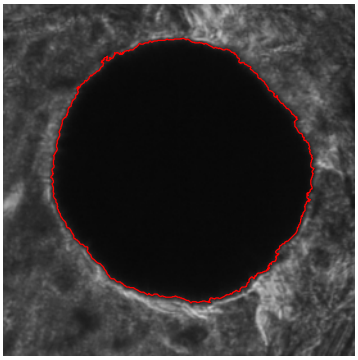
Experiment Setup



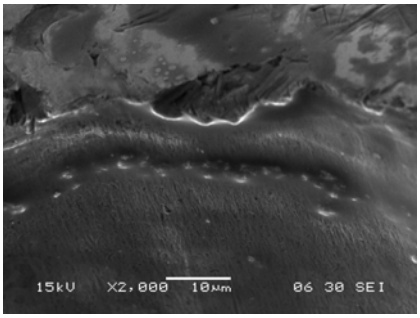
SEM/Optical Microscopy of Nozzle Exit: Sandia

- Microscopic imaging of nozzle exit to examine exit condition
- Optical to get exit geometry
- SEM to see surface finish?
- Only works very region very near the nozzle exit
- SEM requires dismounting the nozzle
- High resolution: < 0.7 µm optical

Injector 370



Optical Microscopy Image (20x objective lens)



SEM Images

Silicone Molds: CMT

- Inject silicone into nozzle, extract, and examine with SEM
- SEM images give much higher resolution than x-ray measurements
- Defects in molding process: tears, sagging
- Requires dismounting of injector
- Resolution: probably limited by mold fidelity

Mold Defects Injector #210675

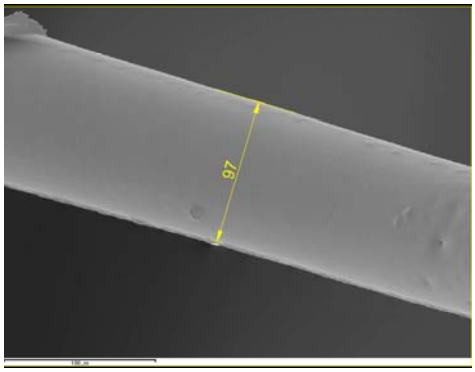
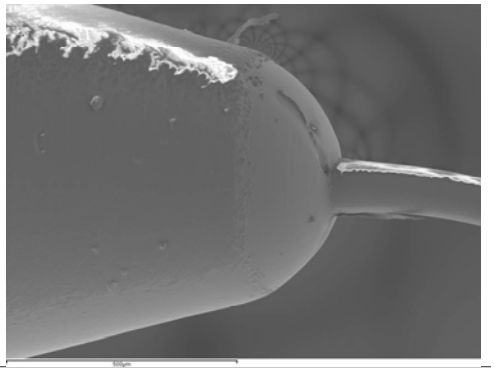


Image of Nozzle Passage

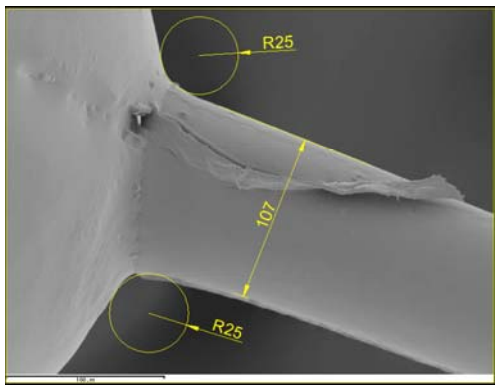


Comparisons Between Methods

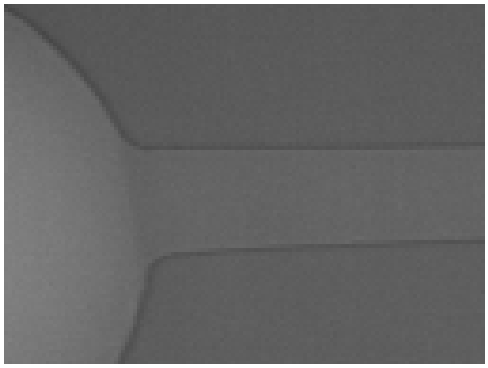
Injector #	Geometry	Tomography	PC Imaging	SEM/Optical	Silicone Molds
370	Spray A Spec.	X		X	
210675	Spray A	X	X		X
210676	Spray A	X			
210677	Spray A	X			
210678	Spray A	X		X	
210679	Spray A	X	X		
211201	Spray B	X	X		

Injector #210675: Phase-Contrast Imaging vs. Silicone Molds

- Images appear to be of same orientation
- PC imaging gives inlet diameter = 106 µm, silicone mold gives 107 µm
- PC imaging gives exit diameter of 86 µm, silicone mold gives 89 µm



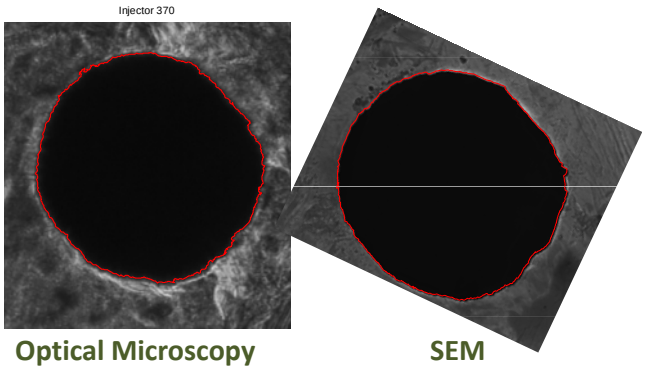
Silicone Mold



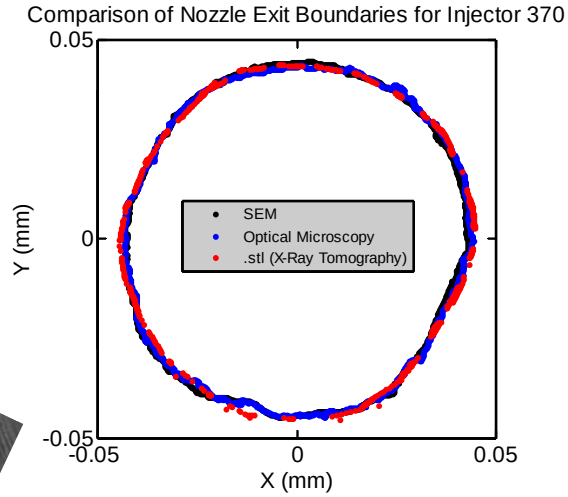
Phase Contrast Imaging

Injector #370: Comparison of SEM, Optical Microscopy, and Tomography

- SEM (best resolution) and Optical Microscopy (0.7 μm resolution) show nearly identical exit shape and diameter.
- X-ray tomography shows more variation.



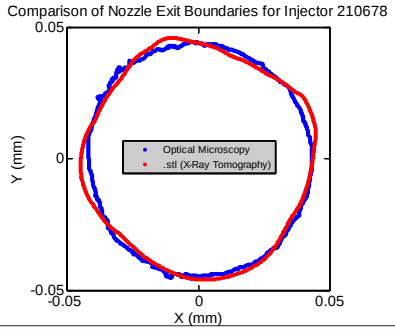
Optical Microscopy **SEM**



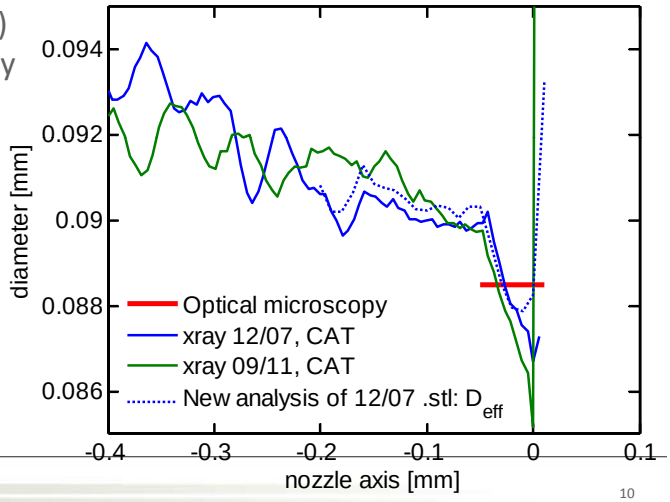
SEM and optical microscopy both measure 88 mm effective diameter.

Injector #210678: Tomography shows artifact at nozzle exit, not measured by optical microscopy

- Exit condition can have artifacts in tomography data.
- Analysis of the .stl tomography file for effective area shows less variation.
- Optical microscopy (0.7 μm res.) preferred over x-ray tomography to measure exit shape and size.

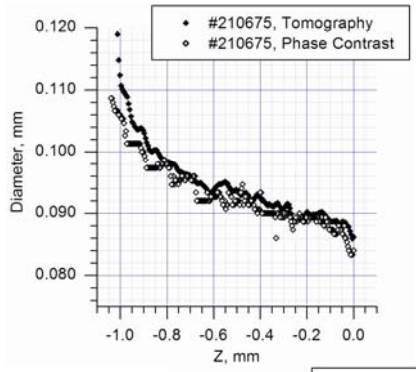


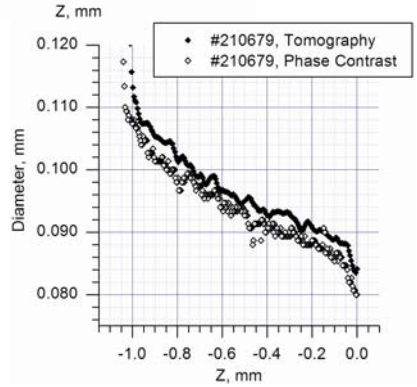
Tomography Axial Profile vs. Microscopy Injector #210678



Injectors #210675 and #210679: Tomography vs. Phase Contrast Imaging

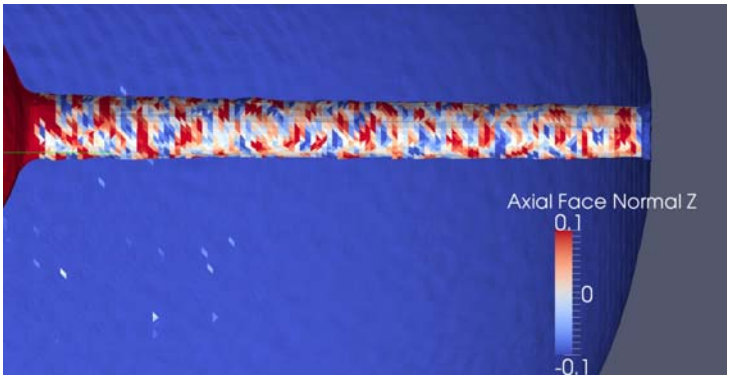
- Diameter results from tomography and phase contrast imaging are quite similar
  - Within 1 pixel (4 µm) for phase contrast images
  - Both measurements show that #210679 has higher K-factor and smaller exit diameter
- Why the offset between the curves, especially for #210679?
  - Bias in phase-contrast images
  - Axial shift: reference is nozzle exit, which may not be indexed the same in the measurements
  - Error in length scale calibration of one or both measurements

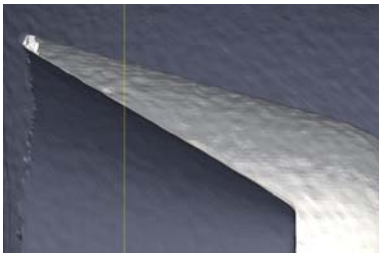


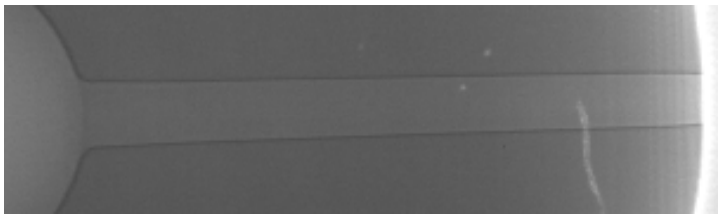


Injector #210679: Tomography vs. Phase Contrast Imaging

- Tomography shows waves that aren't evident in phase contrast images
- Transition from needle seat to sac blurred in tomography

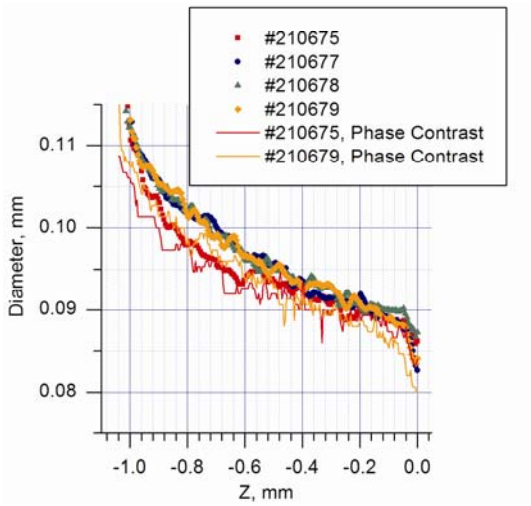


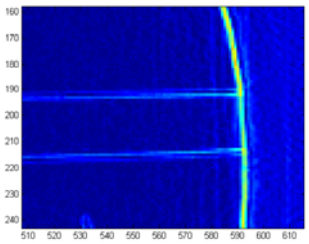




Static Geometry Results

- Nozzles K-factors vary
  - Most KS 2.0 – 2.5
  - Not conical; converge a little more quickly near inlet
- Exit diameter for all nozzles < 90 µm
- All nozzles converge in last 50 µm
- We need good measurements at exit
  - Phase contrast and SEM/optical microscopy can help
  - 2% change in d = 4% change in area



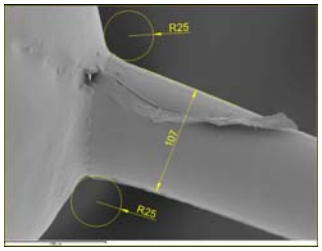


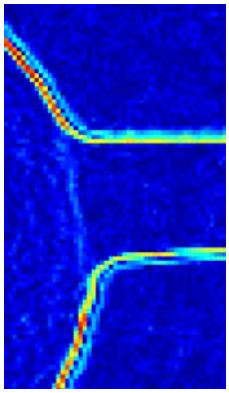
Nozzle Exit Phase Contrast Image Edge Filter Applied

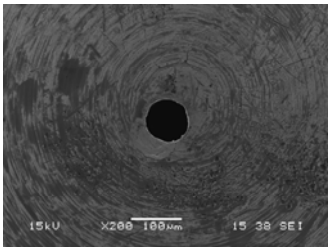
Nozzle Diameter by Tomography and Phase Contrast Imaging

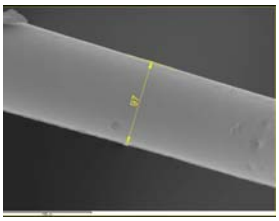
Static Geometry Results (cont.)

- Inlet radius ~ 25 µm vs. x-ray axial spacing of points of 4-8 µm
  - Only a handful of points to fit arc
  - Silicone mold is best for this
- All holes are misaligned
  - Turning angle at inlet varies
  - May cause asymmetry in nozzle flow
- Surface of silicone mold looks reasonably smooth: no evidence of waves seen in tomography

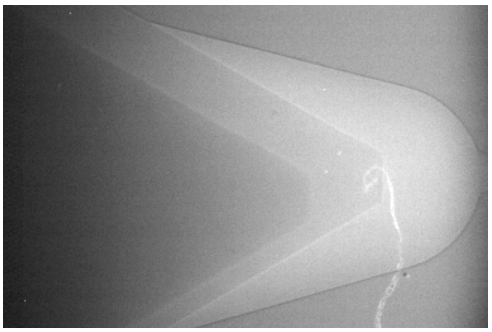


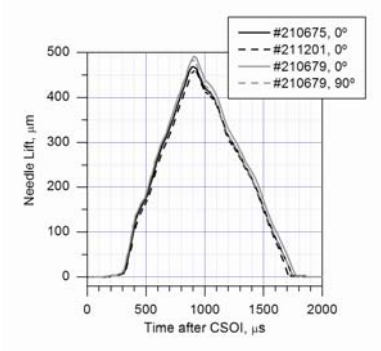


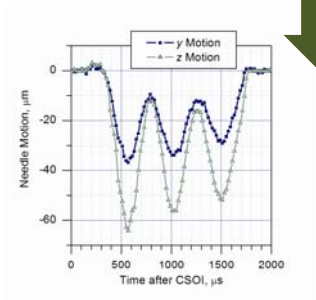


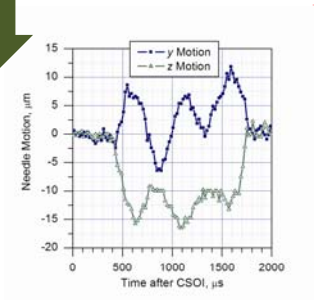


Phase-Contrast Imaging of Needle Motion









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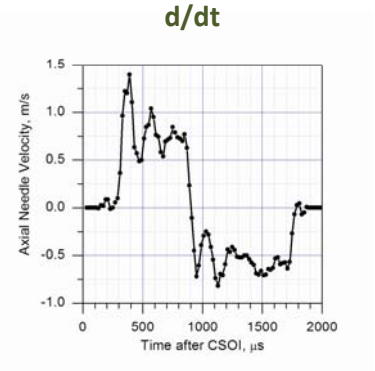

Recommendations and Outstanding Issues

Recommendations

- X-ray tomography provides good base dataset for nozzle geometry, but corrections are needed
- Use other techniques to provide corrections
  - Optical for exit
  - Silicone molds for inlet radius
- Phase contrast imaging shows actual needle motion is complex and 3D
- Need more cross-comparisons between techniques
- Experimenters need to record injector orientation
  - Significant asymmetries in nozzle geometry and needle motion
  - Suggest using fuel inlet as a reference

Outstanding Issues

- If exit diameter is < 90 µm, are nozzle coefficients that assume 90 µm wrong?
- Need to develop a consistent way to create a useful surface for meshing
  - How to combine different techniques?
  - Fit surfaces for needle and seat?
- Is .stl the best file format to use?
  - Triangulation doesn't match curvature, but neither will CFD cells
  - Surfaces interfering at very low levels of needle lift?
- Should a CFD mesh be created to allow apples-to-apples comparisons of in-nozzle flow models?
- Will all nozzles need to be dismounted?

Conclusions from Discussion

- General agreement that the risk of dismounting the nozzles for silicone molding outweighs the benefits
- STL file format was agreed to be suitable for a reference geometry
- Smoothing will be required to develop a suitable reference geometry
- Agreement that the injector fuel inlet is a suitable reference for describing the orientation of the injector