Real-Time 3-D Volume Imaging and Mass-Gauging of High Temperature Flows and Power System Components in a Fossil Fuel Reactor Using Electrical Capacitance Volume Tomography

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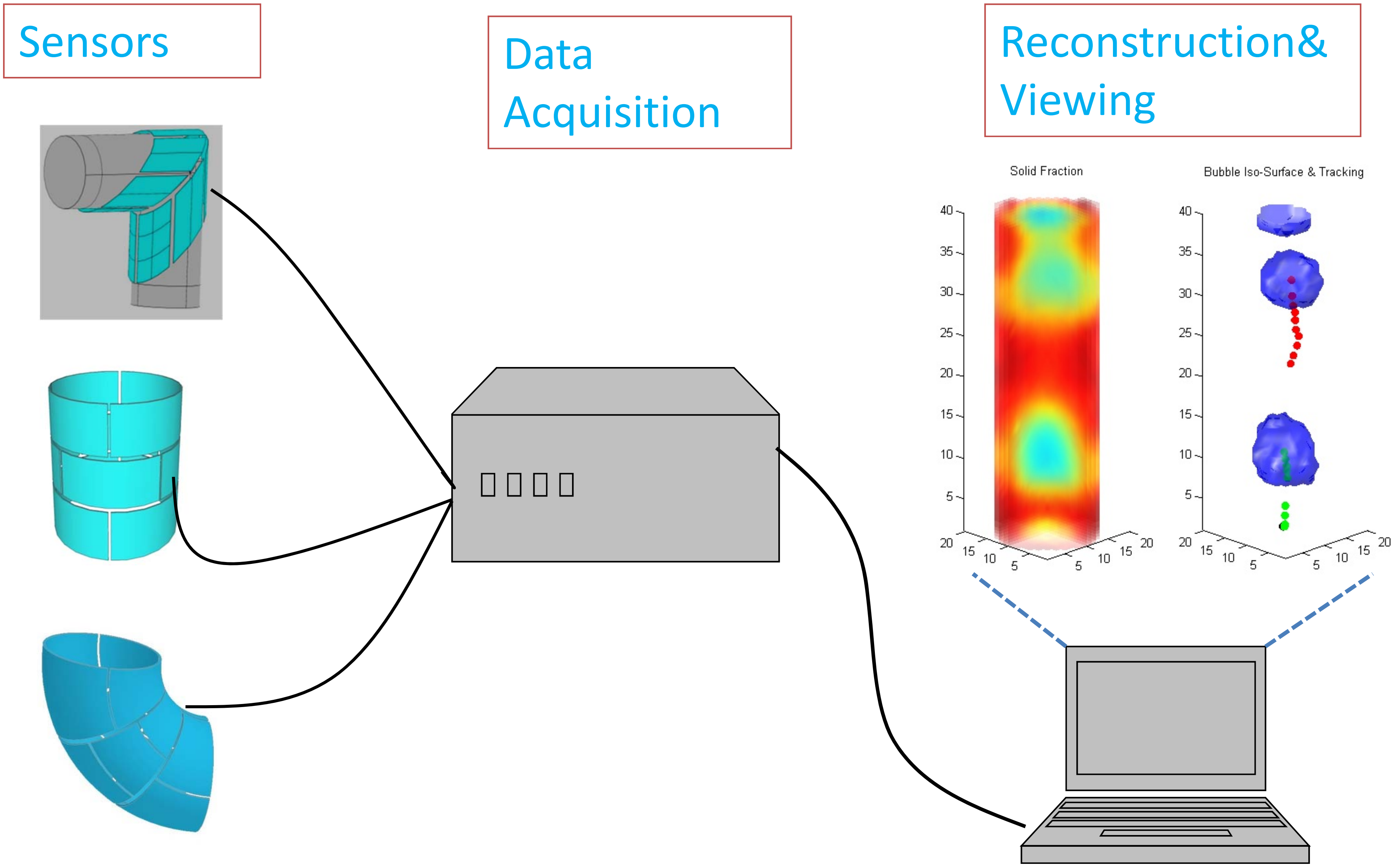
Introduction

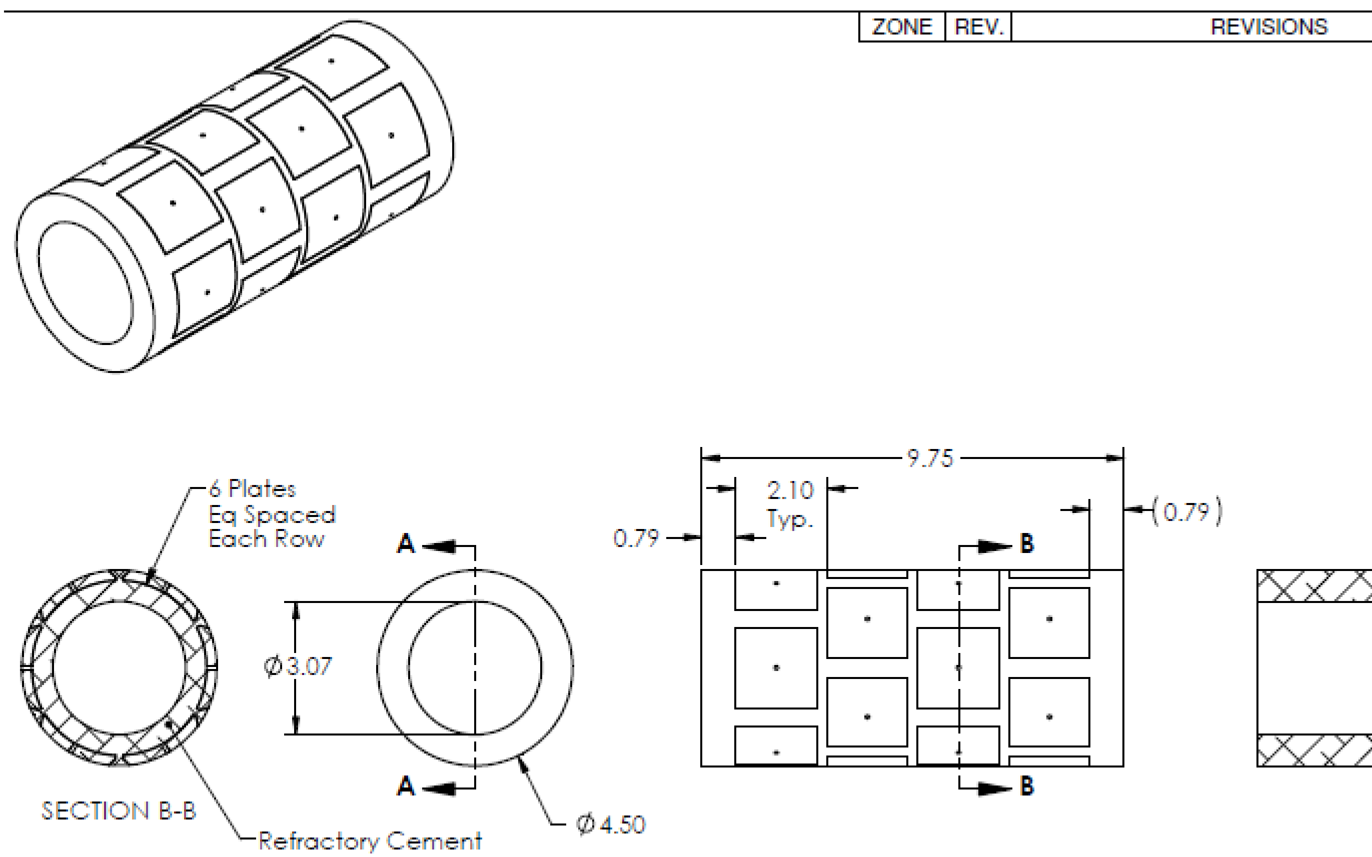
- Electrical Capacitance Volume Tomography (ECVT) is a 3D imaging technique for Multi-phase flow measurement.
- ECVT is among few know non-invasive imaging tools that can be used for commercial applications (low cost, suitable for scale-up, fast, and safe)
- Three-Phase flow systems are used in many energy processes.
- A high temperature ECVT system and sensor was developed and fabricated for testing and demonstration.

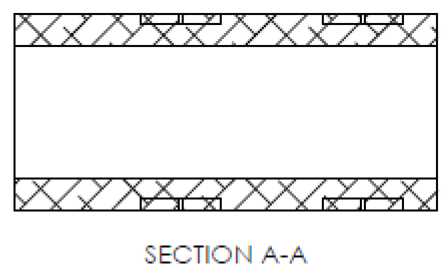
Complete ECVT System

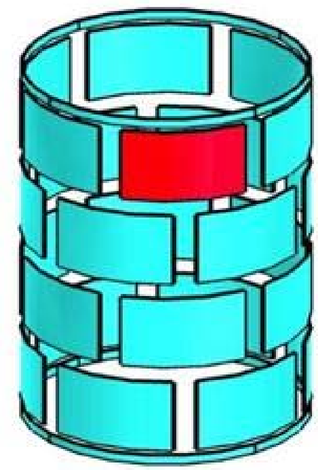


4 TECH IMAGING

Sensor Design

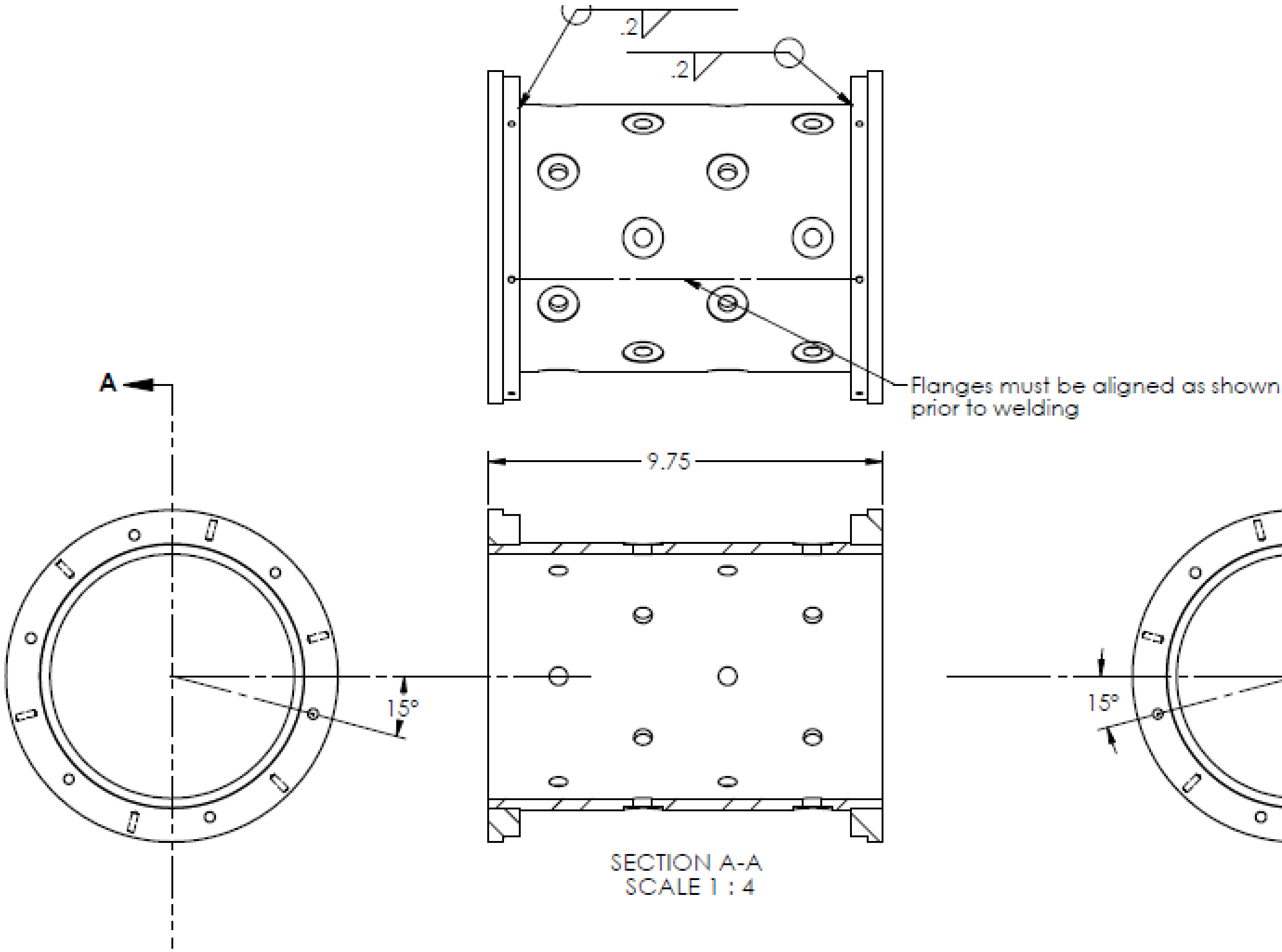






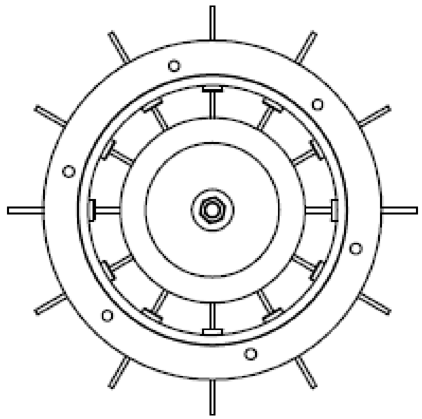
24 channel Sensor

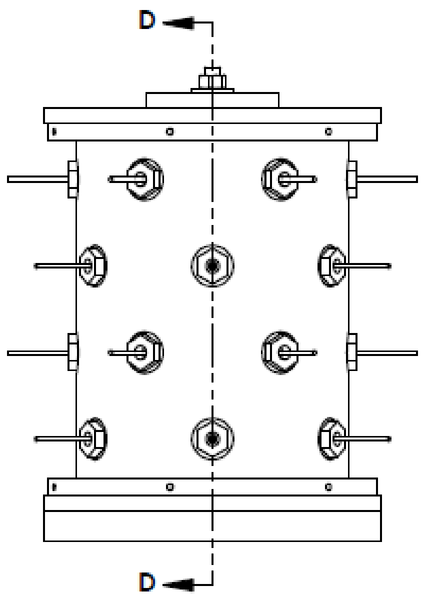
Inner Shell



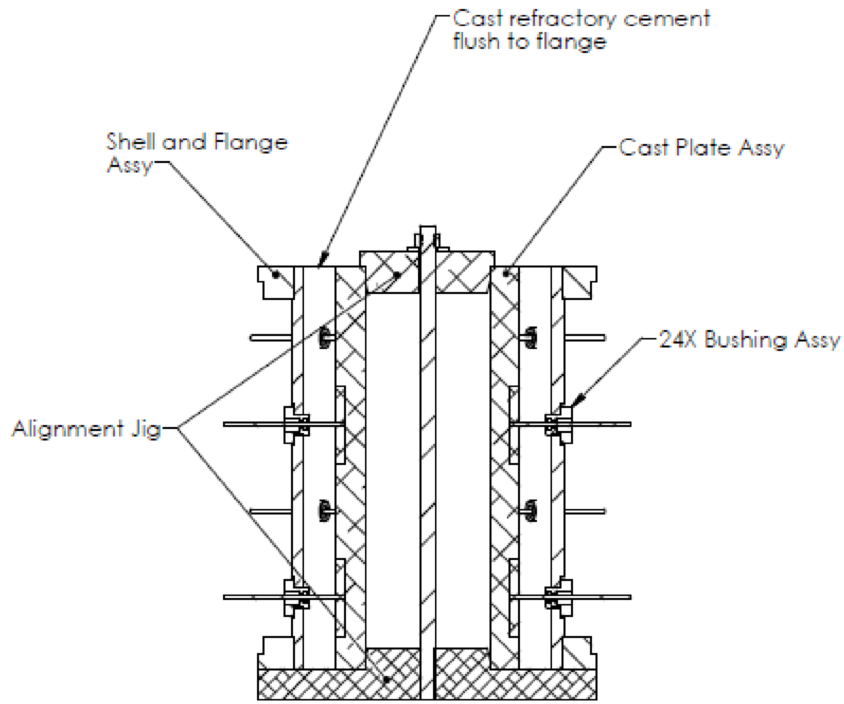
.2
.2
Flanges must be aligned as shown
prior to welding
A
9.75
15°
15°
SECTION A-A
SCALE 1 : 4

Plates to Outer Shell



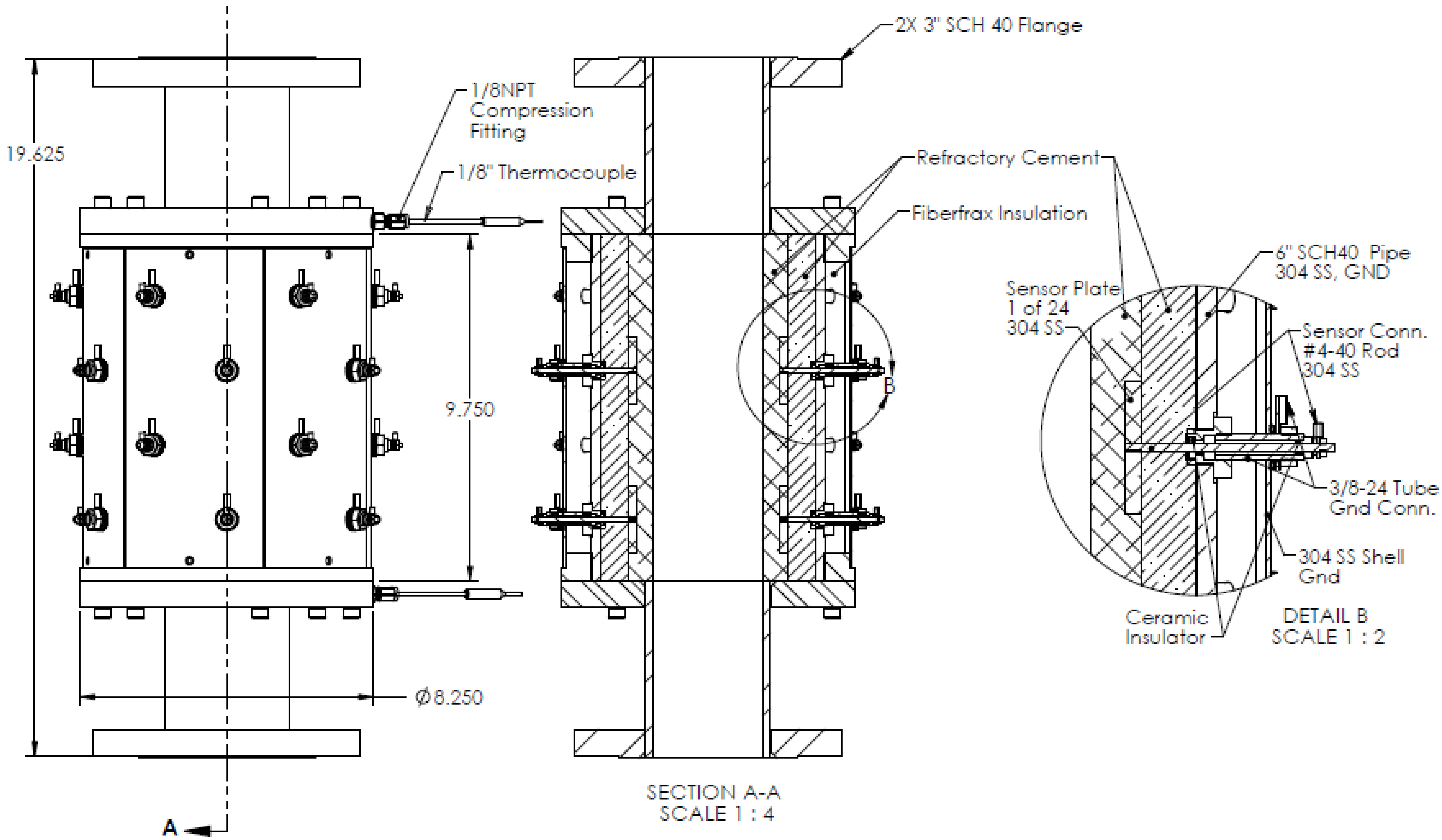


Install sensor plate assy in shell
Use aligment jig to center assy
Install 24 bushing assemblies
Cast annulus with refractory cement.
After cure, remove alignment jig.



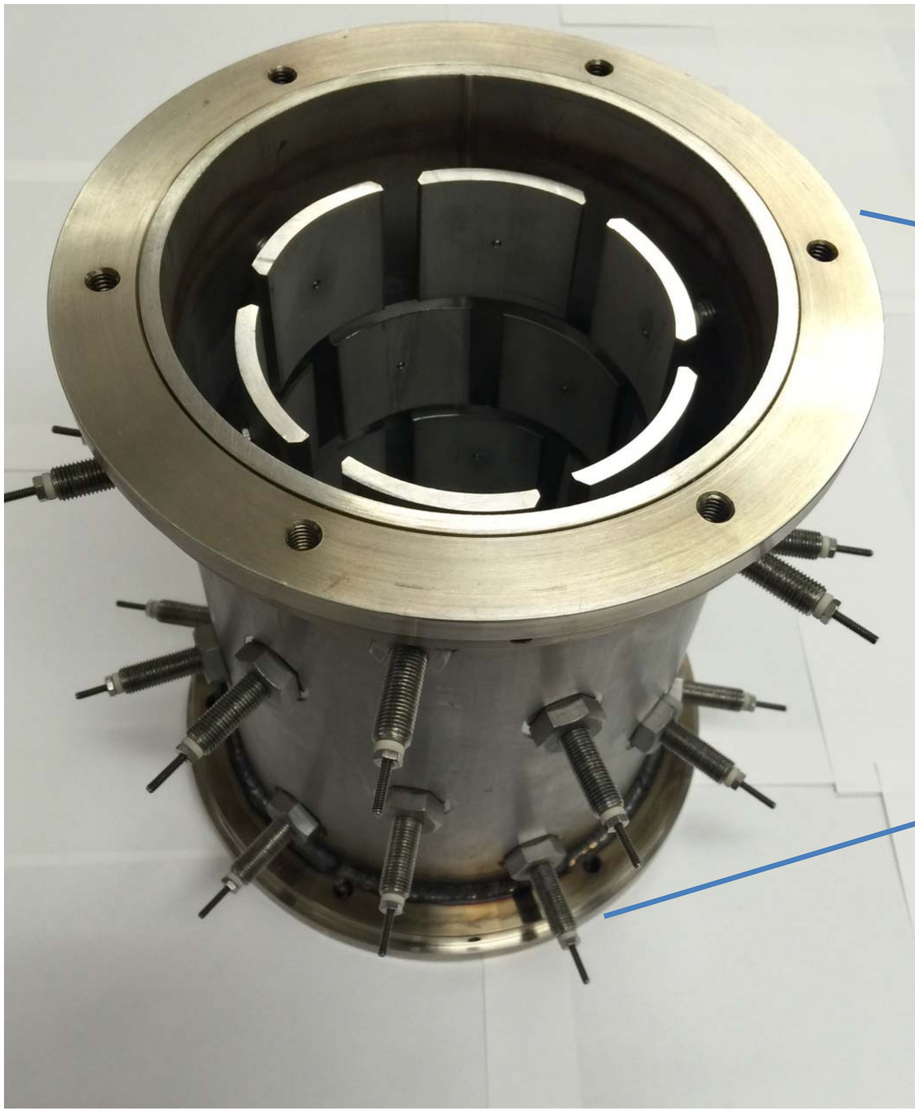
SECTION D-D
SCALE 1 : 4

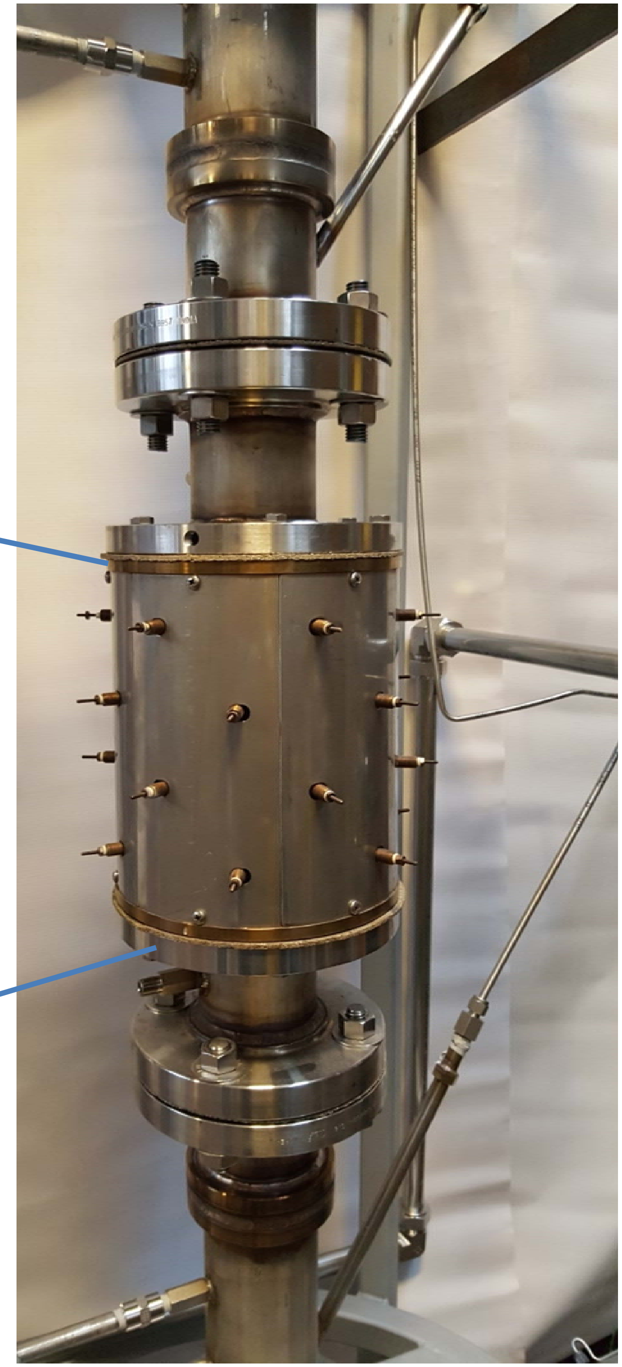
Integrated Sensor



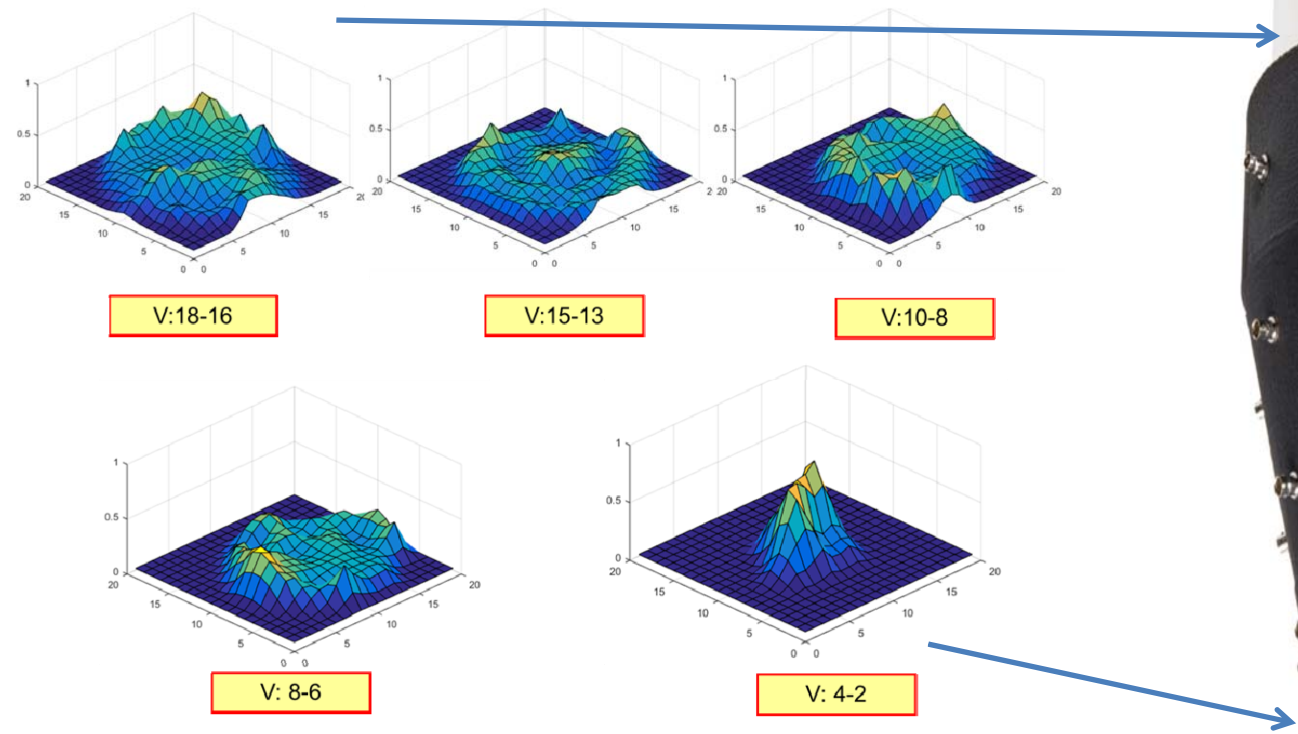
4 TECH IMAGING

ECVT Hot Unit





Velocity Profile Using ECVT Tapered section



Velocity profile of solids down a tapered section.
A wet layer of solids was used as a tracer.

Project Schedule

Year 1:

1&2 Finalize ECVT sensor design- <u>end of 2nd quarter.</u>

3 Fabrication of ECVT sensor- <u>end of 4th quarter.</u>

4 Fabrication of testing chamber- <u>end of 4th quarter.</u>

Year 2:

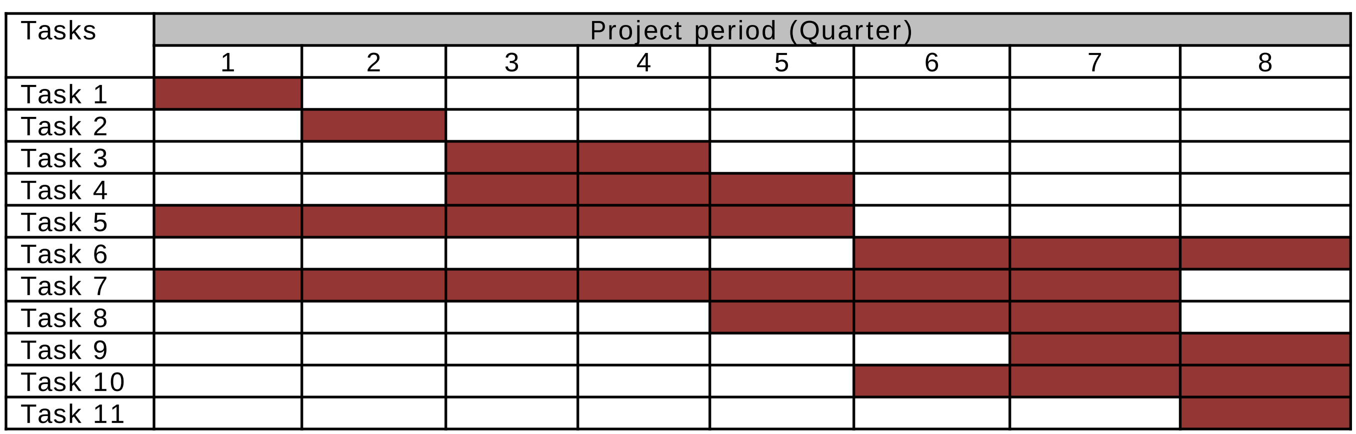
5 Finalize DAS- <u>end of 5th quarter.</u>

7 Finalize image reconstruction and feature extraction- <u>end of 11th quarter.</u>

8 & 9 Demonstrate integrated system- <u>end of 7th quarter.</u>

6 & 10 Finalize GUI- <u>end of project.</u>

11 Finalize demonstration unit and develop virtual experience- <u>end of project.</u>

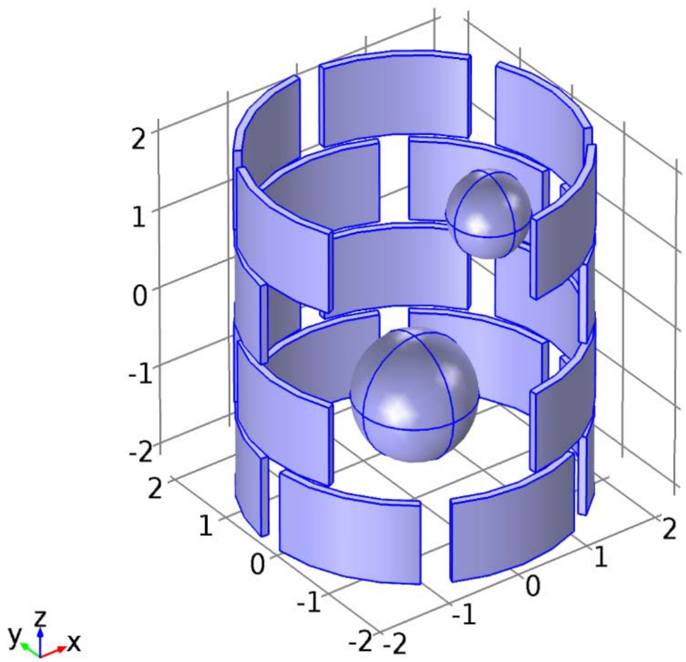


Velocimetry

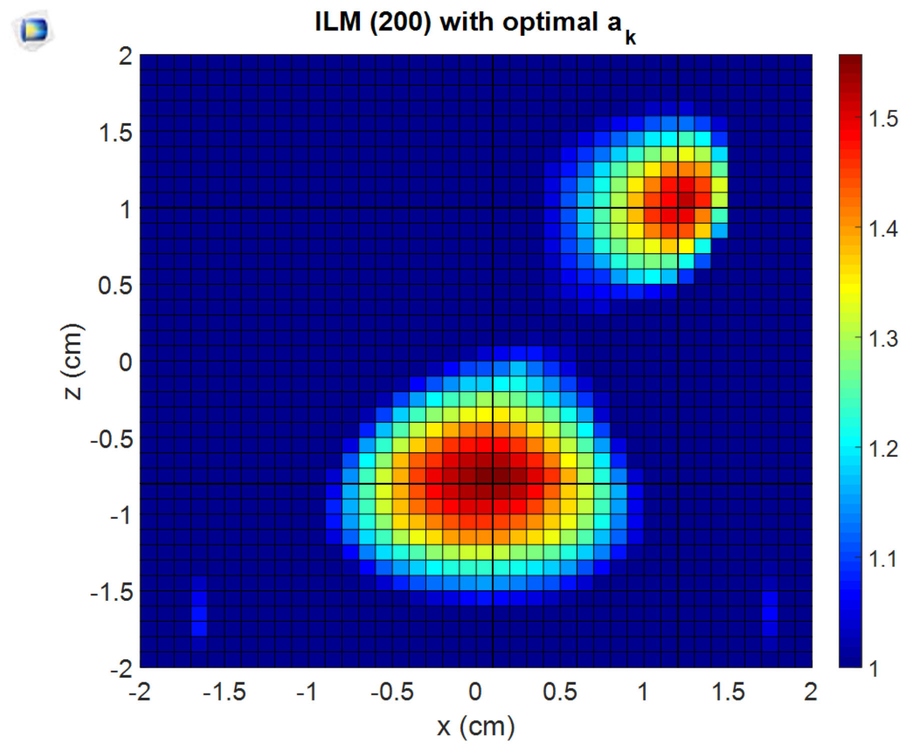
- Velocities of each phase in 3D
- Volume fractions and distribution of each phase
- Mass flow rate of each phase
- Catalyst velocity estimation
- Reaction rate

Image Reconstruction Using Sensitivity Matrix

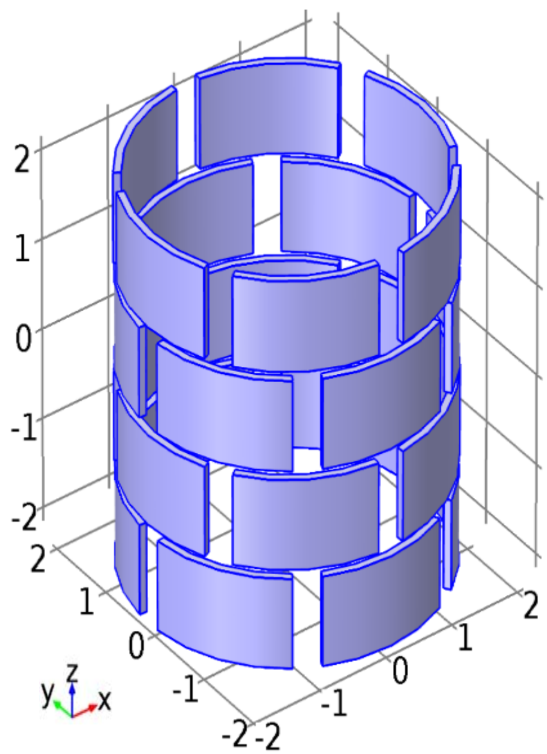
(a)

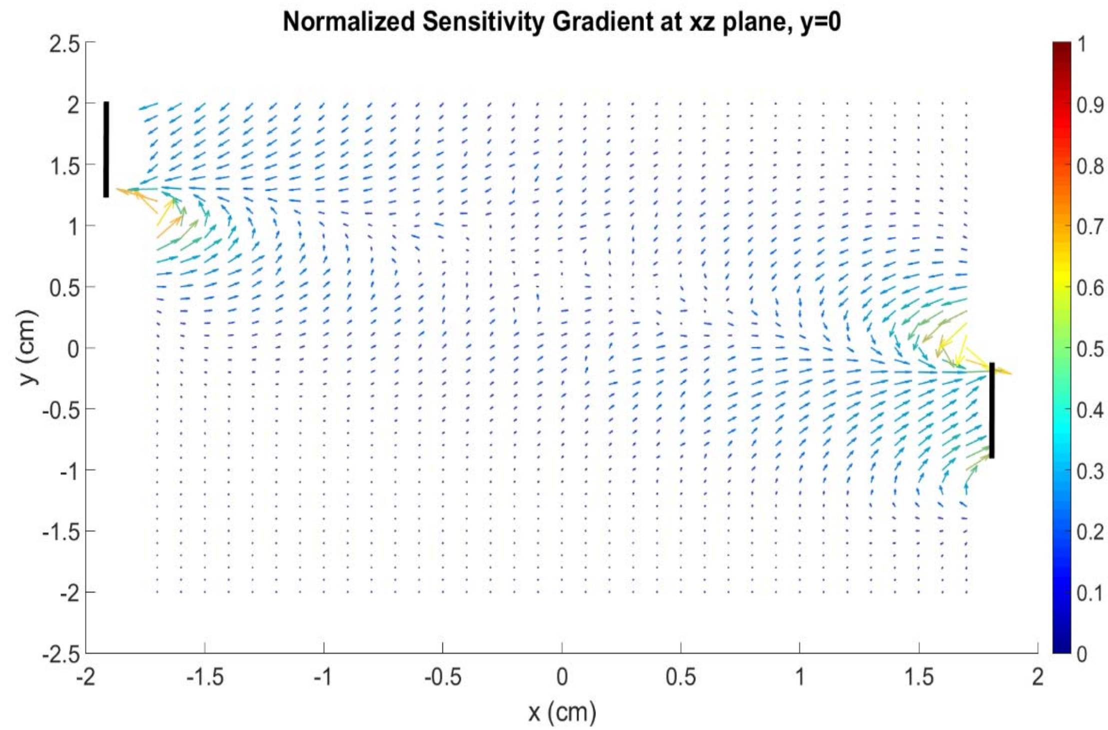


(b)



Sensitivity Gradient





$$\vec{F} = \vec{\nabla} S = \hat{a}_x \frac{\partial S}{\partial x} + \hat{a}_y \frac{\partial S}{\partial y} + \hat{a}_z \frac{\partial S}{\partial z}$$

Sensitivity Gradient

S Gradient

$$\vec{F} = \hat{a}_x F_x + \hat{a}_y F_y + \hat{a}_z F_z = \hat{a}_x \frac{\Delta S}{\Delta x} + \hat{a}_y \frac{\Delta S}{\Delta y} + \hat{a}_z \frac{\Delta S}{\Delta z}$$

Measured C

$$\Delta C = (\vec{F}_A . \vec{u})\epsilon = \left(F_x u_x + F_y u_y + F_z u_z\right)_{|at\ A}\ \epsilon$$

Measured t

$$\frac{\Delta C}{\Delta t} = \left(F_x \frac{u_x}{\Delta t} + F_y \frac{u_y}{\Delta t} + F_z \frac{u_z}{\Delta t}\right)_{|at\ A}\ \epsilon$$

$$\dot{C} = \left(F_x v_x + F_y v_y + F_z v_z\right)_{|at\ A}\ \epsilon$$

Generalization

$$\dot{\boldsymbol{C}} = (\boldsymbol{G} \odot \boldsymbol{F}_x)\boldsymbol{v}_x + (\boldsymbol{G} \odot \boldsymbol{F}_y)\boldsymbol{v}_y + (\boldsymbol{G} \odot \boldsymbol{F}_z)\boldsymbol{v}_z$$

3D Velocity Formulation

The notations used in are all scalar matrices and can be described as,

Generalization $\dot{\boldsymbol{C}} = (\boldsymbol{G} \odot \boldsymbol{F}_x)\boldsymbol{v}_x + (\boldsymbol{G} \odot \boldsymbol{F}_y)\boldsymbol{v}_y + (\boldsymbol{G} \odot \boldsymbol{F}_z)\boldsymbol{v}_z$

Notation	Dimension	Description
$\dot{\boldsymbol{C}}$	$M \times 1$	$\dot{\boldsymbol{C}} = \frac{\boldsymbol{C}^{t_2} - \boldsymbol{C}^{t_1}}{t_2 - t_1}$ denotes the time rate change of capacitance
$\boldsymbol{G}$	$M \times N$	A matrix with identical rows, each row is essentially the reconstructed permittivity vector $\boldsymbol{g}^T$ at time t_1
$\boldsymbol{F}_x, \boldsymbol{F}_y, \boldsymbol{F}_z$	$M \times N$	x, y, and z components of the sensitivity gradient, calculated from sensitivity matrix $\boldsymbol{S}$
$\boldsymbol{v}_x, \boldsymbol{v}_y, \boldsymbol{v}_z$	$N \times 1$	x, y, and z components of the velocity profile
$\odot$		Element wise product of two matrices, i.e. $\boldsymbol{C} = \boldsymbol{A} \odot \boldsymbol{B} \Leftrightarrow c_{ij} = a_{ij} b_{ij}$

For simplification, defining terms as $\boldsymbol{g}_x = \boldsymbol{G} \odot \boldsymbol{F}_x$,$\boldsymbol{g}_y = \boldsymbol{G} \odot \boldsymbol{F}_y$, and $\boldsymbol{g}_z = \boldsymbol{G} \odot \boldsymbol{F}_z$,

Image Reconstruction

S Gradient

$$\dot{\boldsymbol{C}} = \boldsymbol{g}_x\boldsymbol{v}_x + \boldsymbol{g}_y\boldsymbol{v}_y + \boldsymbol{g}_z\boldsymbol{v}_z$$

$$\boldsymbol{g}_x = \boldsymbol{G}\odot\boldsymbol{F}_x, \boldsymbol{g}_y = \boldsymbol{G}\odot\boldsymbol{F}_y, \text{ and } \boldsymbol{g}_z = \boldsymbol{G}\odot\boldsymbol{F}_z$$

<u>Applying Linear Back Projection:</u>

$$\boldsymbol{v}_x = {\boldsymbol{g}_x}^T\dot{\boldsymbol{C}}$$

$$\boldsymbol{v}_y = {\boldsymbol{g}_y}^T\dot{\boldsymbol{C}}$$

$$\boldsymbol{v}_z = {\boldsymbol{g}_z}^T\dot{\boldsymbol{C}}$$

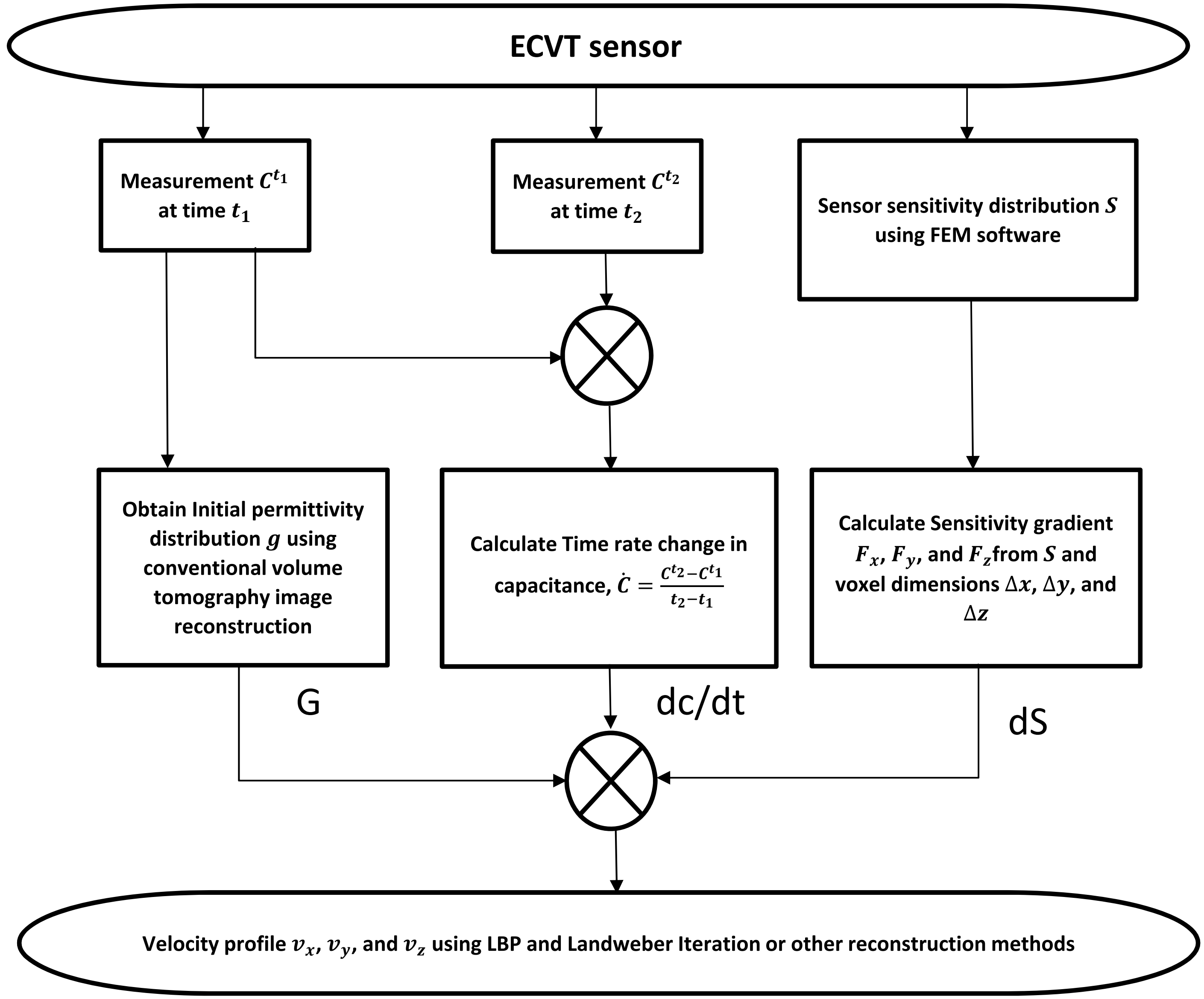
<u>Iterative Back Projection:</u>

$$\boldsymbol{v}_{x|k+1} = \boldsymbol{v}_{x|k} + \alpha_{xk}{\boldsymbol{g}_x}^T\left(\dot{\boldsymbol{C}} - \boldsymbol{g}_x\boldsymbol{v}_{x|k} - \boldsymbol{g}_y\boldsymbol{v}_{y|k} - \boldsymbol{g}_z\boldsymbol{v}_{z|k}\right)$$

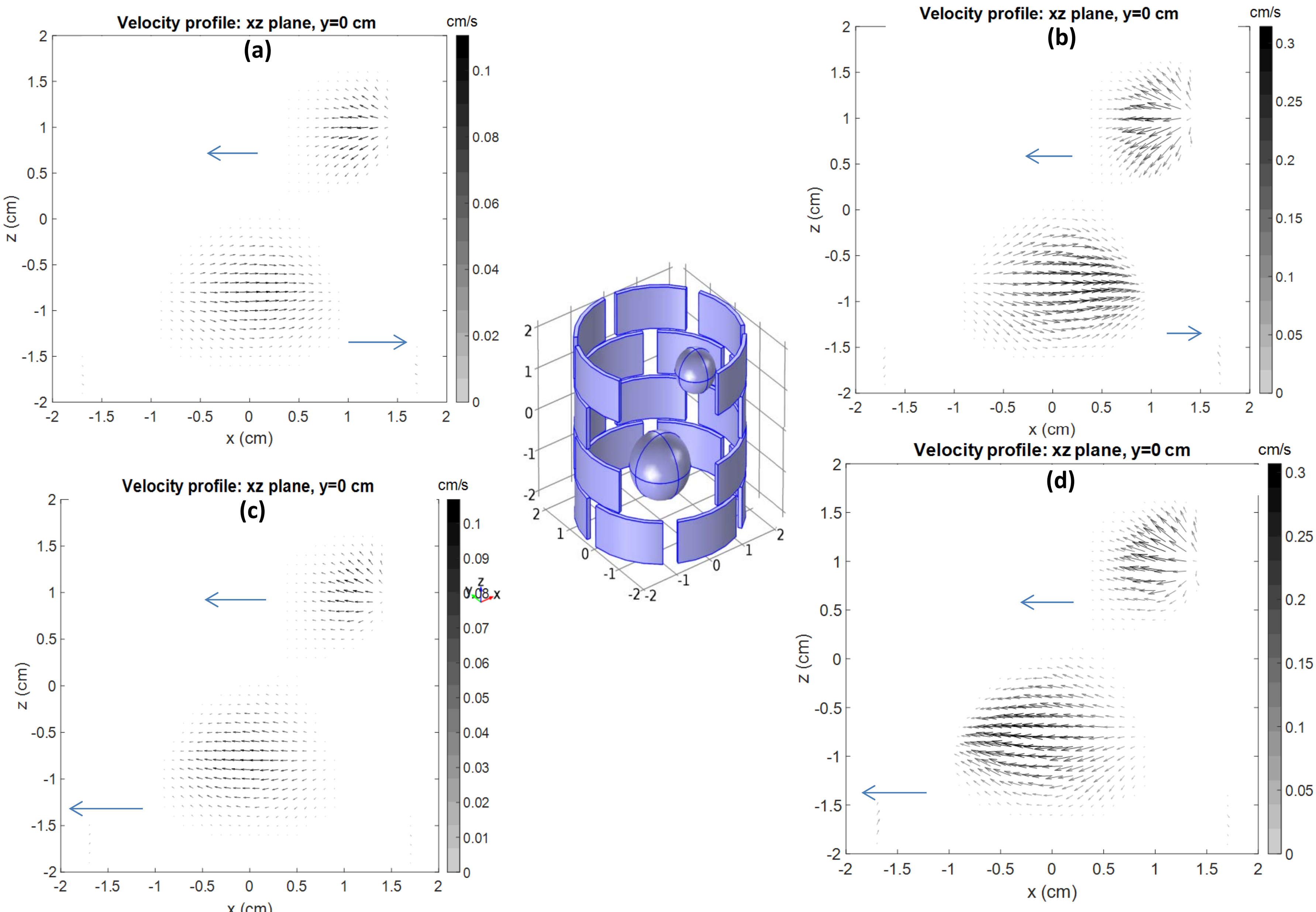
$$\boldsymbol{v}_{y|k+1} = \boldsymbol{v}_{y|k} + \alpha_{yk}{\boldsymbol{g}_y}^T\left(\dot{\boldsymbol{C}} - \boldsymbol{g}_x\boldsymbol{v}_{x|k+1} - \boldsymbol{g}_y\boldsymbol{v}_{y|k} - \boldsymbol{g}_z\boldsymbol{v}_{z|k}\right)$$

$$\boldsymbol{v}_{z|k+1} = \boldsymbol{v}_{z|k} + \alpha_{zk}{\boldsymbol{g}_z}^T\left(\dot{\boldsymbol{C}} - \boldsymbol{g}_x\boldsymbol{v}_{x|k+1} - \boldsymbol{g}_y\boldsymbol{v}_{y|k+1} - \boldsymbol{g}_z\boldsymbol{v}_{z|k}\right)$$

Velocity Vector Field Method

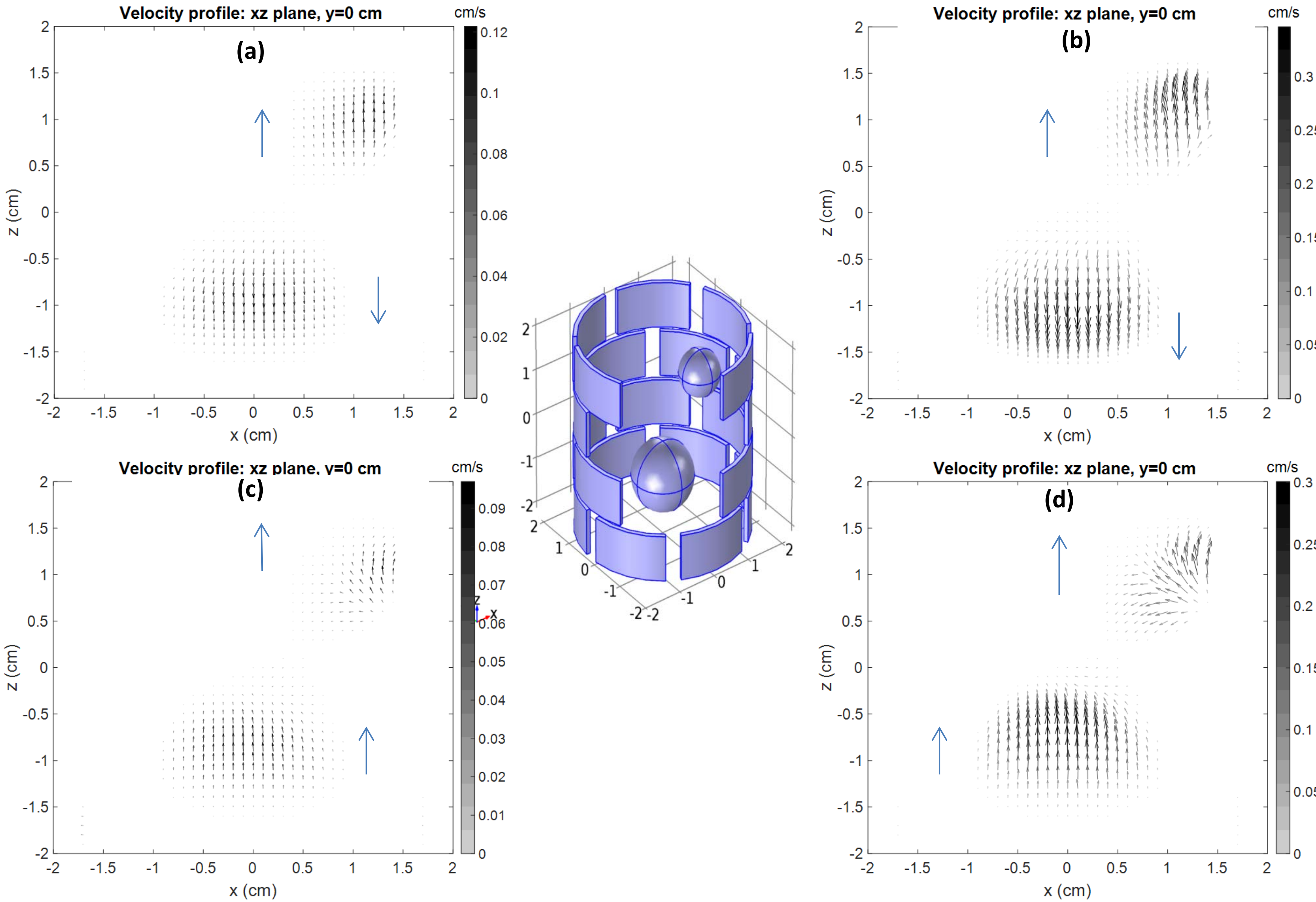


Velocity profile: Spheres are Moved in x Direction



(a) $\vec{v}_1 = -.1\ \hat{a}_x\ cm/s,\ v_2 = .1\ \hat{a}_x\ cm/s$, (b) $\vec{v}_1 = -.3\ \hat{a}_x\ cm/s,\ v_2 = .3\ \hat{a}_x\ cm/s$,
(c) $\vec{v}_1 = -.1\ \hat{a}_x\ cm/s,\ v_2 = -.1\ \hat{a}_x\ cm/s$, and (d) $\vec{v}_1 = -.3\ \hat{a}_x\ cm/s,\ v_2 = -.3\ \hat{a}_x\ cm/s$

Velocity profile: Spheres are Moved in z Direction



(a) $\vec{v}_1 = .1\ \hat{a}_z\ cm/s$, $v_2 = -.1\ \hat{a}_z\ cm/s$, (b) $\vec{v}_1 = .3\ \hat{a}_z\ cm/s$, $v_2 = -.3\ \hat{a}_z\ cm/s$, (c) $\vec{v}_1 = .1\ \hat{a}_z\ cm/s$, $v_2 = .1\ \hat{a}_z\ cm/s$, and (d) $\vec{v}_1 = .3\ \hat{a}_z\ cm/s$, $v_2 = .3\ \hat{a}_z\ cm/s$

Conclusion

- ECVT sensor for high temperature applications was constructed
- Velocimetry is a new technology for imaging velocity vector fields in multi-phase flow systems:
  - Sensitivity Gradient is used to reconstructed 3D maps of velocities.
  - Sensitivity gradient is coupled with image reconstruction to provide quantitative velocity maps.
  - Capacitance is captured at different times for time difference measurement.
  - The three velocity images are then solved together for velocity mapping.