CFD Design of Tubular Showerhead

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March 31, 2014

Design Objective

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Increase spatial uniformity of gas flow field injected onto the substrate in a AP-PECVD

1. While it is desirable to maintain uniform hole density close to the substrate, it is also beneficial to increase the linear density of holes with the decreasing Peclet number (convective flow strength).
2. Increasing gas residence time and turbulence inside the injector should increase flow field homogenization by increasing eddy diffusivity for momentum transfer.

Design Proposal

Study Proposal

Include an auxiliary inner showerhead and demonstrate the effect of

1. spatially non-uniform distribution of holes located along the side of the inner tube;
2. spatial shift of inner tube holes with respect to outer tube holes resulting in mutual hole misalignment;
3. variable rotation angle ϕ of the inner tube with respect to the outer reference tube.

We measure the effects in terms of local Reynolds number Re$=\frac{UH}{\nu}$ and vorticity magnitude $\omega = |\nabla \times \mathbf{u}|$.

Injector Geometry

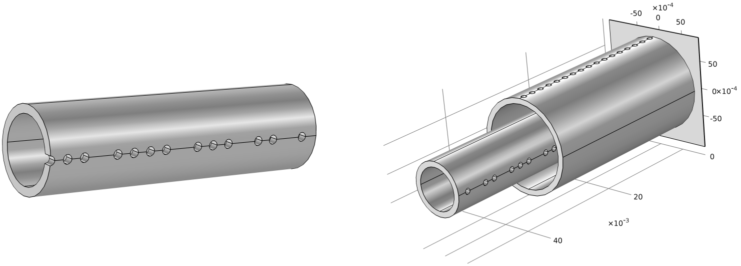


Fig.: *Left: Inner tube with non-uniform hole distribution. Right: Composite injector with inner tube retracted for visualization in the direction of gas inlet. Rotation angle $\phi = \pi/2$, symmetry plane far right.*

Hole Distribution on Inner Tube

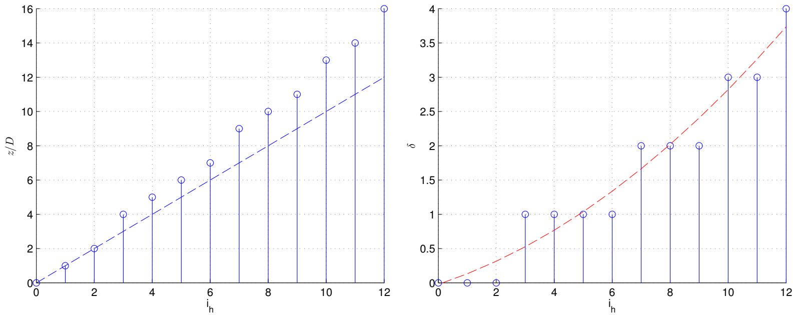


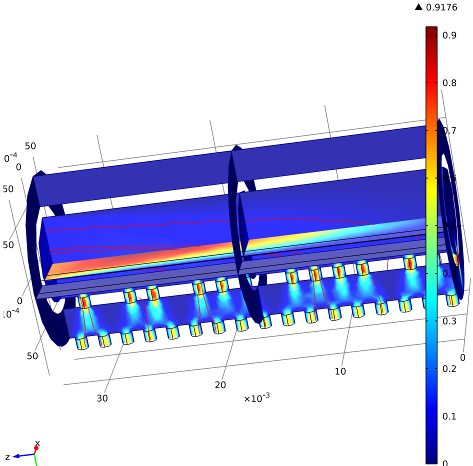
Fig.: *Left: Axial hole position z/D vs hole index $i_h = 0$, with $i_h = \{0$ (symmetry plane) ..12 (gas inlet)$\}$. Right: Degree of non-uniformity $\delta = z/D - i_h$ with a quadratic fit.*

Key Model Parameters

- Tube diameters
  - $D_1 = 15/2$ mm (auxiliary, inner)
  - $D_2 = 15$ mm (reference, outer)
- Hole diameter $d = 1$ mm
- Inter-hole spacing $D = 2d = 2$ mm
- Tube thicknesses $w = 1$ mm
- Scale-down factor ~ 18 (compared to the reference industrial injector)
  - Tube length $L = 68$ mm
  - Number of holes $n_1 = 25$ (inner tube), $n_2 = 34$ (outer tube)
  - Inlet gas velocity $u_0 = 0.1$ m/s
- Normal pressure T_0 and temperature p_0

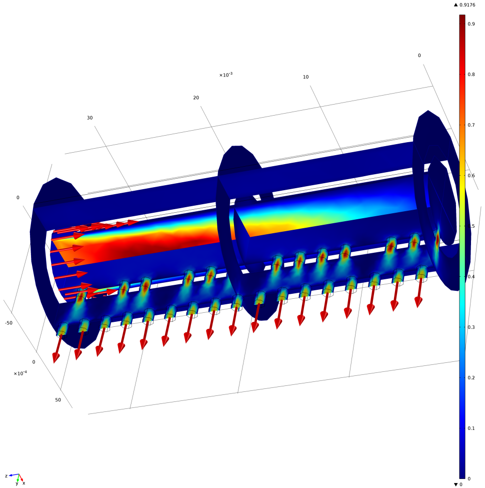
Velocity Magnitude with Representative Streamlines

Fig.: *Progressive decrease of velocity magnitude in the direction of flow is compensated by the increased density of holes in the inner tube towards the symmetry plane.*



Velocity Magnitude with Representative Velocity Vectors

Fig.: *Uniform velocity field along the length of the outer tube.*



Effect of ϕ (Reynolds number)

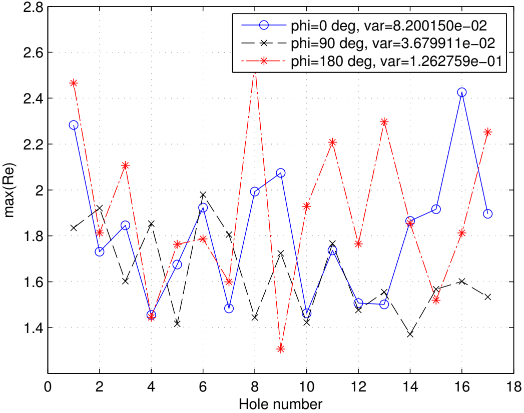


Fig.: *Maximum local Reynolds numbers at outlet holes, with the corresponding variances.* $\phi = \pi/2$ *yields lowest variance and thus most uniform velocity field. Tubes with holes misaligned.*

Effect of ϕ, cont'd (vorticity)

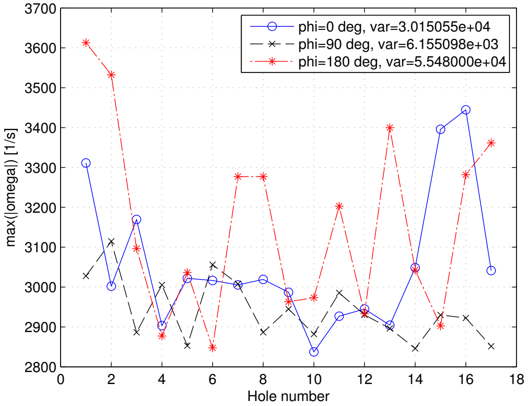


Fig.: *Maximum vorticity magnitude at outlet holes, with the corresponding variances. $\phi = \pi/2$ yields lowest variance and thus most uniform vorticity field. Tubes with holes misaligned.*

Effect of hole alignment and uniformity (Reynolds number)

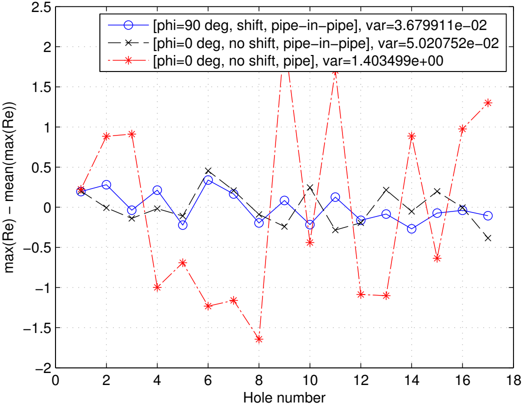


Fig.: *'Shift' denotes mutual misalignment of inner tube and outer tube holes. 'Pipe-in-pipe' denotes injector head with auxiliary inner tube. Reference injector denoted with red asterisks.*

Effect of hole alignment and uniformity, cont'd (vorticity)

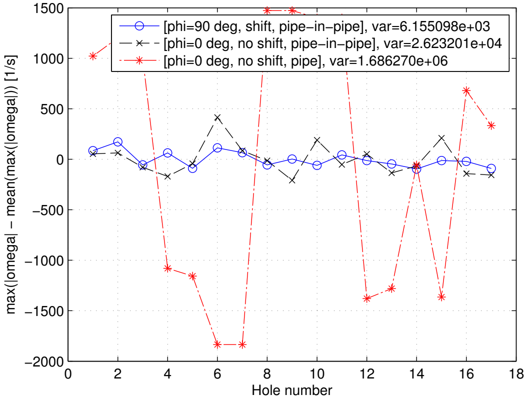


Fig.: *'Shift' denotes mutual misalignment of inner tube and outer tube holes. 'Pipe-in-pipe' denotes injector head with auxiliary inner tube. Reference injector denoted with red asterisks.*

Conclusions

- The highest spatial uniformity in outlet velocity and vorticity fields is achieved with
  - moderately rotated inner tube,
  - spatially non-uniform hole distribution of the inner tube, with the hole density inversely proportional to the gas axial velocity,
  - inner tubes holes misaligned with respect to outer tube holes.
- The injector fitted with an auxiliary inner tube significantly outperforms the reference injector (single tube with uniform hole distribution) in terms of spatial uniformity of the gas flow field ejected onto the substrate surface. Proportional increase in the deposition uniformity across the substrate width can be expected.

Final Remarks on Generalizations

- Non-uniform density of inner tube holes with constant diameter is expected to yield qualitatively similar results to those obtained with holes of variable diameter.
- The qualitative conclusions of this study are expected to hold in the presence of additional parallel lines of holes. Such a modification will however further reduce outlet velocity by increasing the outlet surface area.

Extensions: Venturi Effect and Flow Uniformity

- Pressure increase in a diverging channel may be used to control flow uniformity at nozzle outlets

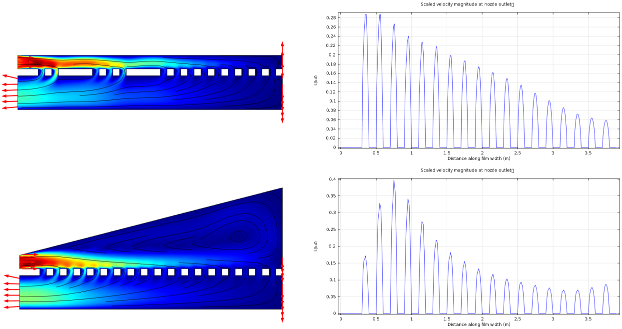


Fig.: *Distribution of velocity magnitude along the axial dimension.*

Extensions: Fine-tuning of Outflow Uniformity

- Outflow assumed already roughly uniform due to optimal design and conditions (see above)
- Requires sufficiently fine mesh

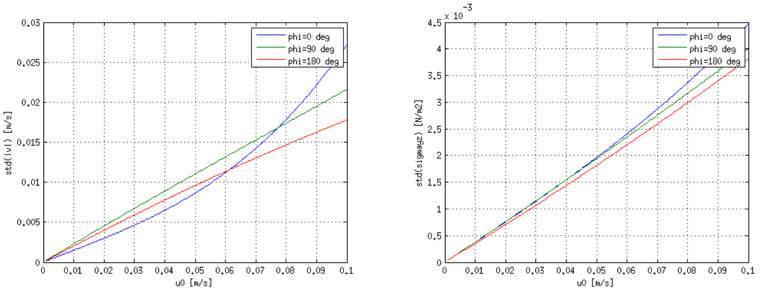


Fig.: *Standard deviation of velocity (left) and shear stress (right) hole averages in the axial direction for varying rotation angles.*

Extensions: CPI Reactor Flow Field

Fig.: *Velocity magnitude, scaled by precursor velocity. Typical conditions.*