Simulation of fluid flow and collection efficiency for an SEA multi-element probe

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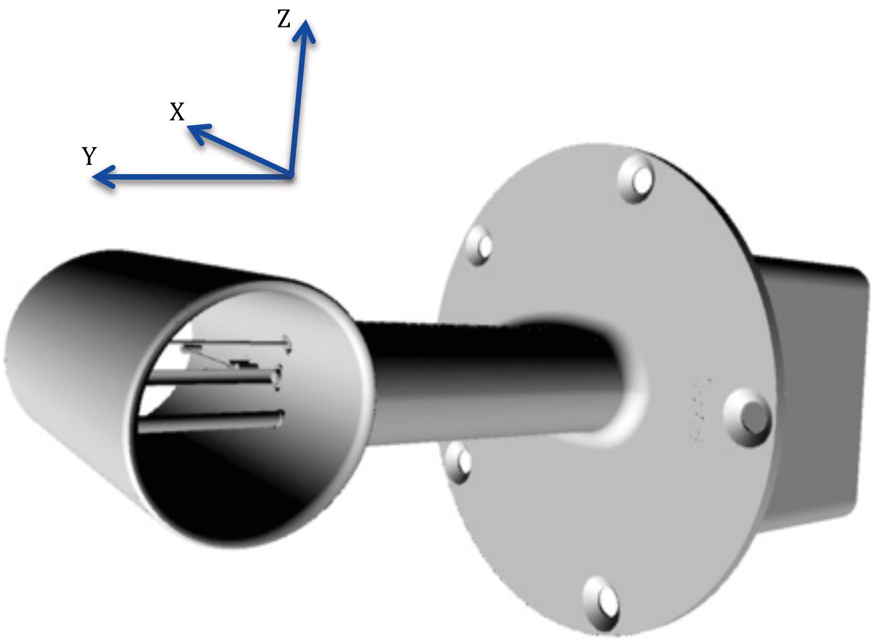
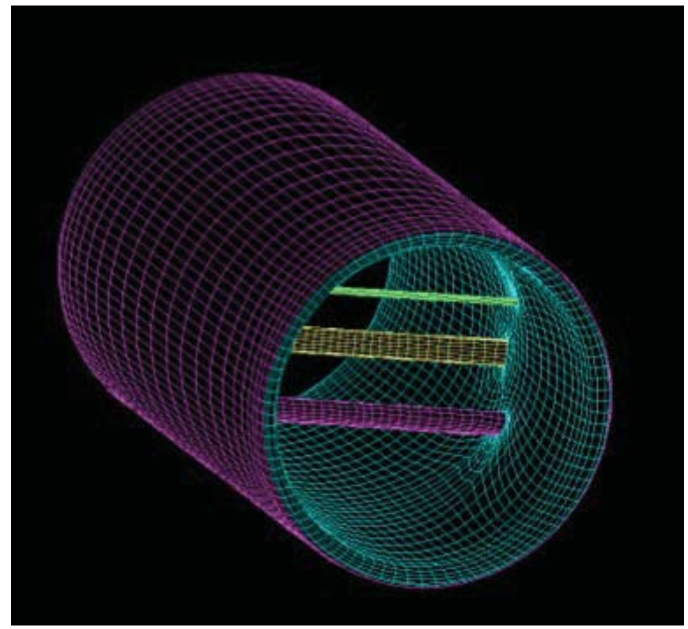
Outline

- Describe problem and simplifications
- Description of cases run
- Some views of the flowfield
- Heat transfer results
- Collection efficiency results

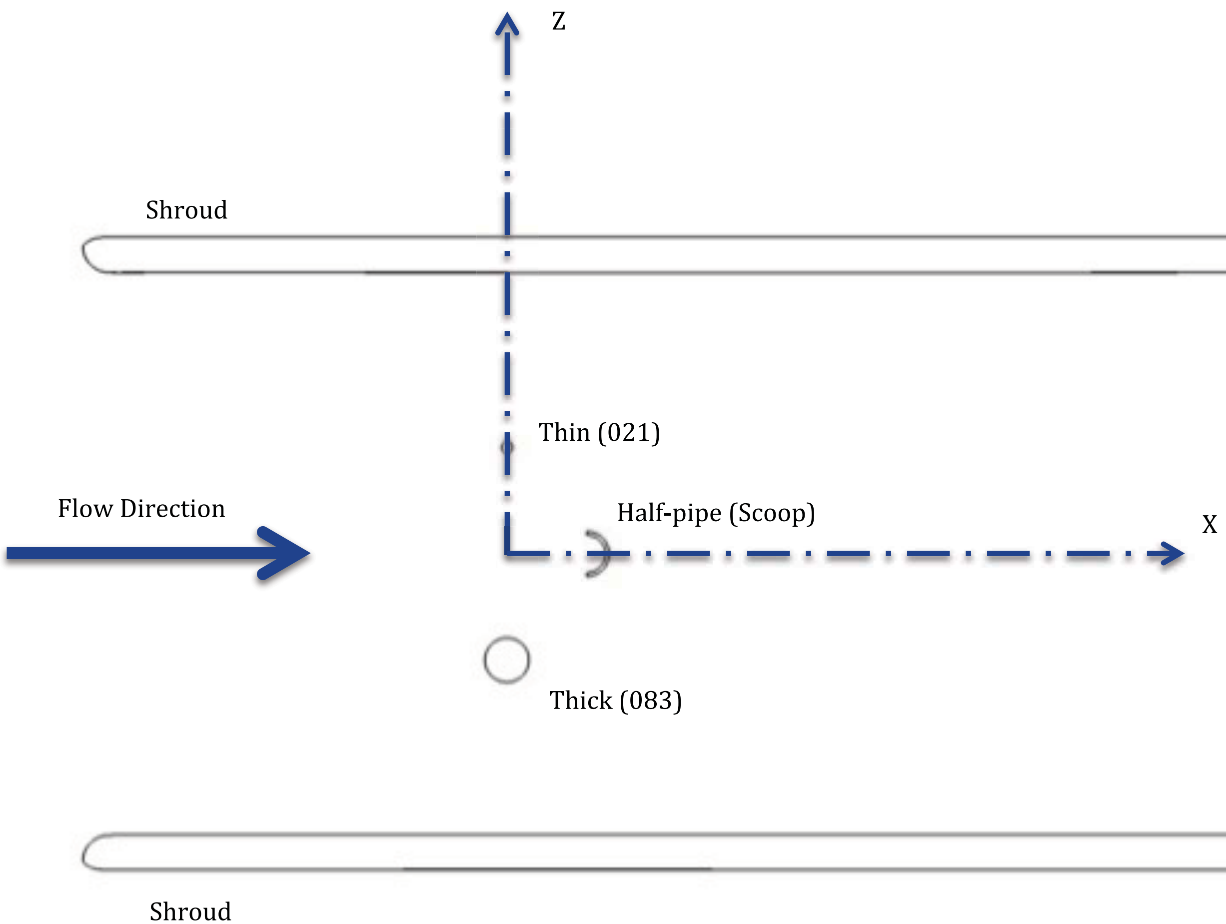
CAD Surface and Grid





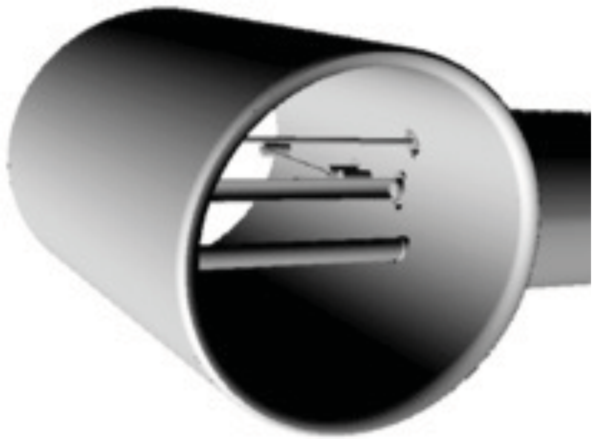
- CAD representation (left) and surface mesh for CFD simulation. Angle of attack refers to a rotation about the Y-axis. Yaw refers to a rotation about the Z-axis.

Schematic showing coordinate system



- Thin wire has a diameter of 0.021 inches
- Thick wire has a diameter of 0.083 inches
- Half-pipe has same diameter as thick wire

Simplifications



- Compensation wire is not modeled
- Mount is not included (in most cases)
- Wires and scoop enter shroud cleanly
- Domain much larger than wind tunnel (in most cases)
- 3D Unsteady Reynolds Averaged Navier-Stokes simulation
  - Focus is on time averaging of the unsteady simulation
- Fixed wall temperature
  - Each heated element is held at a fixed temperature of 140° C
  - The shroud is held at 50° C
- Freestream static temperature is -5° C for all cases

Description of Cases Run

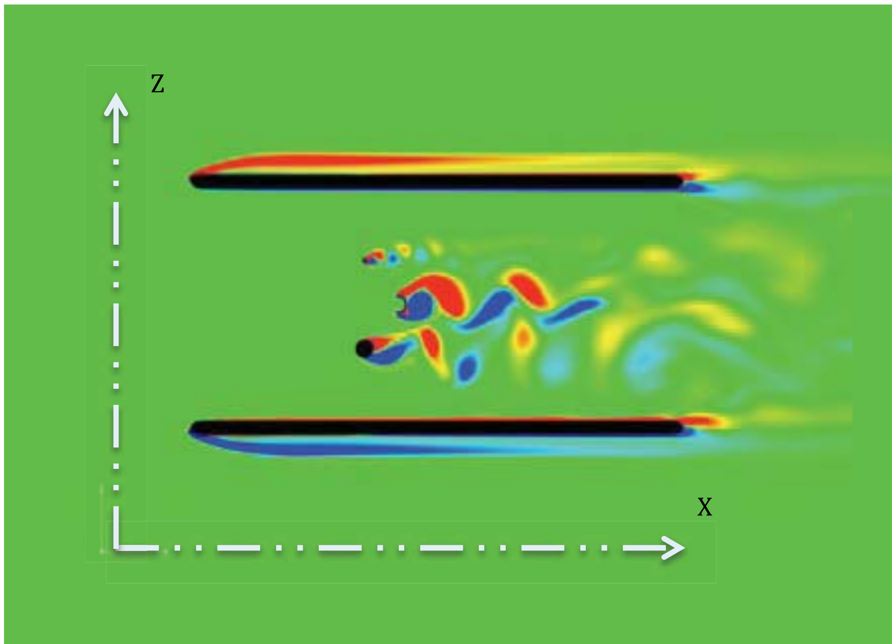
- Isolated, no support
  - Straight on
    - Total Pressure = 13.5 psi; Velocity = 85, 100, 135 m/s
    - Total Pressure = 6.5 psi; Velocity = 85, 100, 135 m/s
  - Total Pressure = 13.5 psi; Velocity = 85
    - Straight on, 5 degrees yaw, 5 degrees pitch
- In tunnel, with support
  - Straight on
    - Total Pressure = 13.5 psi; Velocity = 85

Table of Cases

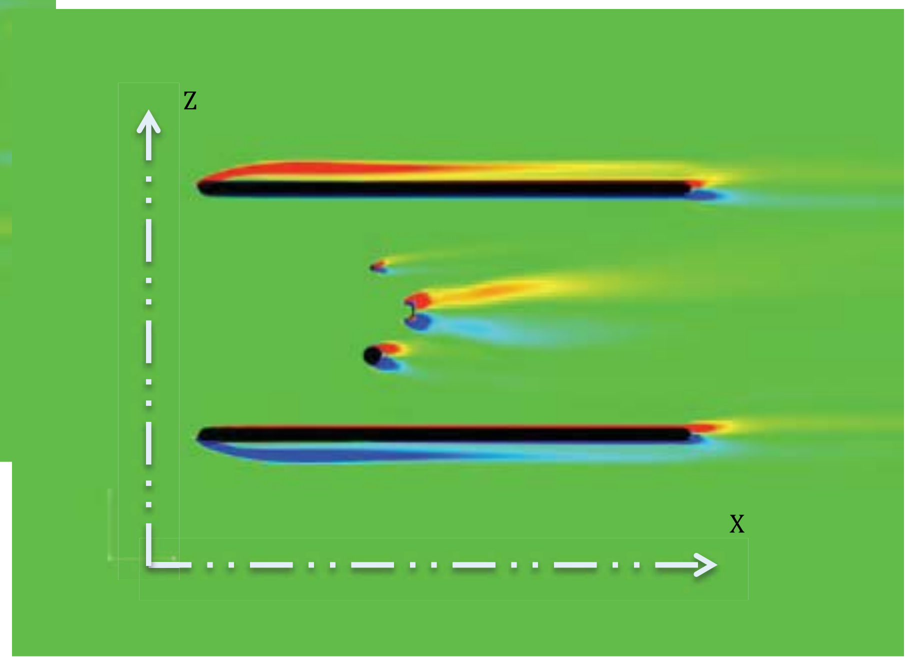
Name	P_0 (psia)	Velocity (m/s)	α ,Pitch (degrees)	γ , Yaw (degrees)	Support	Grid
Pt06p5V085	6.5	85	0	0	No	Normal
Pt06p5V100	6.5	100	0	0	No	Normal
Pt06p5V135	6.5	135	0	0	No	Normal
Pt13p5V085	13.5	85	0	0	No	Normal
Pt13p5V100	13.5	100	0	0	No	Normal
Pt13p5V135	13.5	135	0	0	No	Normal
Attack5deg	13.5	85	5	0	No	Normal
Yaw5deg	13.5	85	0	5	No	Normal
Support	13.5	85	0	0	Yes	Normal
Pt13p5V085c	13.5	85	0	0	No	Coarsened
Pt13p5V085f	13.5	85	0	0	No	Refined

Instantaneous vs Time-Averaged Result

- Instantaneous Snapshot



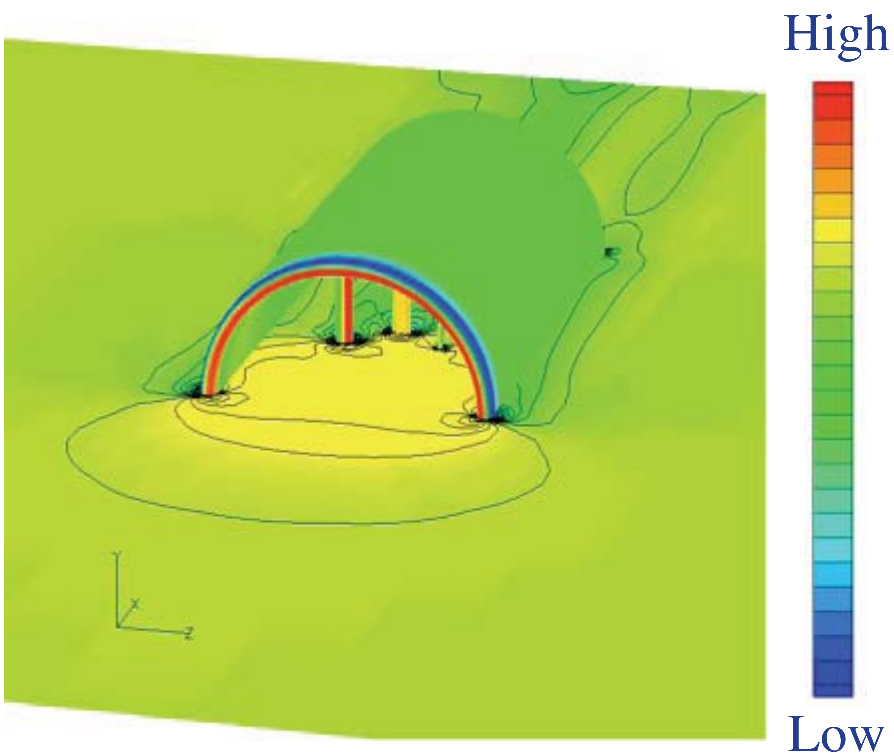
- Time Averaged



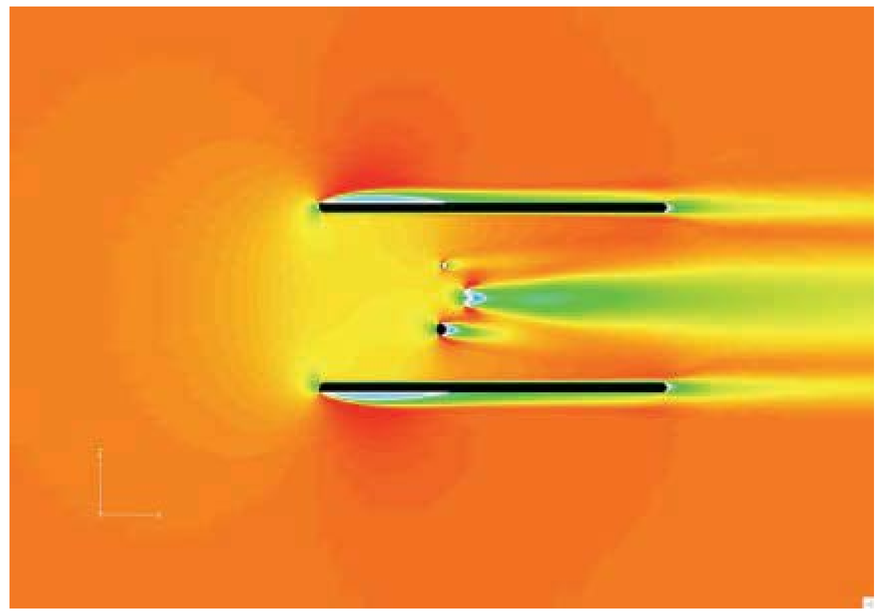
- Y-vorticity (red is positive, blue is negative)

Pressure and Axial Velocity

- Pressure in symmetry plane and on surfaces

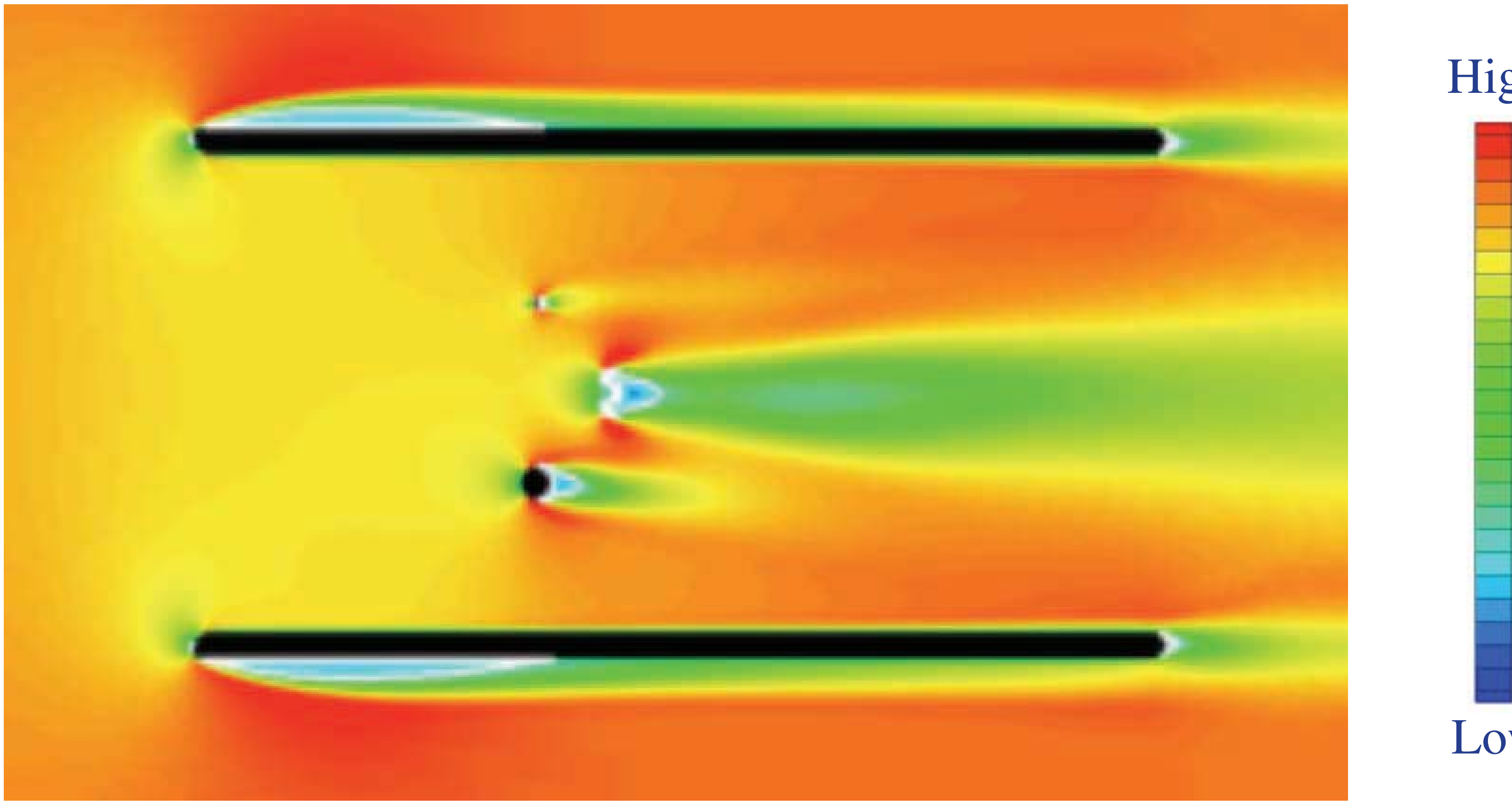


- Axial velocity in symmetry plane



White lines, representing zero velocity, enclose reverse flow regions

Axial Velocity (closer view)



White lines, representing zero velocity, enclose reverse flow regions

Table of Shroud Mass Flux

Name	Normalized Average Shroud Mass Flux
Pt06p5V085	0.7905
Pt06p5V100	0.7855
Pt06p5V135	0.7895
Pt13p5V085	0.7988
Pt13p5V100	0.7975
Pt13p5V135	0.7917
Attack5deg	0.7977
Yaw5deg	0.8045
Support	0.8034
Pt13p5V085c	0.8344
Pt13p5V085f	0.7871

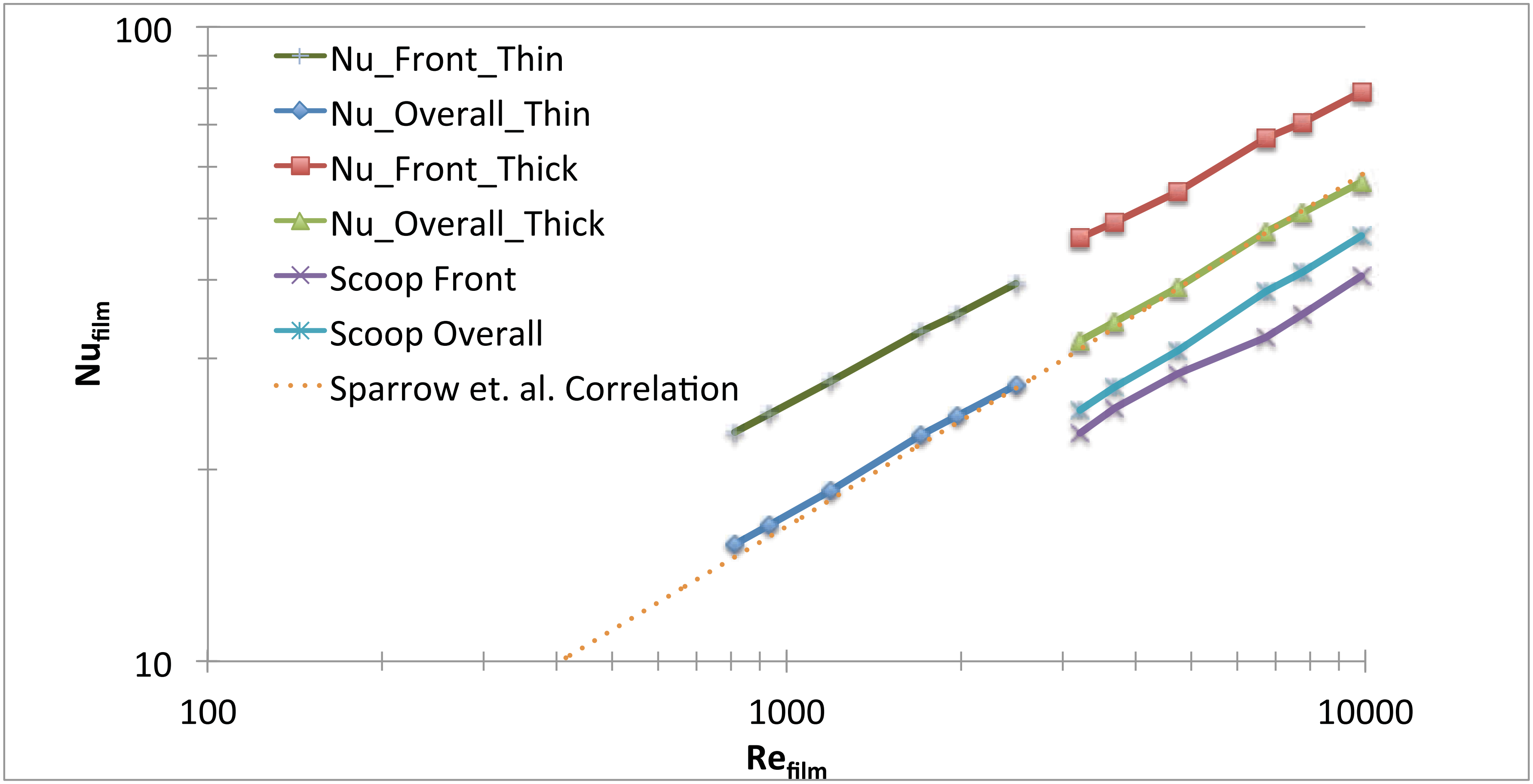
- Shroud mass flux is approximately 80% of freestream mass flux for all cases

Heat Transfer Results

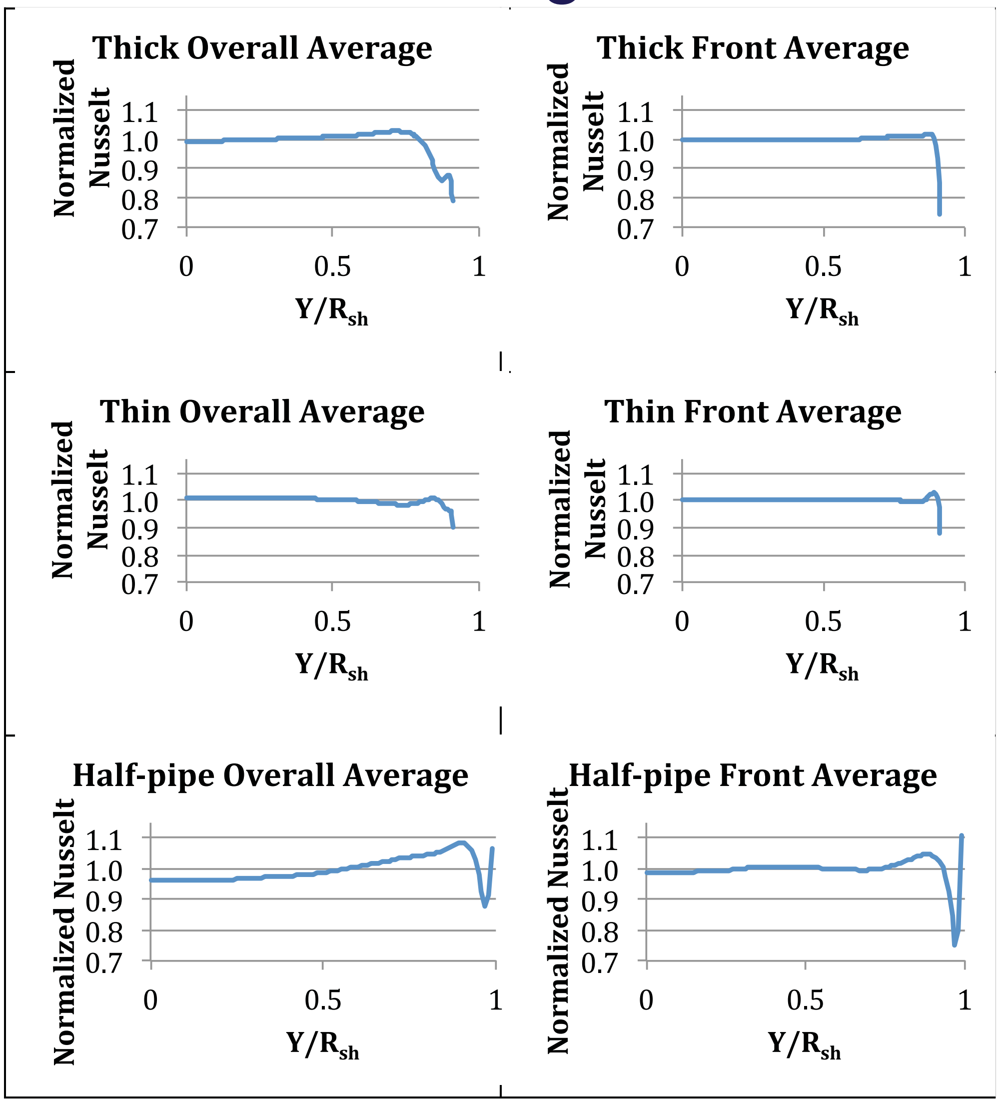
- Presented in terms of Nusselt number
  - Nu=h*d/k
    - h = $q/(T_{wall}-T_{t,\infty})$
    - q = wall heat flux
    - T_{wall} = wall temperature
    - $T_{t,\infty}$ = freestream total temperature
    - d = wire diameter
    - k = air thermal conductivity
- Overall, as well as frontal results are generated
  - Frontal results are of interest because particles only impact the front of each heated element
- Spanwise variation of the heat transfer is also investigated
- Angle of attack, yaw, and the case with the support produced little change in the heat transfer
  - Details are in the paper, but not presented here in the interest of time

Nusselt number results for straight on cases

- Overall refers to an average over the entire heated element
- Front refers to averaging over the upstream facing surface



Normalized Nusselt number averaged from all six straight on cases

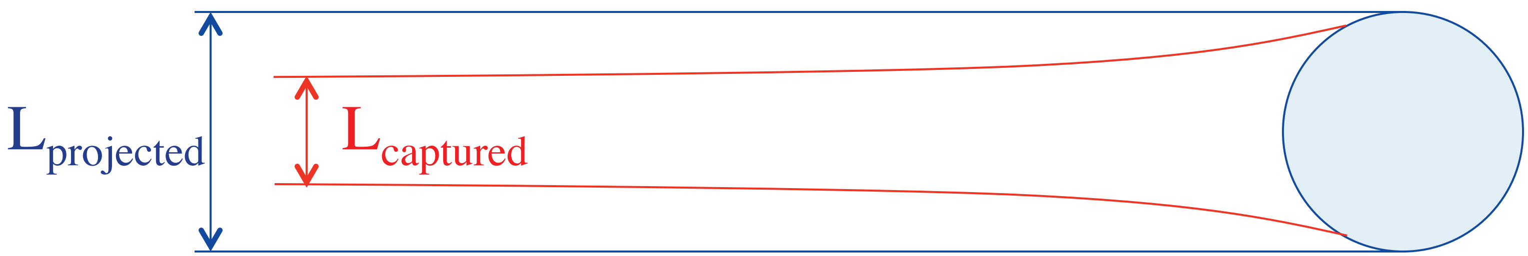


Collection Efficiency Results

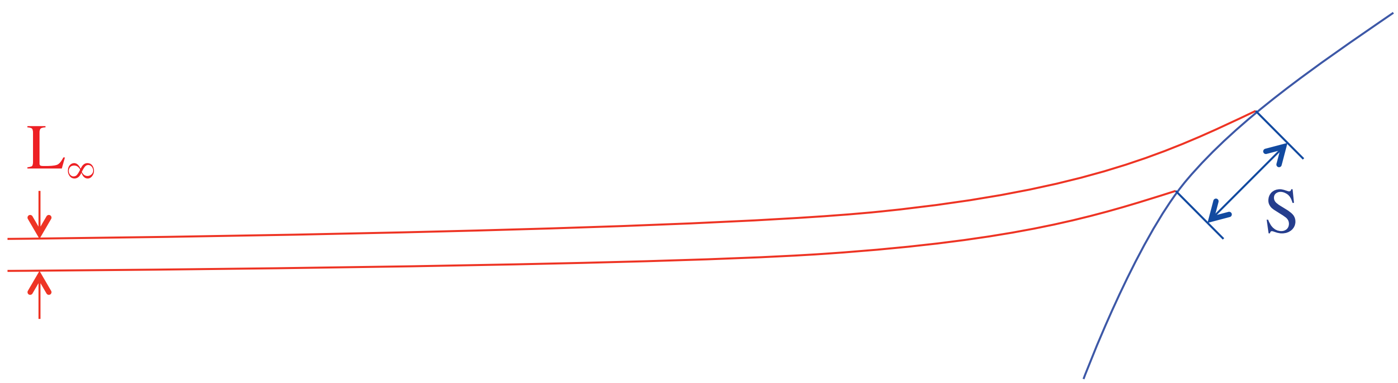
- Collection efficiency is a calculated using the LEWICE3D code
  - Uses the Navier-Stokes results from Glenn-HT
  - Particles sizes of 5, 20, 50, and 100 microns are investigated
  - Results from an SLD splashing model are also included for the 100 micron cases
- Both total and local collection efficiency results are presented
  - Total collection efficiency, E_m, is the ratio of the particle mass impinging on a body to the free stream impingement rate through an area equal to the projected area of the body
  - Local collection efficiency, β, is defined as the ratio of the surface mass flux of particles to the free stream mass flux of particles

Total versus Local Collection Efficiency (a visual explanation)

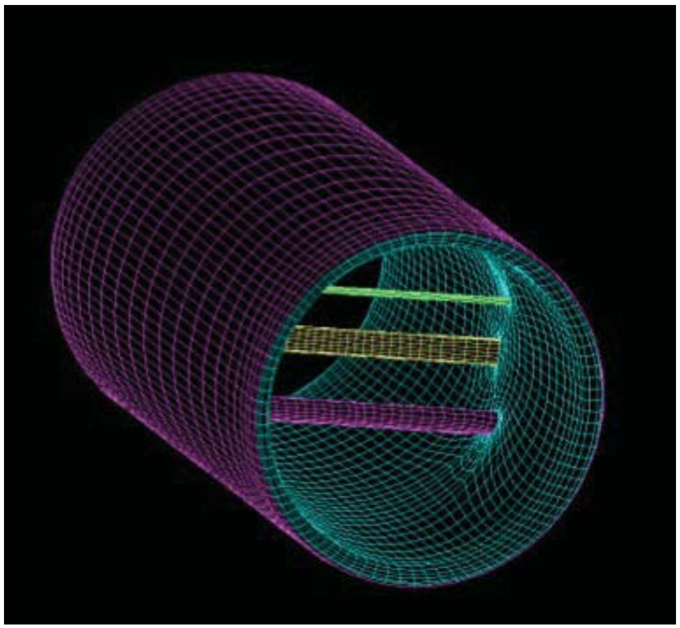
Total Collection Efficiency, $E_m = L_{captured}/L_{projected}$

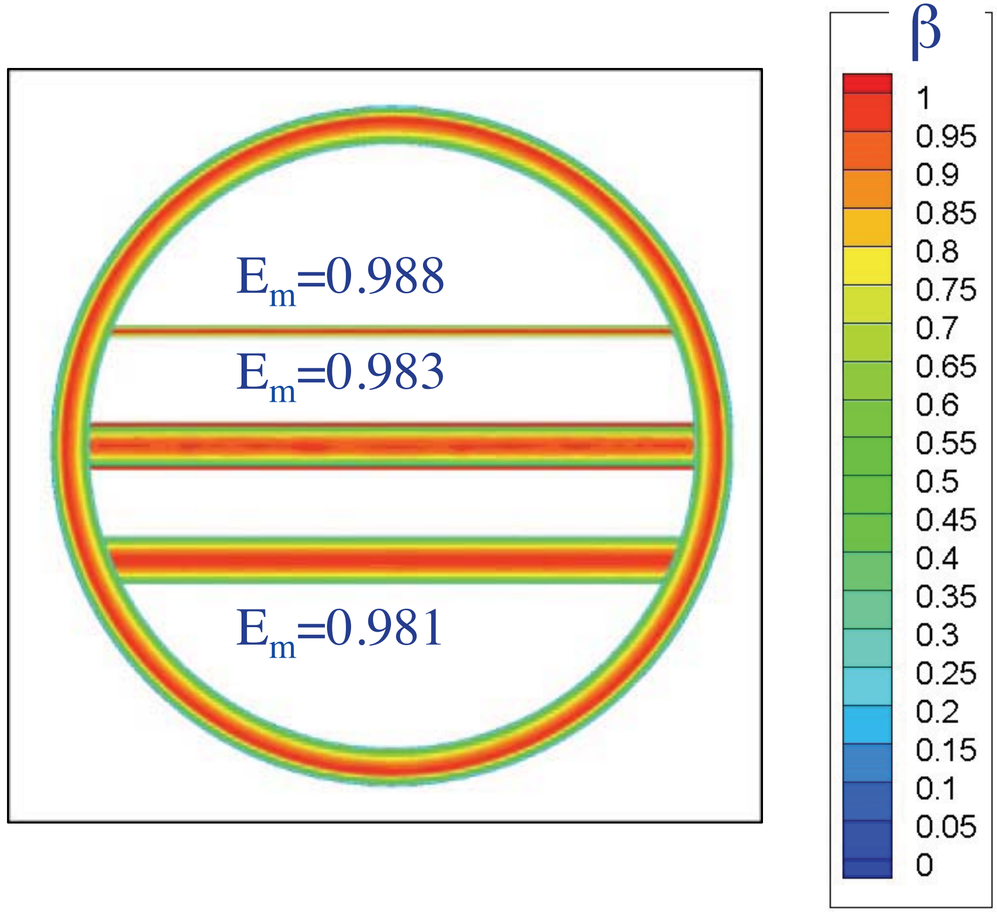


Local Collection Efficiency, $\beta = L_{\infty}/S$

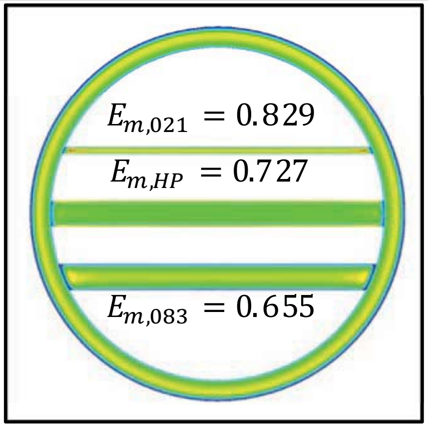
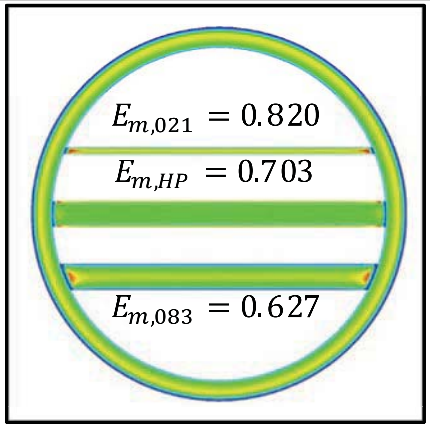
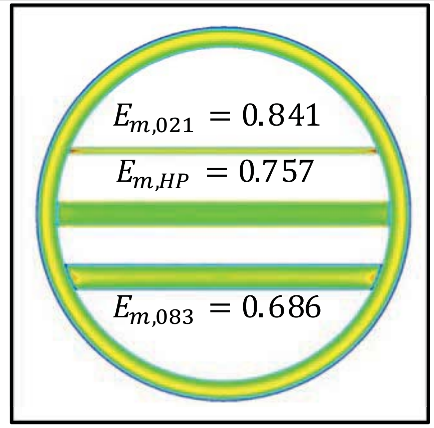
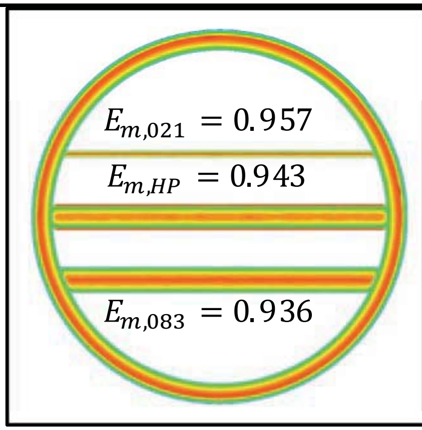
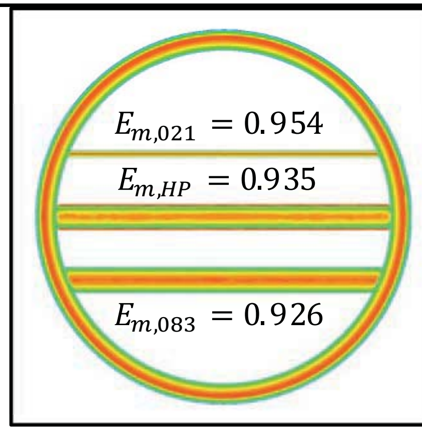
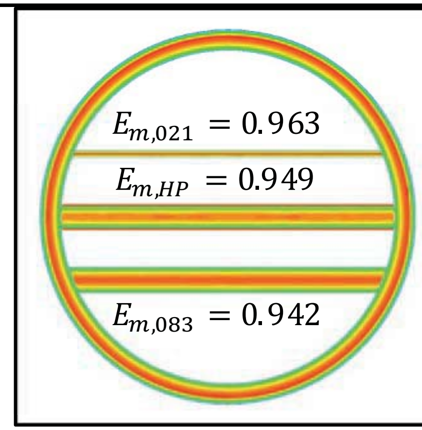


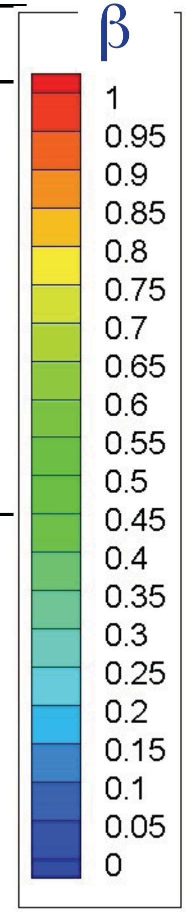
Local Collection Efficiency (Looking from upstream)



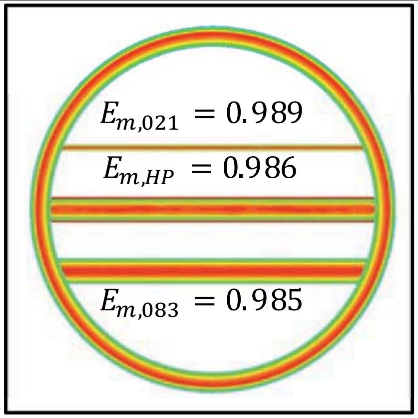
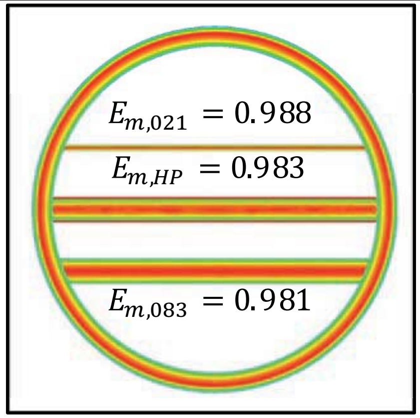
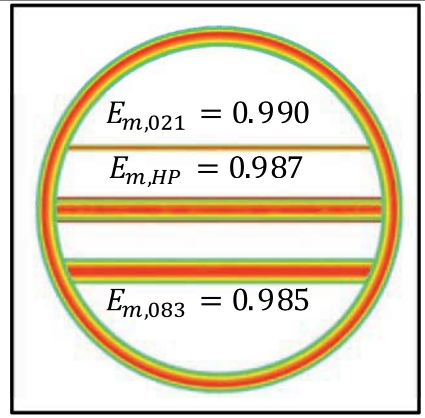
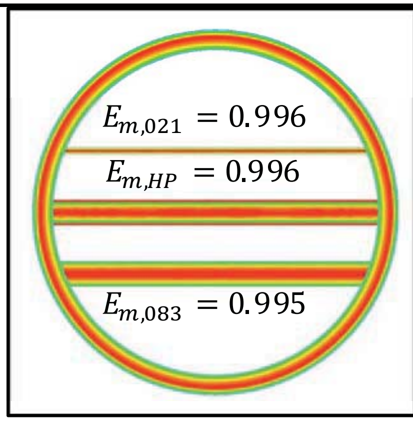
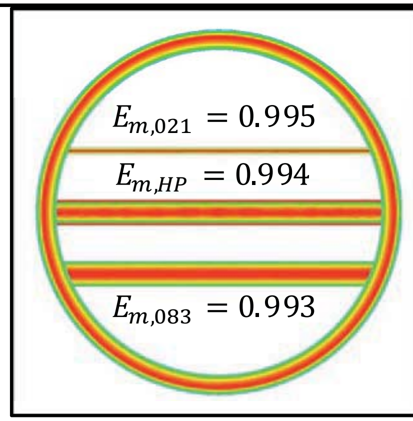
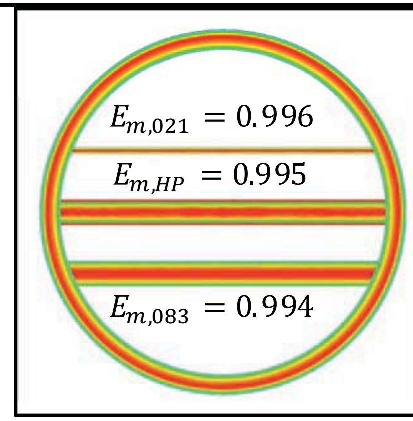


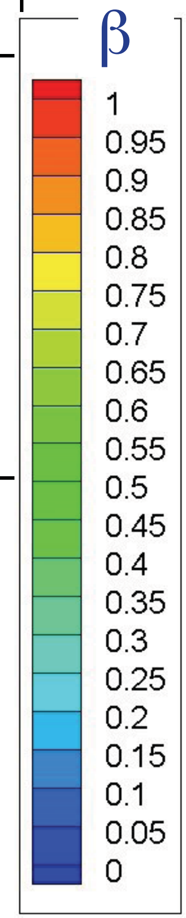
Local Collection Efficiency for several particle sizes (straight on cases).

Particle Size	Pt=6.5 psia, V=85 m/s, α=0, γ=0	Pt=13.5 psia, V=85 m/s, α =0, γ =0	Pt=13.5 psia, V=135 m/s, α =0, γ =0
5 μm			
20 μm			

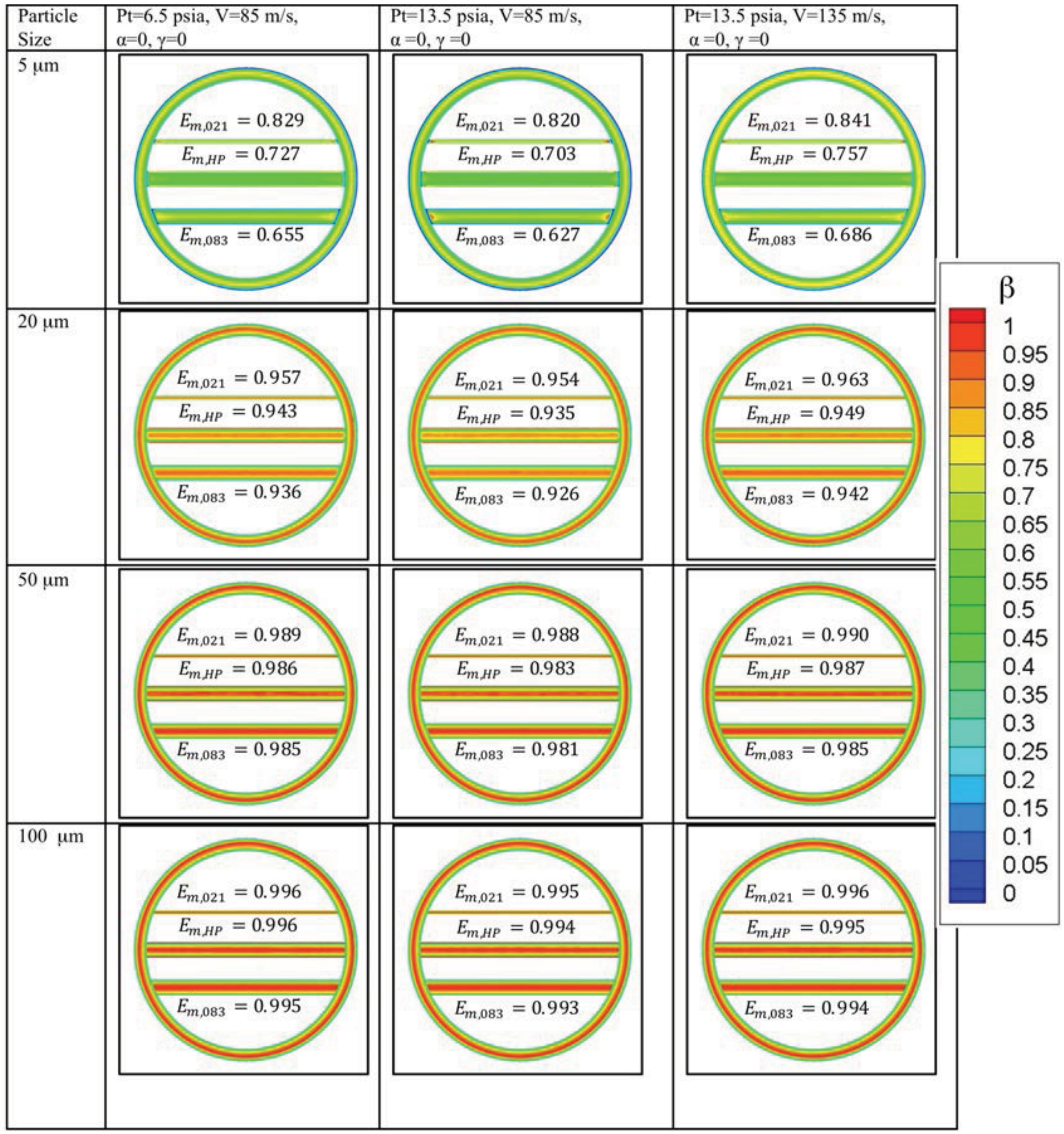


Local Collection Efficiency for several particle sizes (straight on cases).

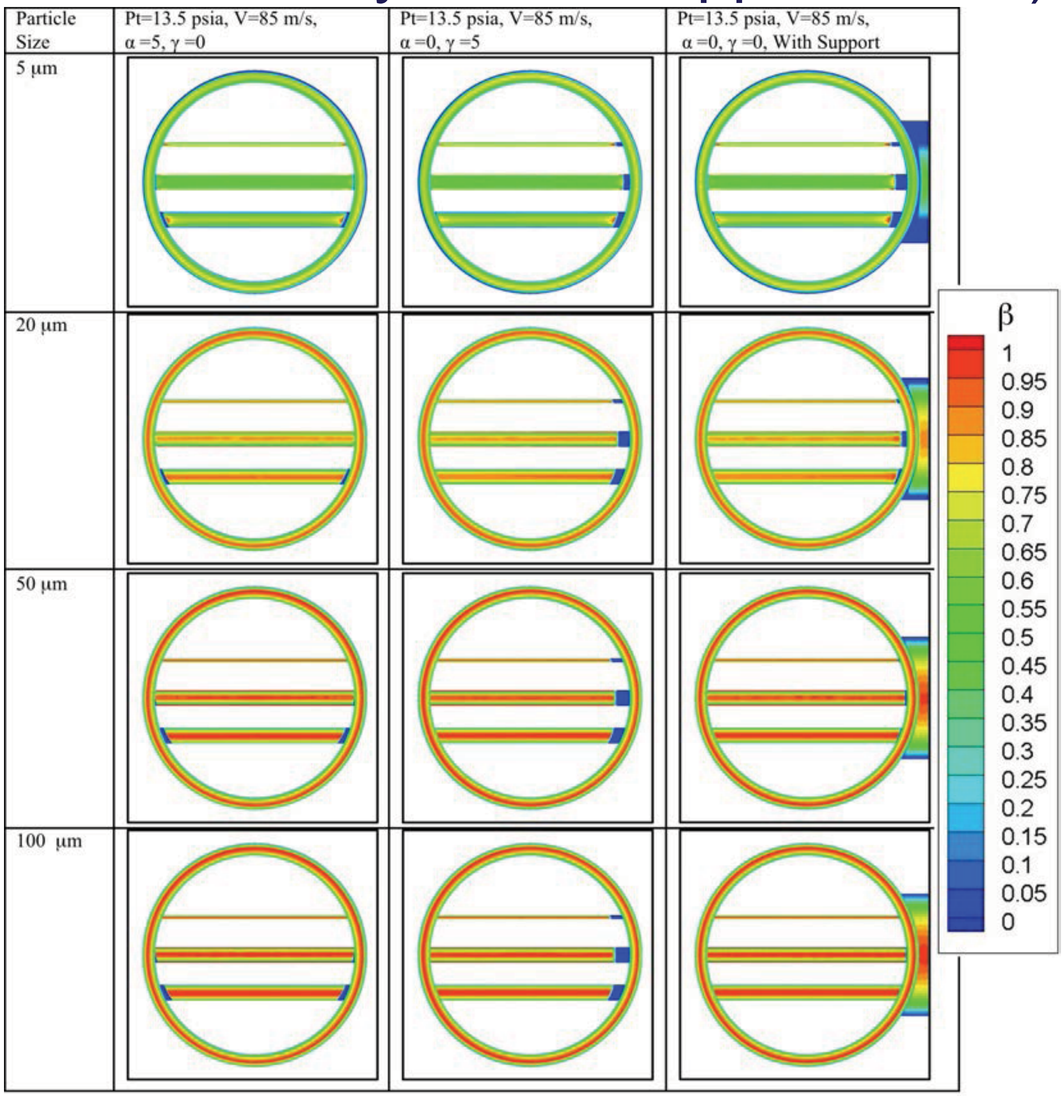
Particle Size	Pt=6.5 psia, V=85 m/s, α=0, γ=0	Pt=13.5 psia, V=85 m/s, α =0, γ =0	Pt=13.5 psia, V=135 m/s, α =0, γ =0
50 μm			
100 μm			



Local Collection Efficiency for several particle sizes (straight on cases).

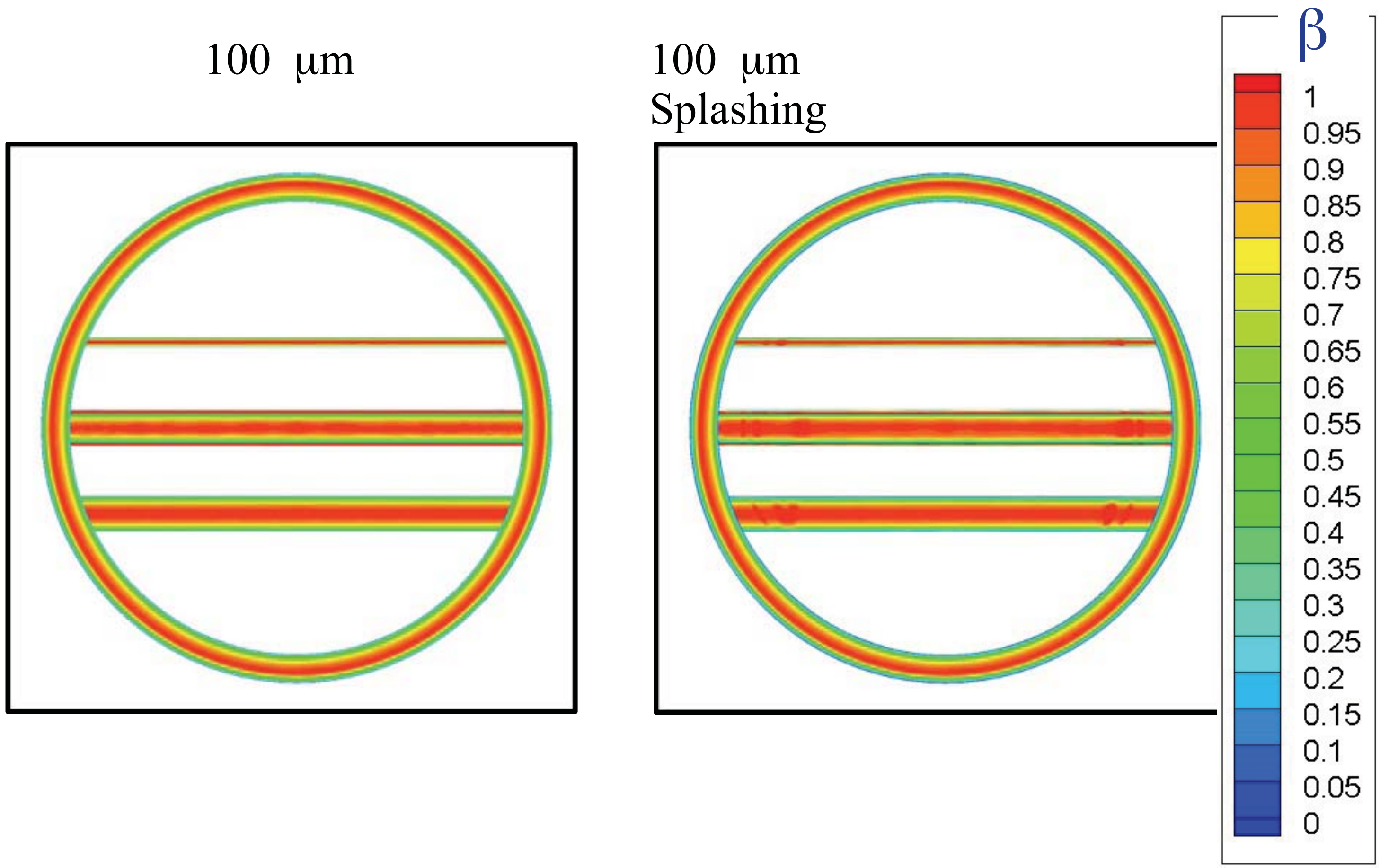


Collection efficiency for several particle sizes (angle of attack, yaw and support cases).



Collection efficiency
Splashing compared to no splashing

Pt=13.5 psia,
V=85 m/s,
$\alpha = 0$, $\gamma = 0$



Total collection efficiency results for straight on cases without support
Thick (083) Heated Element

Geometry	Total Pressure	Airspeed	Drop Size	K_0	E_m,2D	E_m,3D	E_m,3D/E_m,2D
	psia	m/s	Microns		Lewice2D	Lewice3D	
Thick (083)	6.5	85	5	2.15	0.782	0.655	83.7%
Thick (083)	6.5	85	20	23.39	0.974	0.936	96.1%
Thick (083)	6.5	85	50	103.26	0.992	0.985	99.2%
Thick (083)	6.5	85	100	304.29	0.996	0.995	99.9%
Thick (083)	13.5	85	5	1.79	0.754	0.627	83.1%
Thick (083)	13.5	85	20	17.82	0.968	0.926	95.7%
Thick (083)	13.5	85	50	74.75	0.990	0.981	99.1%
Thick (083)	13.5	85	100	213.24	0.995	0.993	99.8%
Thick (083)	13.5	135	5	2.53	0.816	0.686	84.0%
Thick (083)	13.5	135	20	24.02	0.975	0.942	96.6%
Thick (083)	13.5	135	50	98.33	0.992	0.985	99.2%
Thick (083)	13.5	135	100	276.34	0.995	0.994	99.9%

Conclusions

- Time average URANS results from Glenn-HT/ LEWICE3D provide reasonable prediction of heat transfer and collection efficiency for the SEA multi-element probe
- Flow within shroud is approximately 80% of freestream flow for all cases
- Nusselt number results follow predictable trend lines as a function of Reynolds number
- Pitch, Yaw, and the inclusion of the support strut have little effect on average Nusselt number results
- Total collection efficiency of heated elements approaches 100% for 50 and 100 micron particles

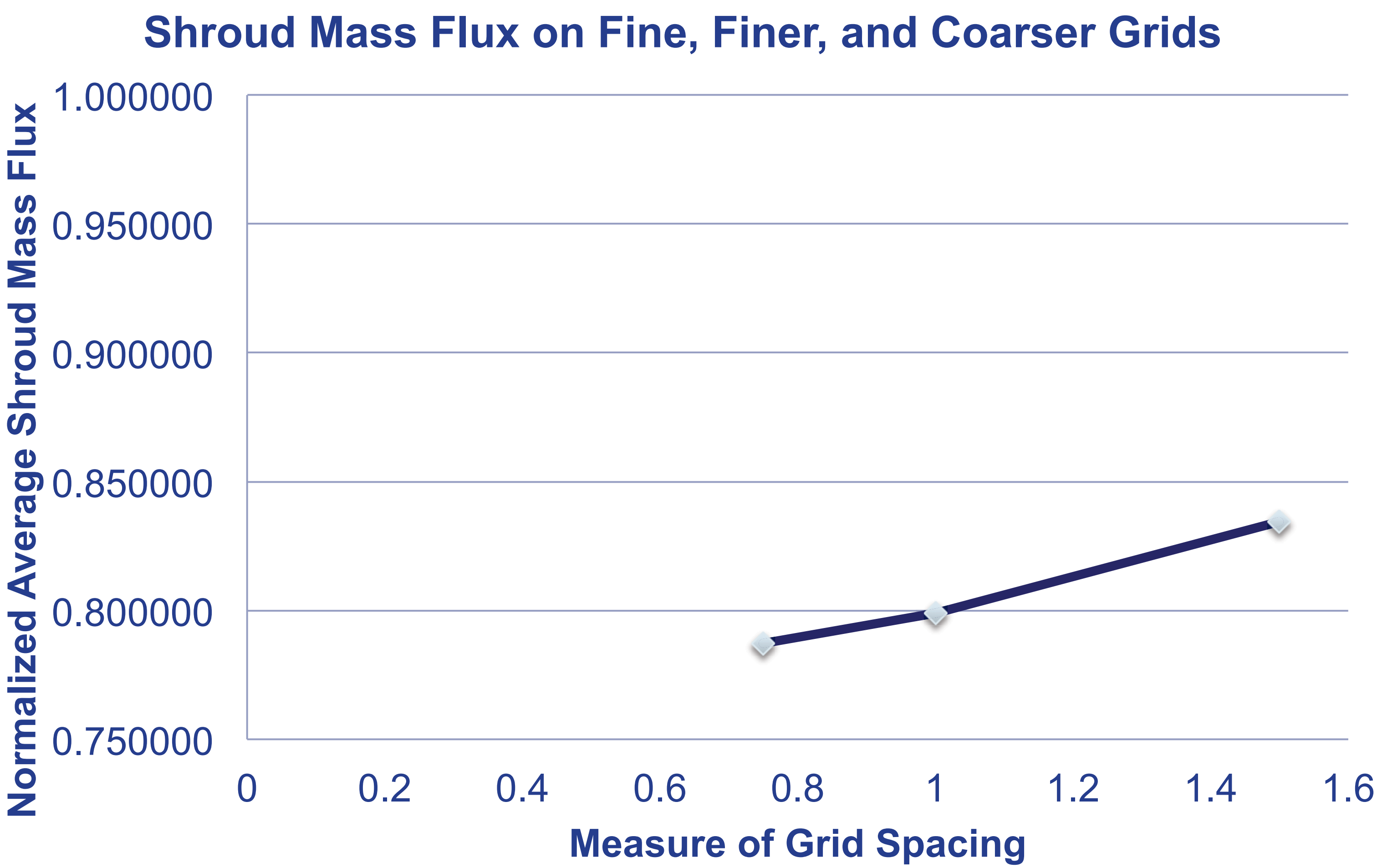
Conclusions (continued)

- Total collection efficiency is reduced as particle size decreases
  - Decreased inertia parameter, as particle size decreases, explains much of reduction
  - Additional reduction observed due to effect of shroud
    - Additional reduction is quantified by comparing 3D and 2D results
    - Reduced flow through shroud causes decrease in flux of particles (compared to freestream) approaching heated elements
    - Reduced velocity within shroud allows particles to more easily avoid heated elements
    - Effect of shroud becomes negligible as particle size increases

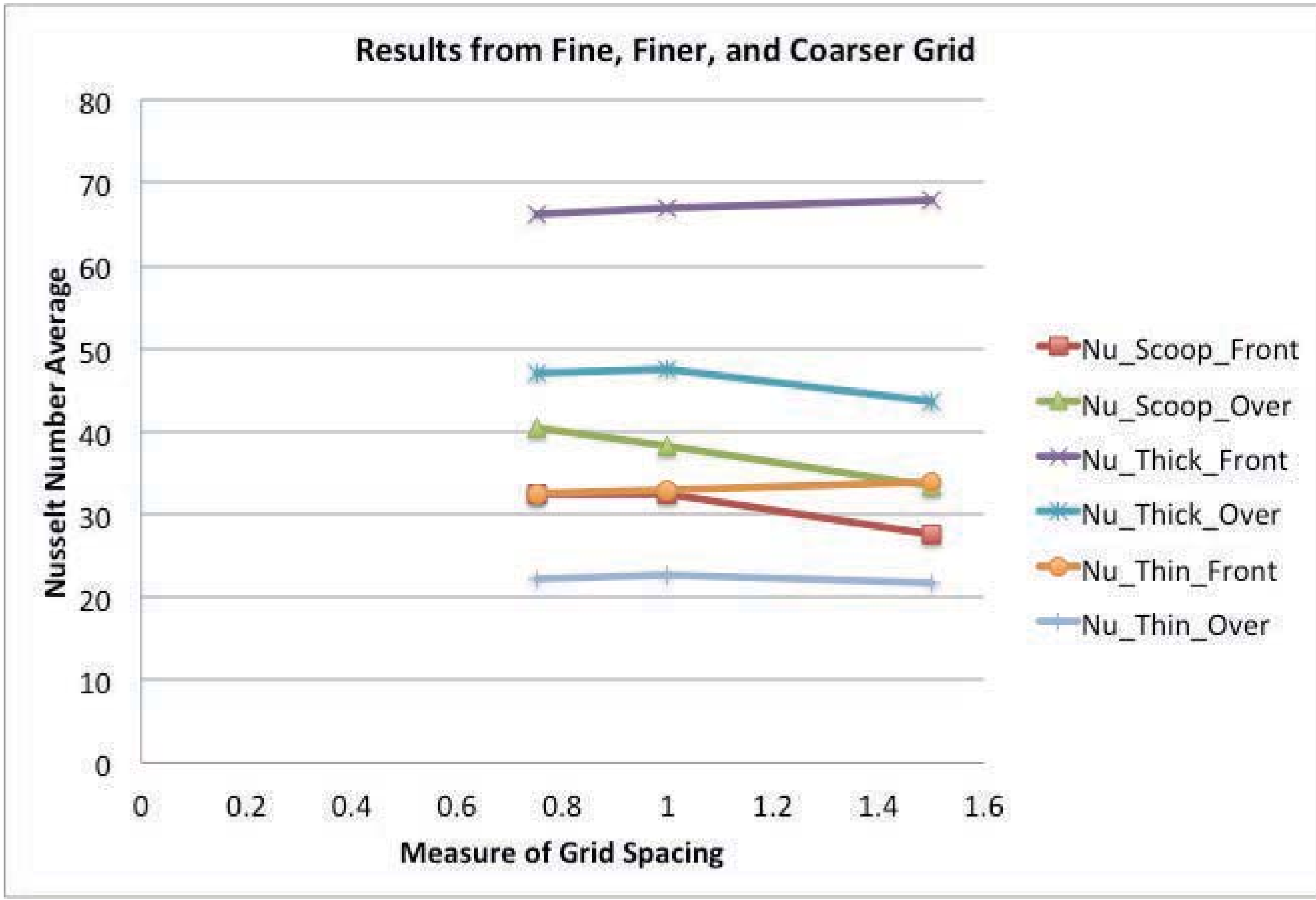
Thank You

Backup Slides

Grid Dependence of Shroud Mass Flux



Grid Dependence of Nusselt Numbers



Effect of Pitch, Yaw, and Support Strut on Average Nusselt numbers

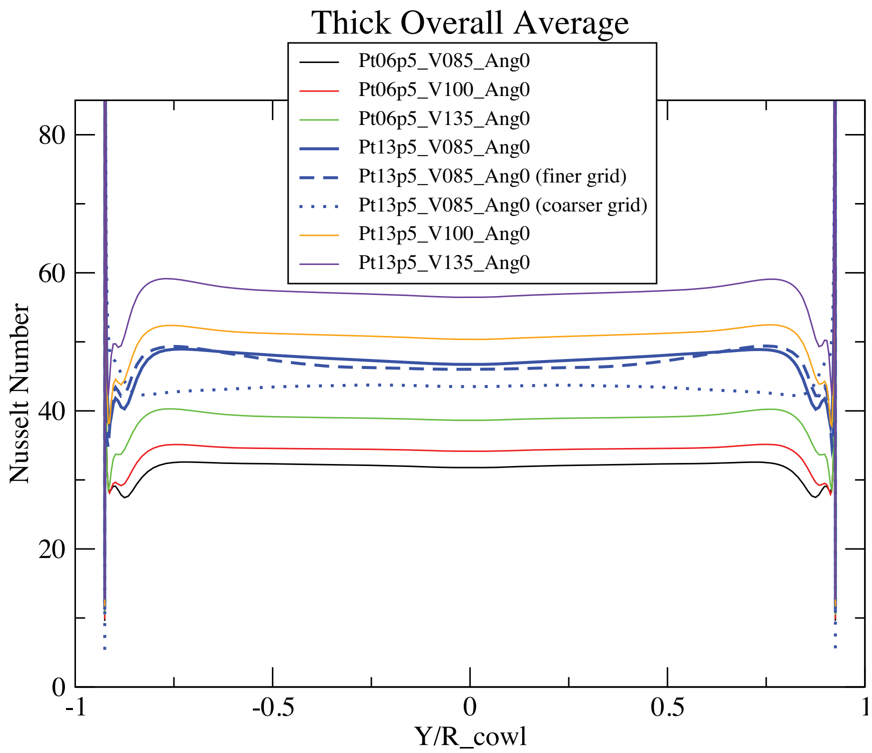
Name	Re_{thick}	Scoop Front	Scoop Overall	Thick Front	Thick Overall
Pt13p5V085	6742	32.349	38.256	66.884	47.388
Attack5deg	6733	32.154	38.132	66.957	47.333
Yaw5deg	6790	32.110	37.691	67.178	47.528
Support	6781	32.039	37.016	66.872	47.475

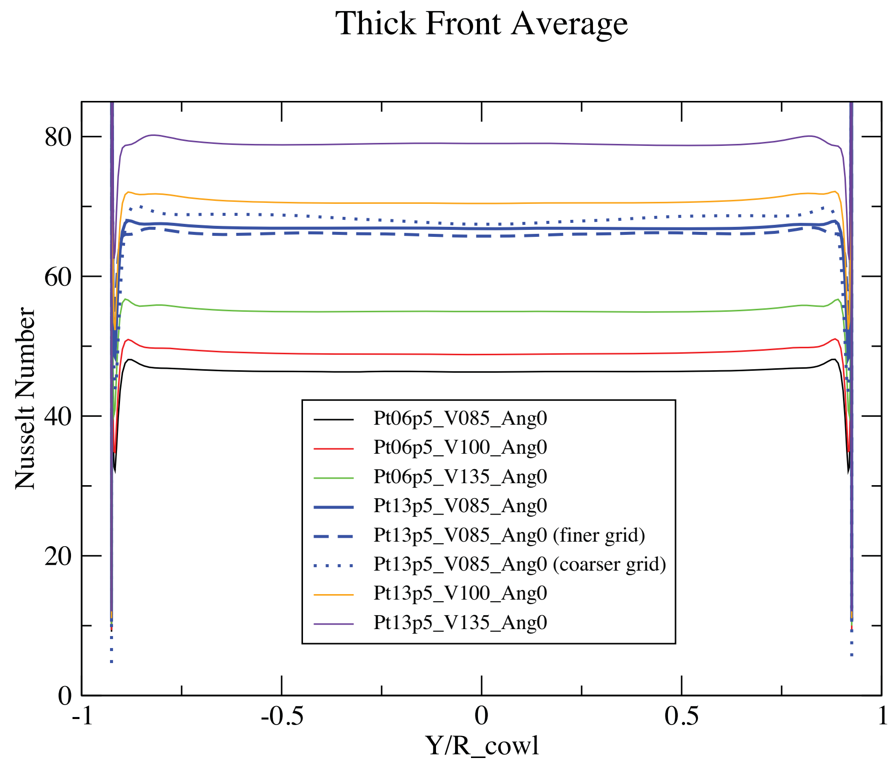
Thick and Scoop average Nusselt numbers for other cases. (Thick and Scoop have the same diameter).

Name	Re_{thin}	Thin Front	Thin Overall
Pt13p5V085	1706	32.992	22.662
Attack5deg	1703	32.863	22.563
Yaw5deg	1718	33.001	22.671
Support	1716	32.970	22.643

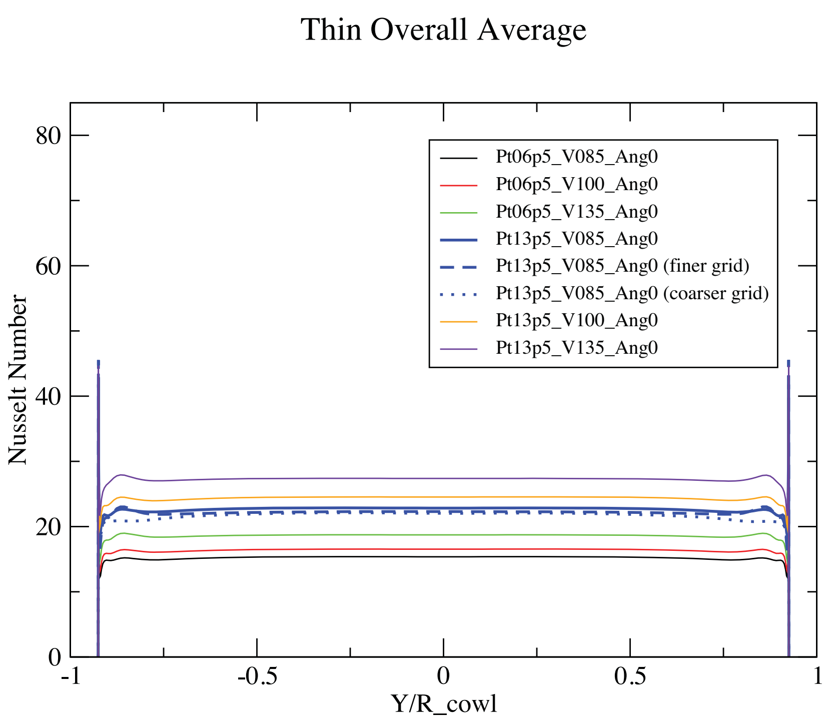
Thin average Nusselt number for other cases.

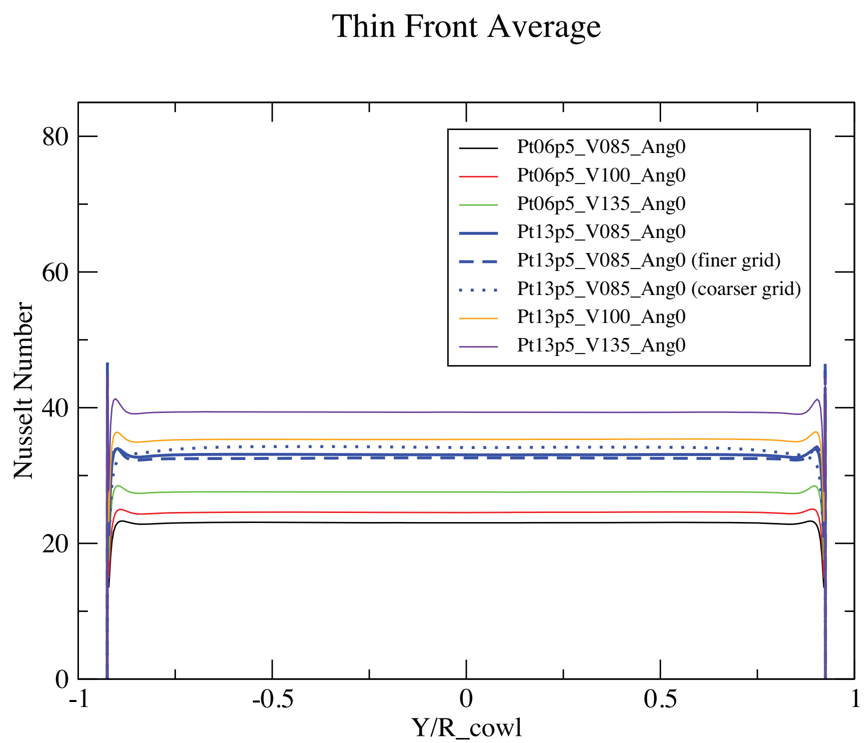
Thick (083) Spanwise Nusselt Number



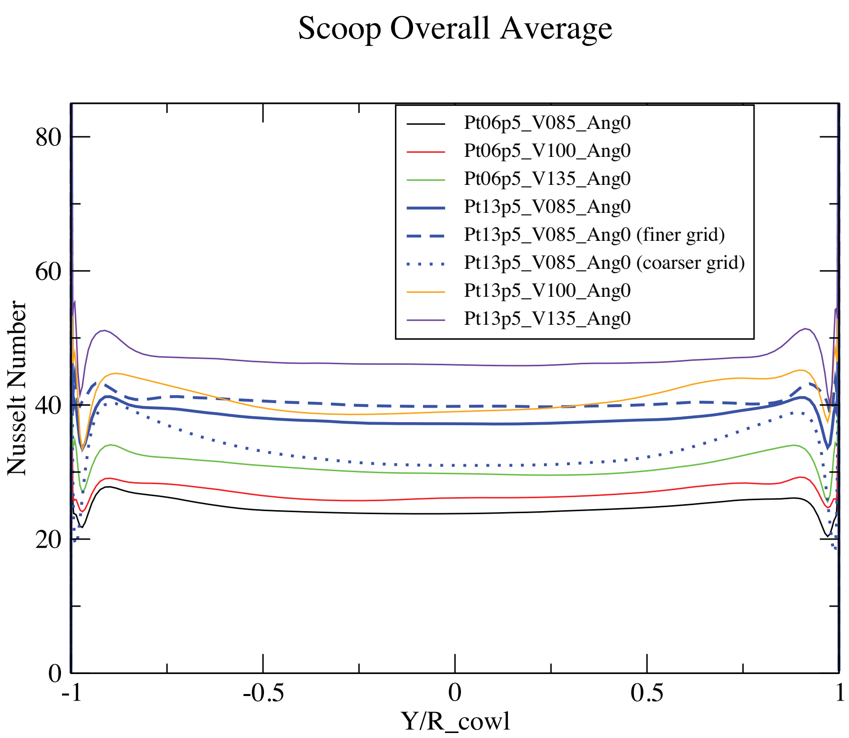


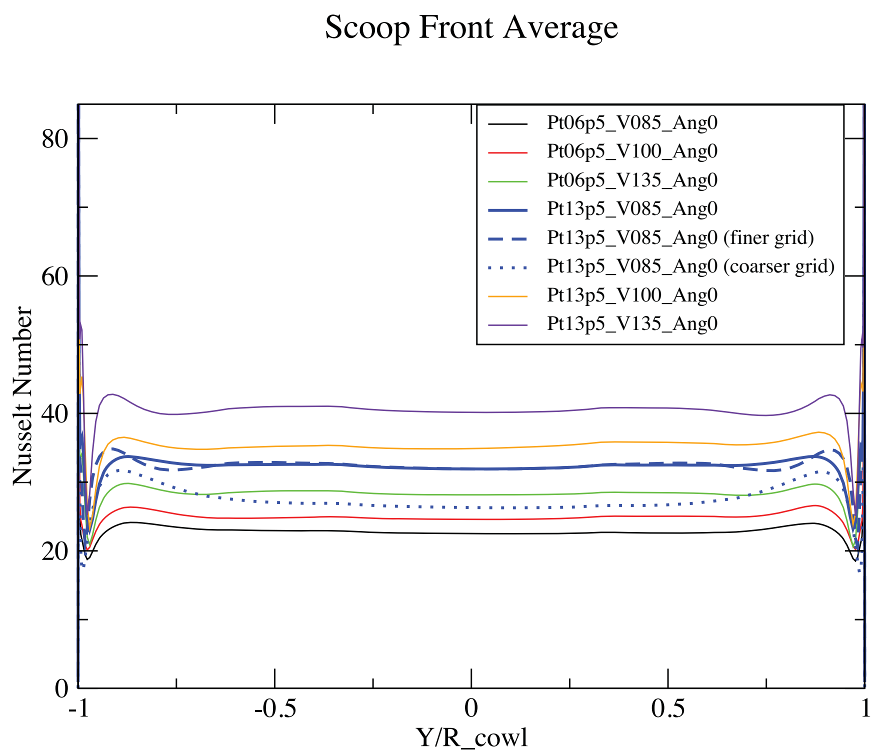
Thin (021) Spanwise Nusselt Number



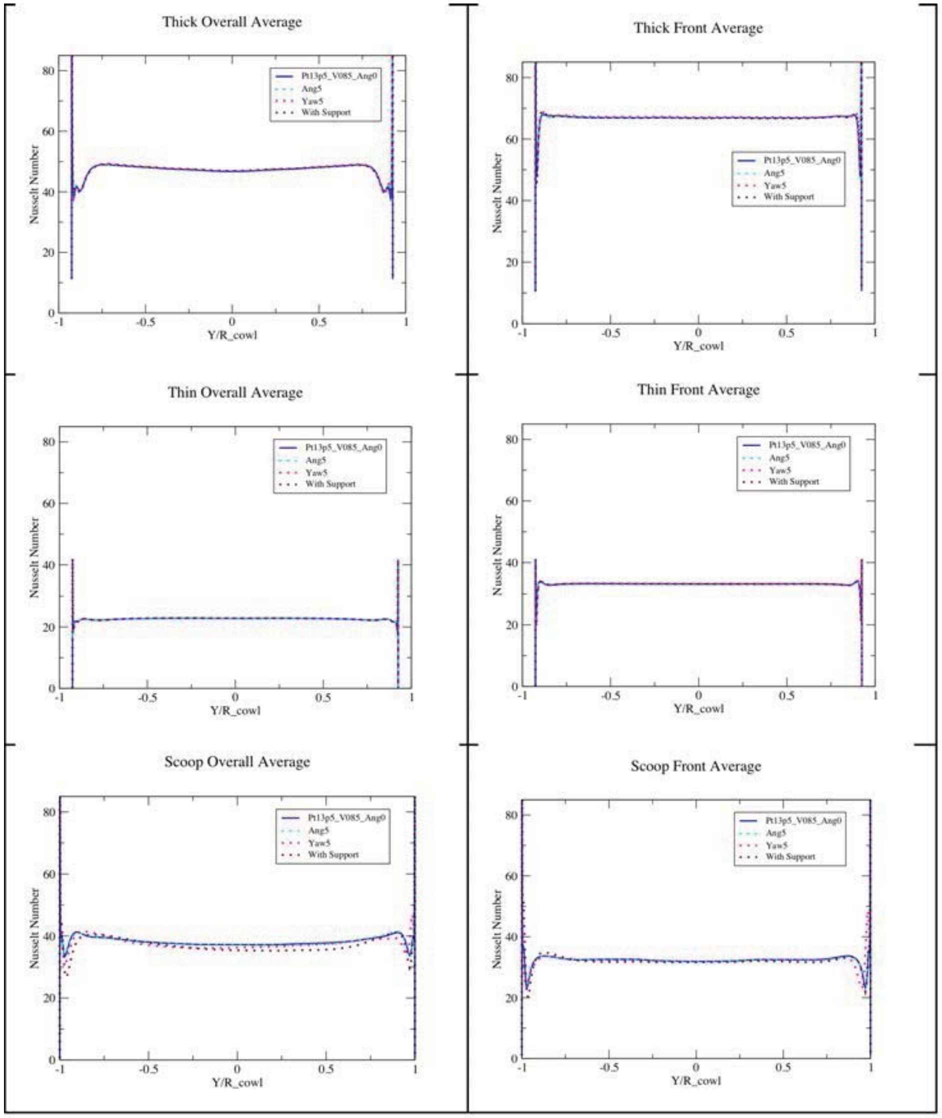


Half-Pipe(HP) Spanwise Nusselt Number

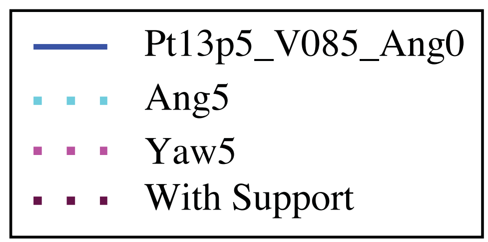




Average Nusselt numbers for Angle of attack, Yaw, and Support cases, compared to straight on at same conditions



- Very little change due to pitch, yaw, or support strut



Total collection efficiency results for straight on cases without support Thin (021) Heated Element

Geometry	Total Pressure	Airspeed	Drop Size	K_0	E_m,2D	E_m,3D	E_m,3D/E_m,2D
	psia	m/s	Microns		Lewice2D	Lewice3D	
Thin (021)	6.5	85	5	8.517	0.93108	0.82913	89.1%
Thin (021)	6.5	85	20	92.454	0.98977	0.95719	96.7%
Thin (021)	6.5	85	50	408.181	0.99512	0.98913	99.4%
Thin (021)	6.5	85	100	1202.878	0.99512	0.99628	100.1%
Thin (021)	13.5	85	5	7.091	0.92325	0.81998	88.8%
Thin (021)	13.5	85	20	70.451	0.98977	0.95366	96.4%
Thin (021)	13.5	85	50	295.481	0.99512	0.98756	99.2%
Thin (021)	13.5	85	100	842.951	0.99512	0.99509	100.0%
Thin (021)	13.5	135	5	10.004	0.94348	0.84129	89.2%
Thin (021)	13.5	135	20	94.972	0.98977	0.96338	97.3%
Thin (021)	13.5	135	50	388.689	0.99512	0.99032	99.5%
Thin (021)	13.5	135	100	1092.380	0.99512	0.99614	100.1%

Total collection efficiency results for straight on cases without support Thick (083) Heated Element

Geometry	Total Pressure	Airspeed	Drop Size	K_0	E_m,2D	E_m,3D	E_m,3D/E_m,2D
	psia	m/s	Microns		Lewice2D	Lewice3D	
Thick (083)	6.5	85	5	2.155	0.78212	0.65481	83.7%
Thick (083)	6.5	85	20	23.388	0.97413	0.93567	96.1%
Thick (083)	6.5	85	50	103.256	0.99226	0.98467	99.2%
Thick (083)	6.5	85	100	304.288	0.99610	0.99472	99.9%
Thick (083)	13.5	85	5	1.794	0.75436	0.62688	83.1%
Thick (083)	13.5	85	20	17.822	0.96767	0.92596	95.7%
Thick (083)	13.5	85	50	74.747	0.99025	0.98096	99.1%
Thick (083)	13.5	85	100	213.238	0.99494	0.99308	99.8%
Thick (083)	13.5	135	5	2.531	0.81610	0.68576	84.0%
Thick (083)	13.5	135	20	24.025	0.97546	0.94182	96.6%
Thick (083)	13.5	135	50	98.325	0.99226	0.98468	99.2%
Thick (083)	13.5	135	100	276.335	0.99543	0.99423	99.9%

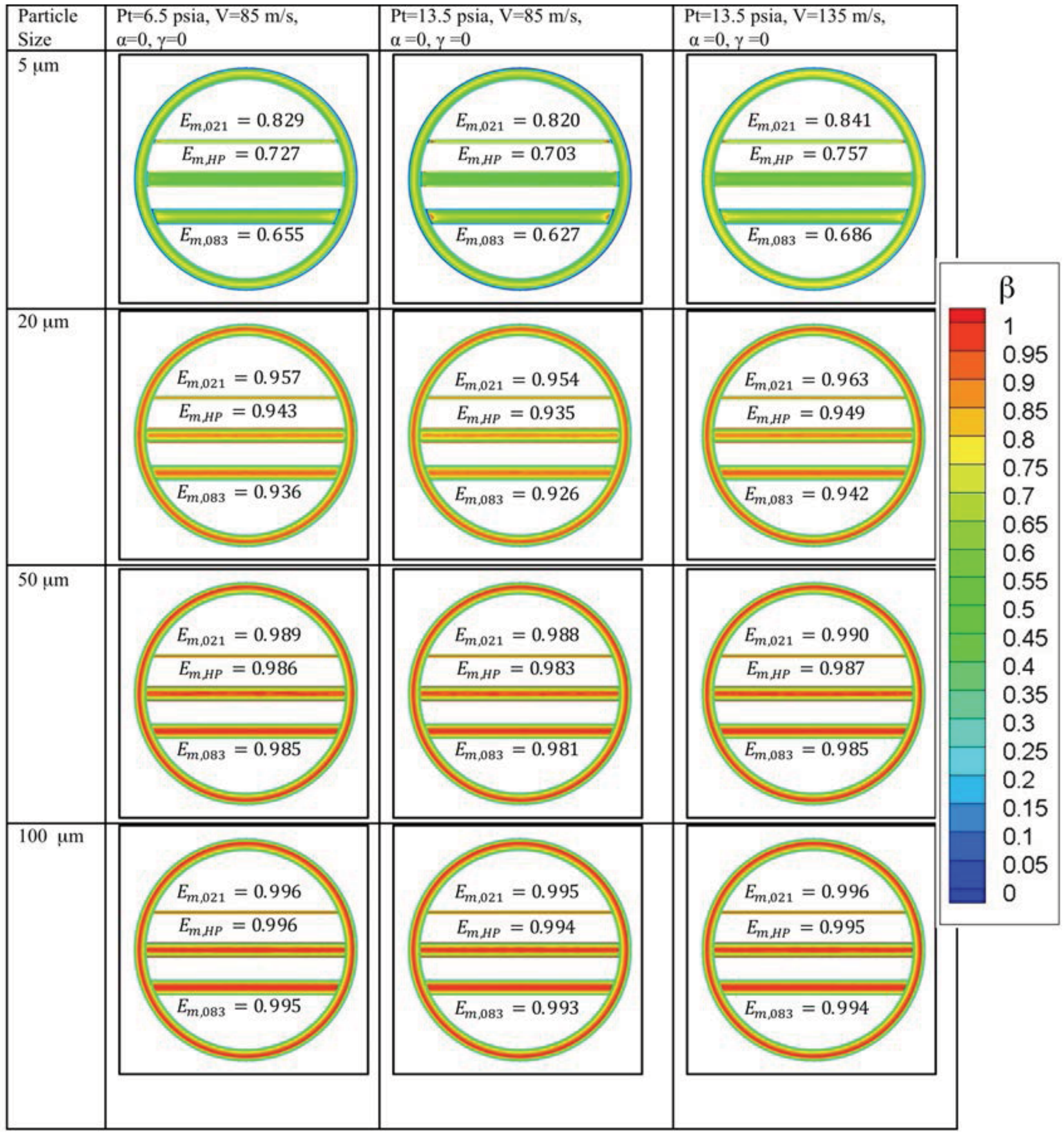
Total collection efficiency results for straight on cases without support
Half-Pipe (HP) Heated Element

Geometry	Total Pressure	Airspeed	Drop Size	K_0	E_m,2D	E_m,3D	E_m,3D/E_m,2D
	psia	m/s	Microns		Lewice2D	Lewice3D	
Half-Pipe	6.5	85	5	2.155	0.89161	0.72710	81.5%
Half-Pipe	6.5	85	20	23.388	0.98309	0.94268	95.9%
Half-Pipe	6.5	85	50	103.256	0.99208	0.98639	99.4%
Half-Pipe	6.5	85	100	304.288	0.99409	0.99570	100.2%
Half-Pipe	13.5	85	5	1.794	0.85435	0.70295	82.3%
Half-Pipe	13.5	85	20	17.822	0.97909	0.93487	95.5%
Half-Pipe	13.5	85	50	74.747	0.99141	0.98320	99.2%
Half-Pipe	13.5	85	100	213.238	0.99409	0.99419	100.0%
Half-Pipe	13.5	135	5	2.531	0.89161	0.75664	84.9%
Half-Pipe	13.5	135	20	24.025	0.98309	0.94940	96.6%
Half-Pipe	13.5	135	50	98.325	0.99208	0.98676	99.5%
Half-Pipe	13.5	135	100	276.335	0.99409	0.99534	100.1%

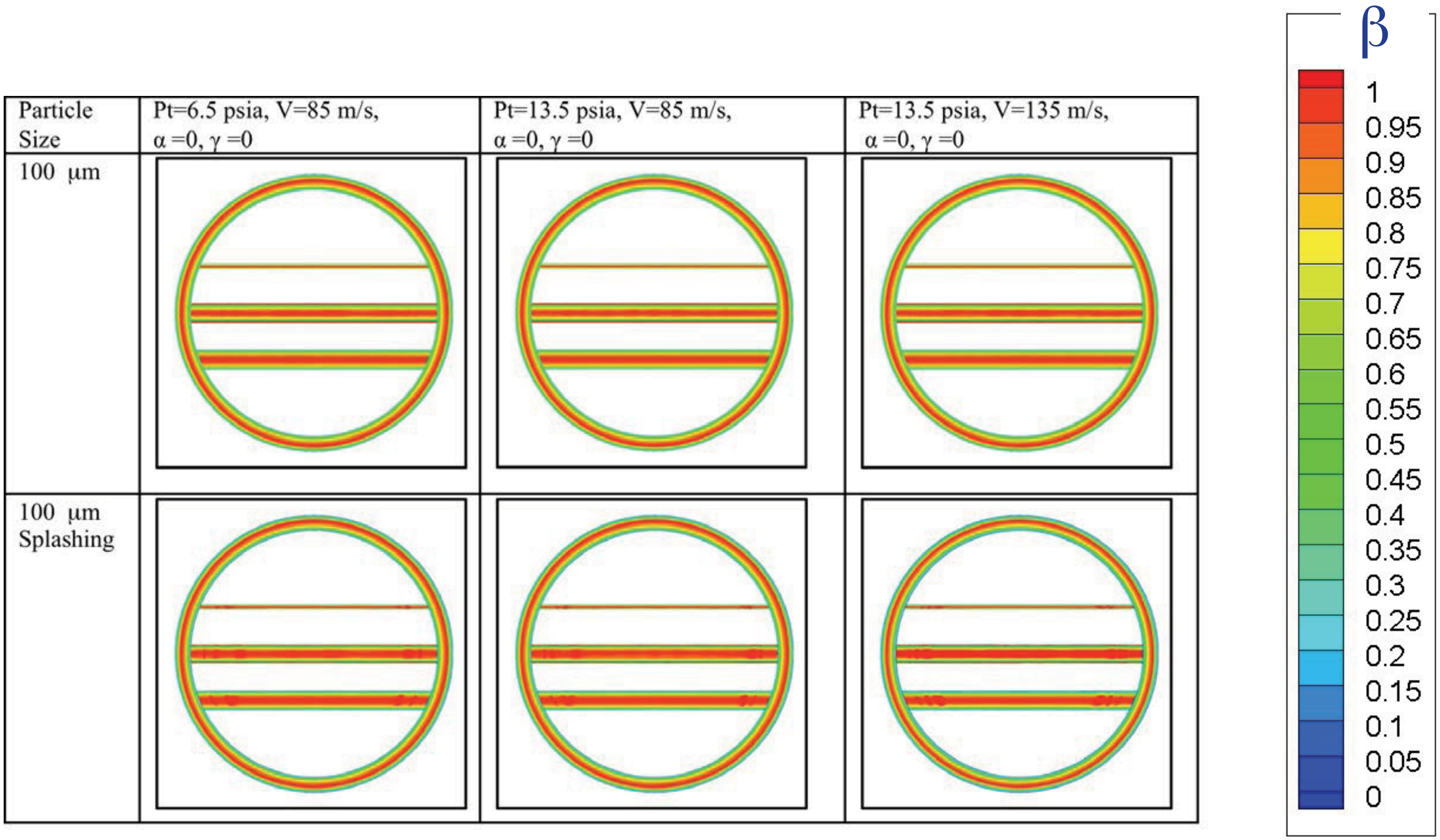
Total collection efficiency results for straight on cases without support

Geometry	Total Pressure	Airspeed	Drop Size	K_0	E_m,2D	E_m,3D	E_m,3D/E_m,2D
	psia	m/s	Microns		Lewice2D	Lewice3D	
Thin (021)	6.5	85	5	8.517	0.93108	0.82913	89.1%
Thin (021)	6.5	85	20	92.454	0.98977	0.95719	96.7%
Thin (021)	6.5	85	50	408.181	0.99512	0.98913	99.4%
Thin (021)	6.5	85	100	1202.878	0.99512	0.99628	100.1%
Thin (021)	13.5	85	5	7.091	0.92325	0.81998	88.8%
Thin (021)	13.5	85	20	70.451	0.98977	0.95366	96.4%
Thin (021)	13.5	85	50	295.481	0.99512	0.98756	99.2%
Thin (021)	13.5	85	100	842.951	0.99512	0.99509	100.0%
Thin (021)	13.5	135	5	10.004	0.94348	0.84129	89.2%
Thin (021)	13.5	135	20	94.972	0.98977	0.96338	97.3%
Thin (021)	13.5	135	50	388.689	0.99512	0.99032	99.5%
Thin (021)	13.5	135	100	1092.380	0.99512	0.99614	100.1%
Thick (083)	6.5	85	5	2.155	0.78212	0.65481	83.7%
Thick (083)	6.5	85	20	23.388	0.97413	0.93567	96.1%
Thick (083)	6.5	85	50	103.256	0.99226	0.98467	99.2%
Thick (083)	6.5	85	100	304.288	0.99610	0.99472	99.9%
Thick (083)	13.5	85	5	1.794	0.75436	0.62688	83.1%
Thick (083)	13.5	85	20	17.822	0.96767	0.92596	95.7%
Thick (083)	13.5	85	50	74.747	0.99025	0.98096	99.1%
Thick (083)	13.5	85	100	213.238	0.99494	0.99308	99.8%
Thick (083)	13.5	135	5	2.531	0.81610	0.68576	84.0%
Thick (083)	13.5	135	20	24.025	0.97546	0.94182	96.6%
Thick (083)	13.5	135	50	98.325	0.99226	0.98468	99.2%
Thick (083)	13.5	135	100	276.335	0.99543	0.99423	99.9%
Half-Pipe	6.5	85	5	2.155	0.89161	0.72710	81.5%
Half-Pipe	6.5	85	20	23.388	0.98309	0.94268	95.9%
Half-Pipe	6.5	85	50	103.256	0.99208	0.98639	99.4%
Half-Pipe	6.5	85	100	304.288	0.99409	0.99570	100.2%
Half-Pipe	13.5	85	5	1.794	0.85435	0.70295	82.3%
Half-Pipe	13.5	85	20	17.822	0.97909	0.93487	95.5%
Half-Pipe	13.5	85	50	74.747	0.99141	0.98320	99.2%
Half-Pipe	13.5	85	100	213.238	0.99409	0.99419	100.0%
Half-Pipe	13.5	135	5	2.531	0.89161	0.75664	84.9%
Half-Pipe	13.5	135	20	24.025	0.98309	0.94940	96.6%
Half-Pipe	13.5	135	50	98.325	0.99208	0.98676	99.5%
Half-Pipe	13.5	135	100	276.335	0.99409	0.99534	100.1%

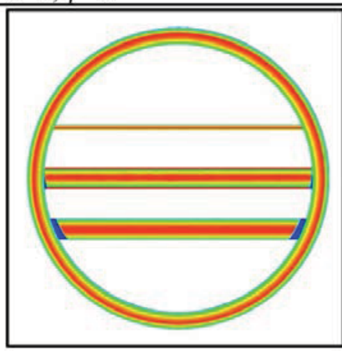
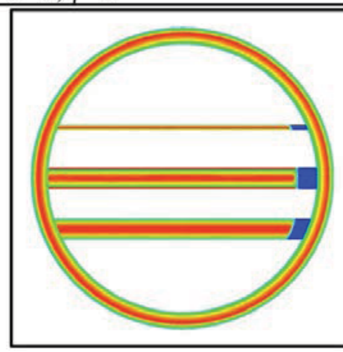
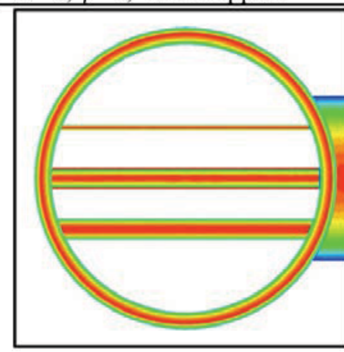
Local Collection Efficiency for several particle sizes (straight on cases).



Collection efficiency. Splashing compared to no splashing (straight on cases)



Collection efficiency. Splashing compared to no splashing (angle of attack, yaw, and support cases

Particle Size	Pt=13.5 psia, V=85 m/s, α =5, γ =0	Pt=13.5 psia, V=85 m/s, α =0, γ =5	Pt=13.5 psia, V=85 m/s, α =0, γ =0, With Support
100 μm			
100 μm Splashing