The Effect of Combustor Hole-set Arrangement when Comparing Two Different Hole-set Design Methods

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science & innovation
Department:
Science and Innovation
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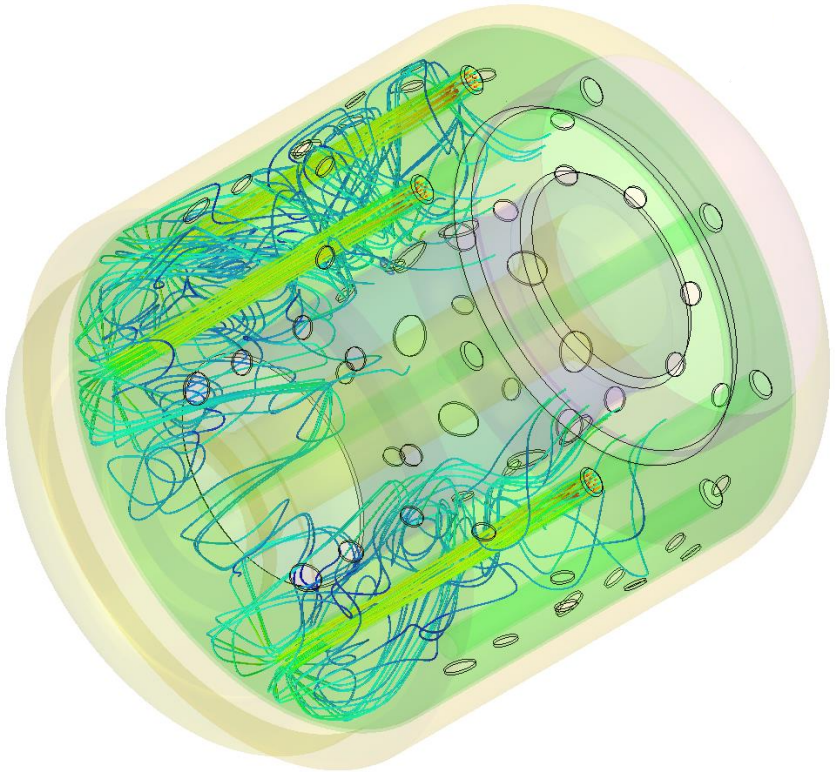
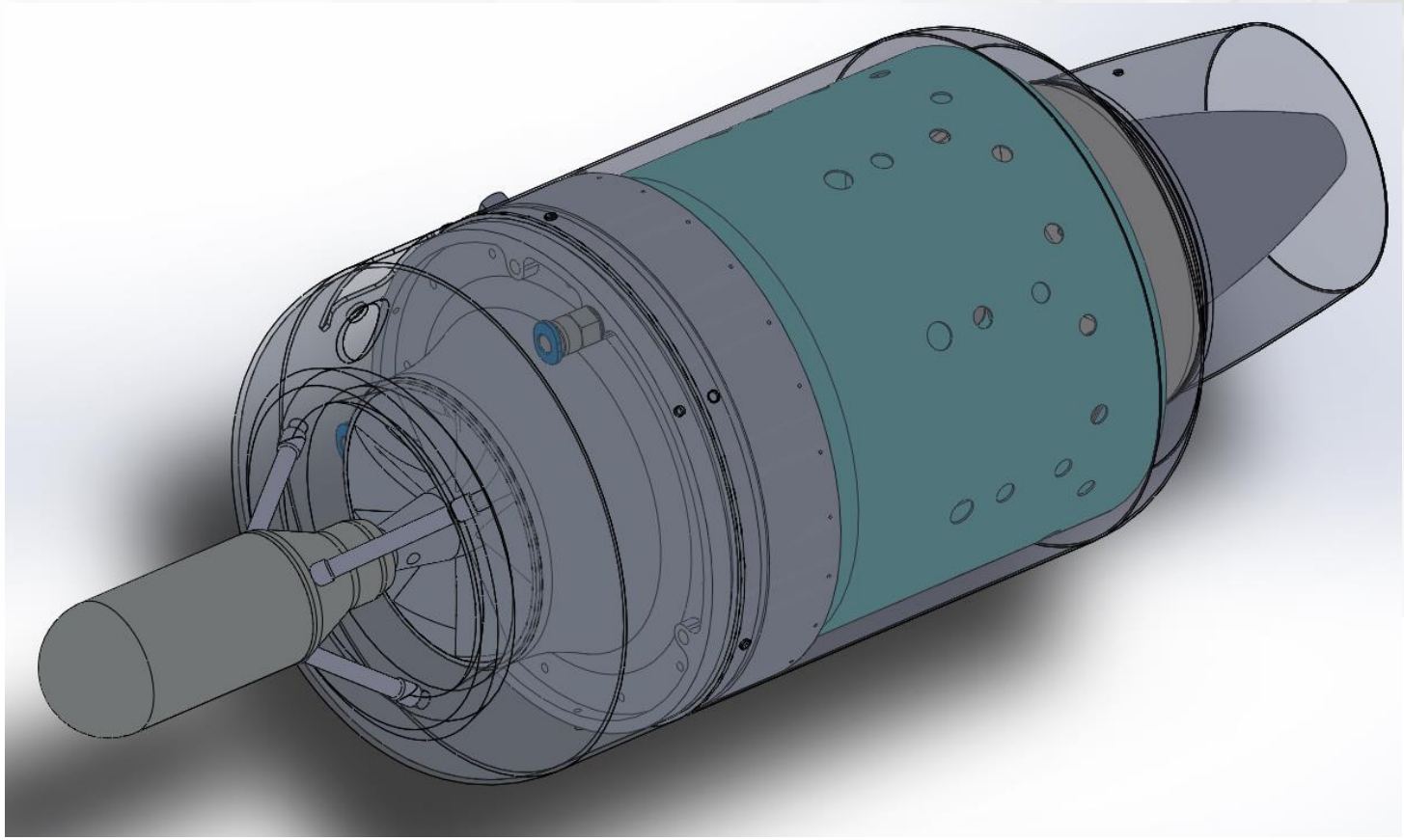
Contents

Introduction

- This work was performed on:
  - 200N micro-gas turbine combustor
  - Model aircraft industry

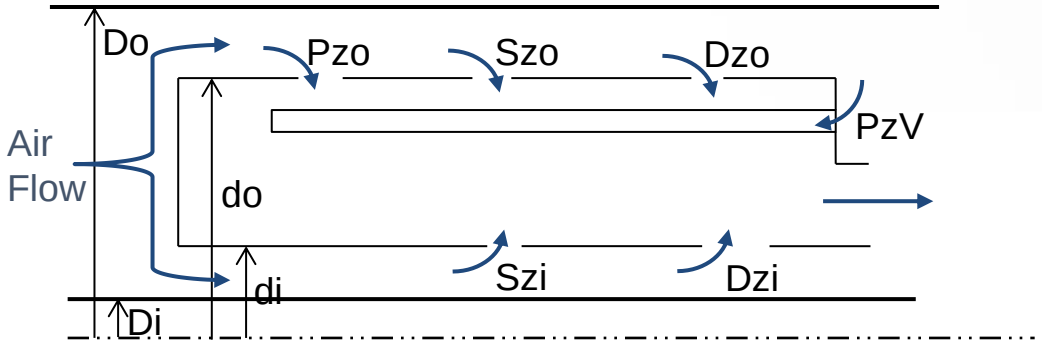




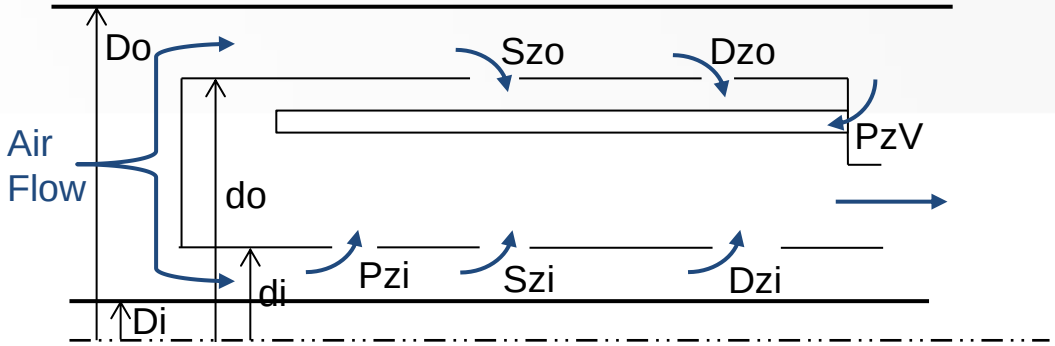
Introduction

Previous work:

- First design phase focused on
  - Correcting the airflow splits between the two annuli
  - Improved Primary zone flow pattern that more closely resembles the recirculation in the theory
  - NREC design method
- A Scoring methodology was devised
  - The combustor CFD results are difficult to interpret meaningfully
  - Methodology to apply a more quantitative method for choosing a preferable design based on what are, initially subjectively analysed aspects
  - Two combustor designs chosen



Option 1



Option 2

Introduction

Previous work (cont.):

- Second design phase focused on
  - The effect of inlet (diffuser outlet) swirl on the internal aerodynamics of the two combustor designs chosen in the previous study was investigated using CFD analysis
  - Varying inlet flow angles: 0° (original simulations from [1]), 10°, 20°, 25°, 30°, 33°, 35°, 37°, 40°
  - The same scoring methodology was used to give an indication of the detrimental or advantageous effect of the inlet swirl on the combustor aerodynamics

This Study:

- The effects and sensitivity of the two initially chosen combustor design to various design methods available in the literature.
- The Lefebvre design method [1] was applied incrementally
  - First only to the Sz & Dz (“No ΔPz” variant)
  - Second Pz, Sz & Dz (“ΔPz” variant)

[1] A. H. Lefebvre, Gas Turbine Combustion, Hemisohere Publishing Corportation, 1983

Design Parameters

- Lefebvre design method
  - Empirically determined Jet penetration models and

$$\frac{Y_{max}}{d_j} = 1.25J^{0.5}\frac{\dot{m}_g}{\dot{m}_g + \dot{m}_j}$$

  - Conservation of energy along a jet

$$nd_j^2 = \frac{15.25\dot{m}_j}{(P_3\,\Delta P_L/T_3)^{0.5}}$$

  - Accounting for Discharge Coefficient

$$d_h = \frac{d_j}{C_D^{0.5}}$$

- There is a different design process provided for each zone

Design Parameters

Primary zone

- Few guidelines are provided and not a full design method
- Empirical Jet penetration model not applicable due to complex flow pattern and entrainment into the Rz
- $n_{outer} = n_{inner} = 2 \times n_{injectors}$ (Vaporizer tubes)
- Variation from these guidelines due to the injectors being Vaporizer tubes instead of atomisers

Secondary zone

- Prescribed a maximum Jet penetration depth, $Y_{max} = 0.2D_L$
- Jet diameter, d_j, determined
- Number of holes, n_{Sz}, determined
- Hole diameter, d_h, determined

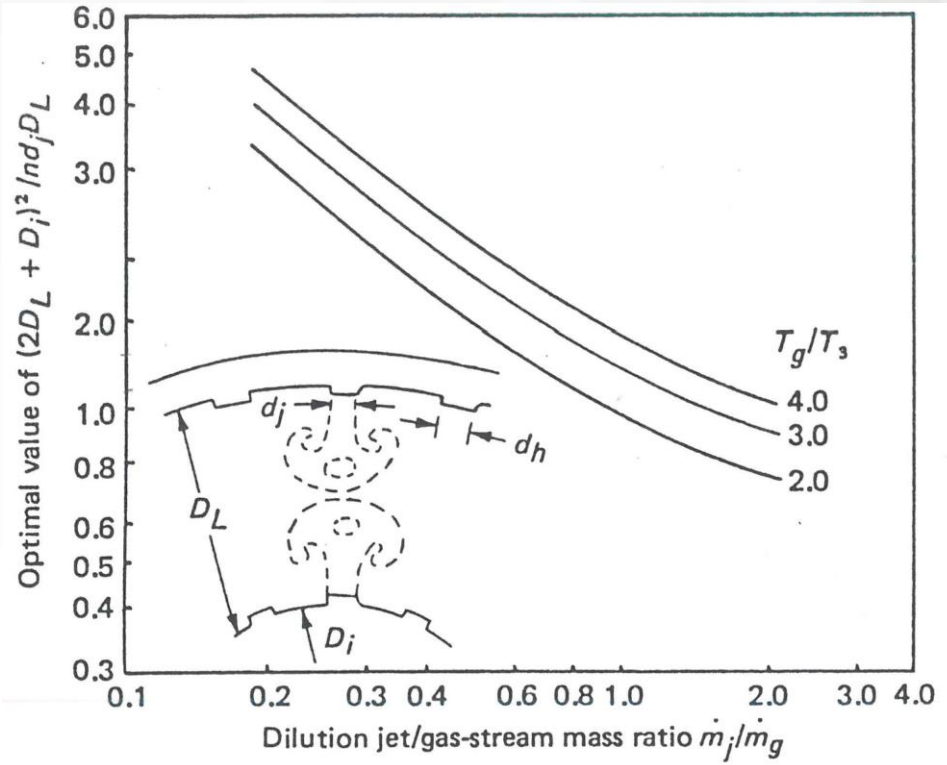
Design Parameters

Dilution zone

- Charts provided for Dz type - Double-sided annular combustor
- Solved simultaneously with equation for flow along a jet
- Jet diameter, d_j, determined
- Number of holes, n_{Dz}, determined
- Hole diameter, d_h, determined

Adjustment for Manufacturability

- Two options:
  - n-d_h constant: Increase the number of rows, until the holes fitted circumferentially AND longitudinally
  - Adjusting the n-d_h combination while maintaining a constant A_{ht} and aiming for a constant $(d_j J^{0.5})$
- Rounding and adjustment for drill sizes or laser limits



Dilution zone design chart for double-sided annular combustors [1]

Methodology

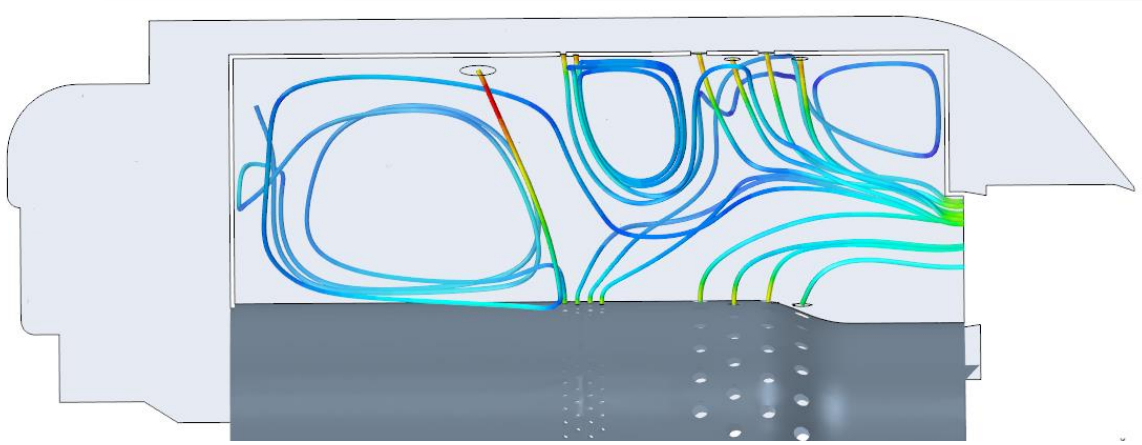
- Test matrix

Design Method:	NREC Vol II (Original)		Lefebvre (No ΔPz)		Lefebvre (ΔPz)	
Design Type:	Option 1	Option 2	Option 1	Option 2	Option 1	Option 2
Base Design:	Design C	Design G	Design K	Design R	Design L	Design S

- CFD Analysis
  - Non-combusting RANS simulations using Star-CCM+
  - Domain: Diffuser outlet plane to NGV inlet plane - 4 million to 16 million cells
  - T_3 = 501K, P_3 = 426kPa, m_3 = 0.35kg/s
  - 4000 iterations: Averaging every 10th iteration for 100 iterations
- Scoring and Ranking
  - Overall pressure drop,
  - Quality of Recirculation zone,
  - Outlet plane flow quality and
  - Amount of mixing occurring

Methodology

- Maximum Jet Penetration Depths
  - Theoretically, defined as the depth at which the jet becomes asymptotic to the cross flow = Axial direction [2]
  - Flow in the modelled combustors is much more chaotic
  - Thu, maximum penetration depth was taken as the depth at which the streamline is entrained into the general combustor flow whether it is in the axial direction or not
  - Perpendicular distance from the wall of the liner to the asymptotic point of a streamline placed at the centre of a representative hole for each hole-set



[2] A. H. Lefebvre and D. R. Ballal, Gas Turbine Combustion: Alternative Fuels and Emissions, 3rd ed., Taylor and Francic Group, 2010

Results and Discussion

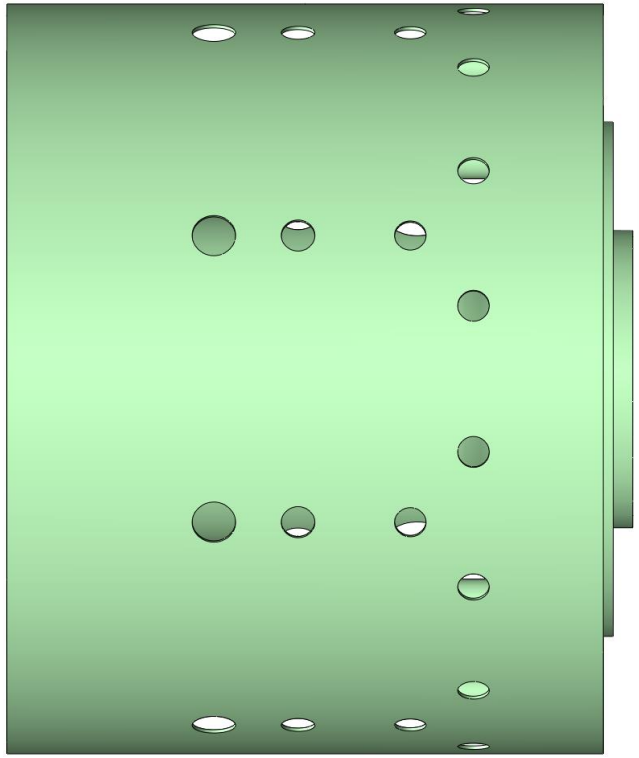
- Resultant designs
- Theoretical vs modelled jet penetration depths
- Trends observed when applying the new design method

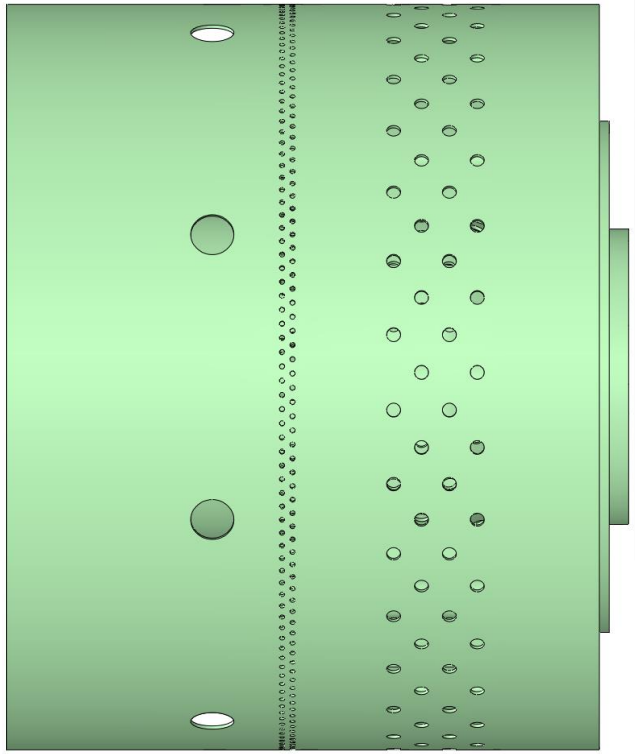
Results and Discussion

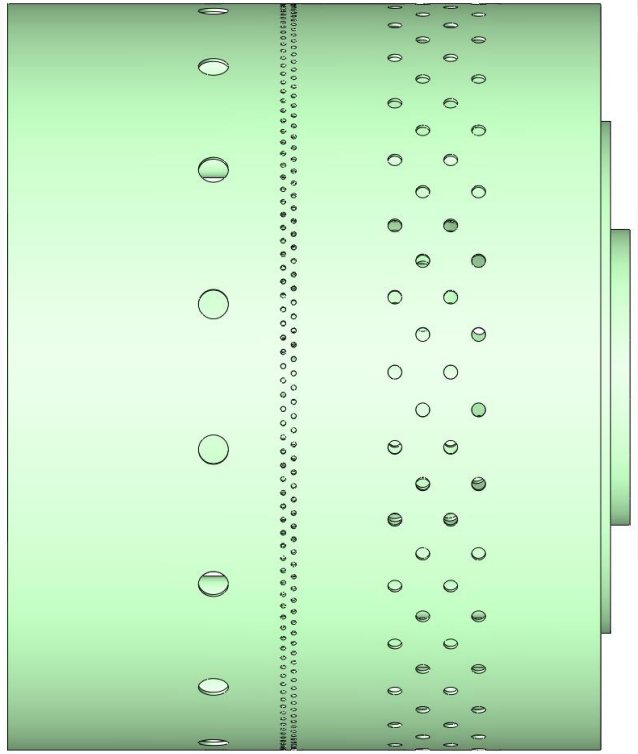
Design Method:		NREC Vol II (Original)		Lefebvre (No ΔPz)		Lefebvre (ΔPz)	
Base Design:		**Design C**	**Design G**	**Design K**	**Design R**	**Design L**	**Design S**
Pz outer	**n**	8	8 (VPz)	8	8 (VPz)	16	8 (VPz)
	d_h [m]	0.0062	0.0051	0.0062	0.0051	0.0043	0.0051
Pz inner	**n**	8 (VPz)	8	8 (VPz)	8	8 (VPz)	16
	d_h [m]	0.0051	0.0060	0.0051	0.0060	0.0051	0.0043
Sz outer	**n**	8	8	328	328	328	328
	d_h [m]	0.0048	0.0048	0.00074	0.00074	0.00074	0.00074
Sz inner	**n**	8	8	328	328	328	328
	d_h [m]	0.0042	0.0047	0.00073	0.00073	0.00073	0.00073
Dz outer	**n**	8, 16	24	123	123	123	123
	d_h [m]	0.0045	0.0045	0.0020	0.0020	0.0020	0.0020
Dz inner	**n**	8	8	123	123	123	123
	d_h [m]	0.0077	0.0077	0.0020	0.0020	0.0020	0.0020

Results and Discussion

NREC Vol II (Original)		Lefebvre (No ΔPz)		Lefebvre (ΔPz)	
Design C		Design K		Design L	

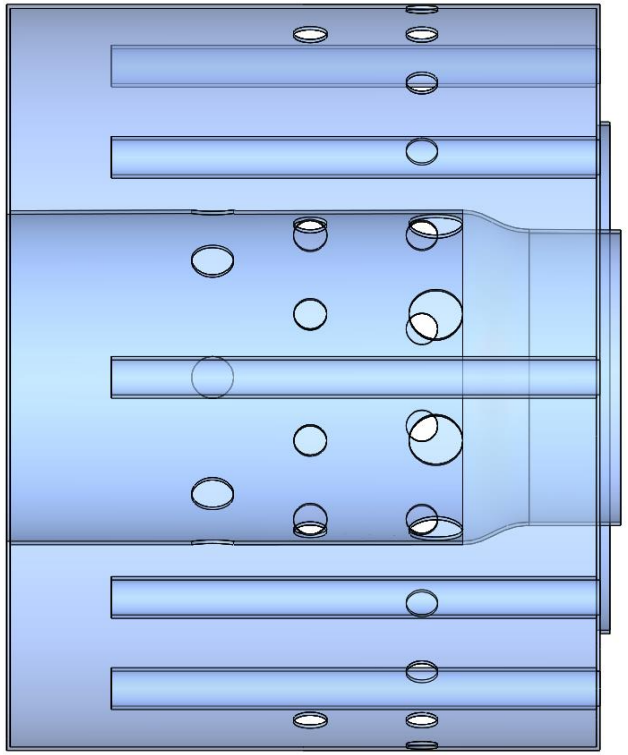


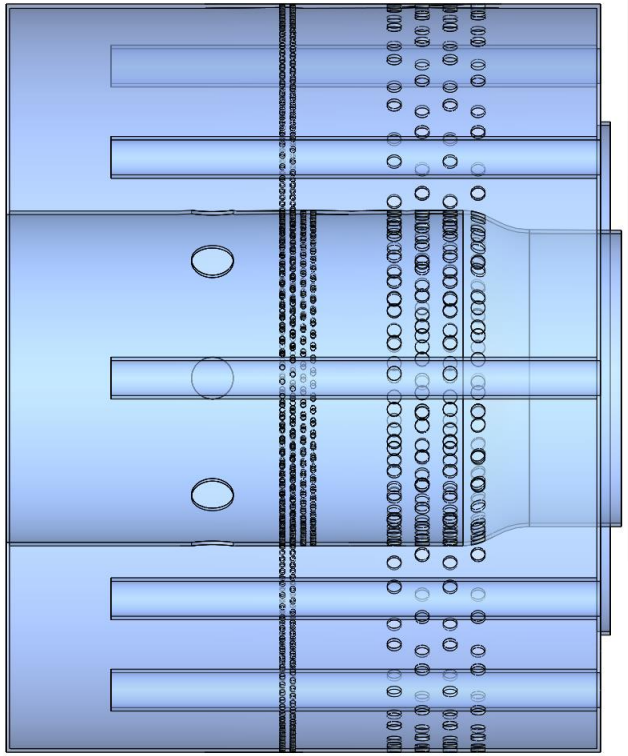


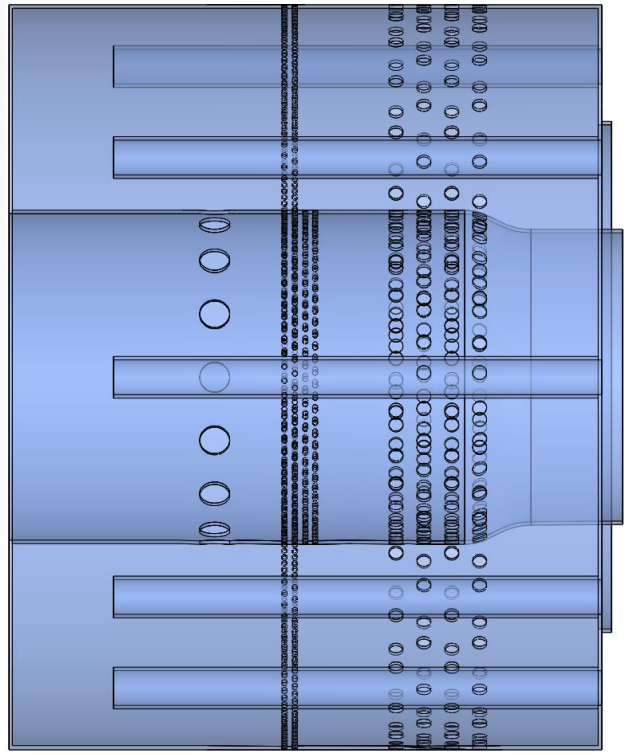


Results and Discussion

NREC Vol II (Original)		Lefebvre (No ΔPz)		Lefebvre (ΔPz)	
	Design G		Design R		Design S





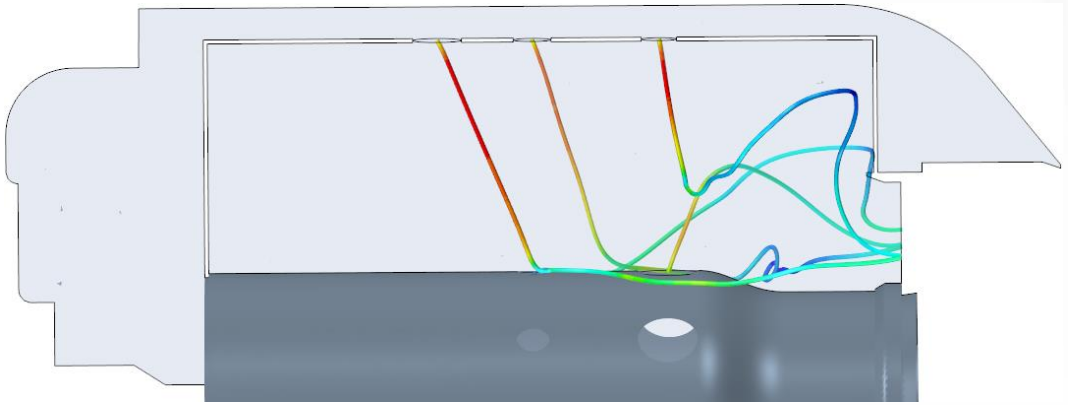


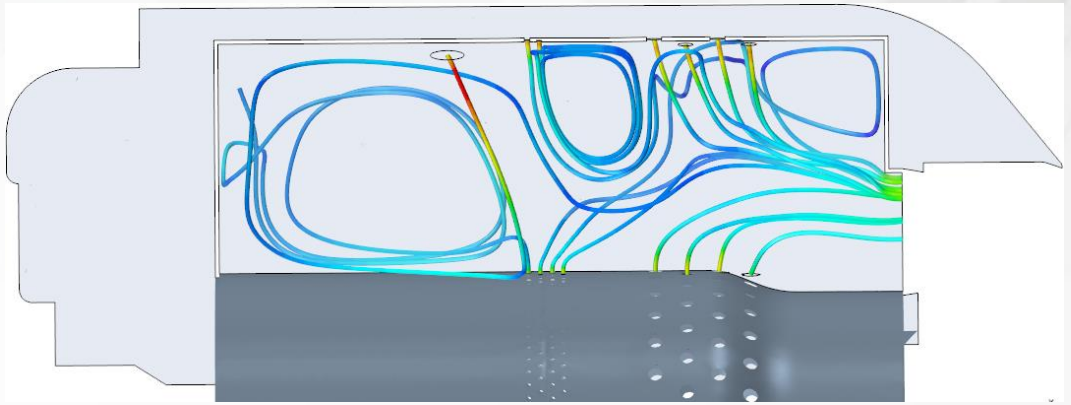
Results and Discussion

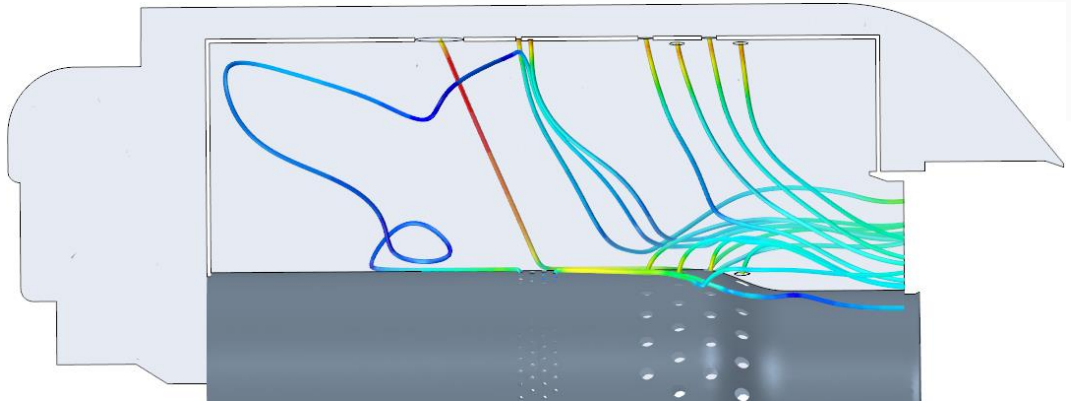
Design Method:		NREC Vol II (Original)		Lefebvre (No ΔPz)		Lefebvre (ΔPz)	
Base Design:		Design C		Design K		Design L	
Annulus		Outer	Inner	Outer	Inner	Outer	Inner
Pz	Theoretical	N/A		N/A		N/A	
	CFD	0.290	N/A	0.290	N/A	0.290	N/A
Sz	Theoretical	N/A		0.006		0.006	
	CFD	0.025	0.000	0.023	0/0.001	0.017	0.004
		-	-	0.015	0/0.001	0.015	0.001
		-	-	-	0/0.001	-	0.001/0.004
		-	-	-	0/0.001	-	0.001
Dz	Theoretical	N/A		<0.014		<0.014	
	CFD	0.017	0.011	0.022	0.007	0.013	0.010
		-	-	0.029	0.004	0.013	0.008
		-	-	0.028	0.004	0.014	0.007
		-	-	0.025	0.005	0.015	0.006

Results and Discussion

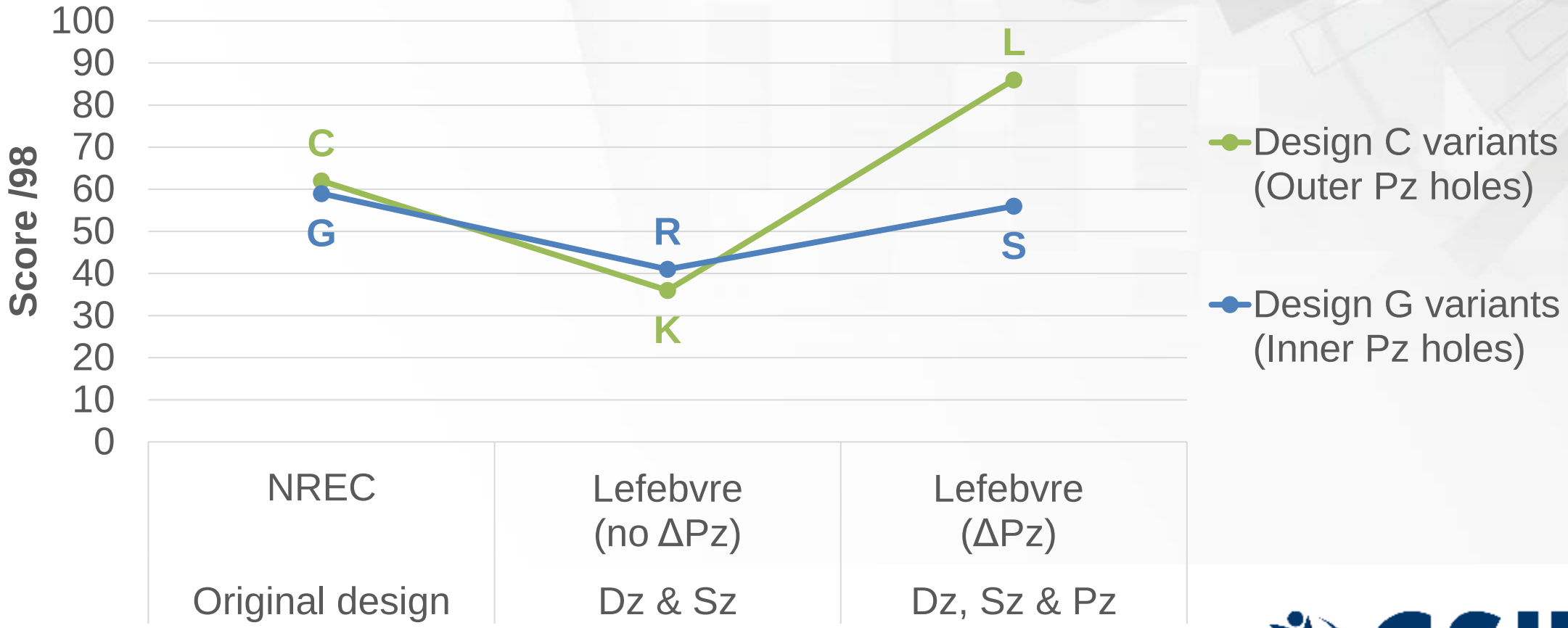
NREC Vol II (Original)		Lefebvre (No ΔPz)		Lefebvre (ΔPz)	
Design C		Design K		Design L	







Results and Discussion



Combustor designs by progressive hole-set variation

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Conclusion

- Although Designs C and G scored highly, there is still potential for improvements to the combustor designs through a change in design method or philosophy
- However, this appears to be dependent on the original design since an improvement was not observed for Design G using the same design method changes
- The large improvement seen when the primary zone was modified for Design C shows that there is still much to be gained from the redesign and improvement of the Primary zone
- However, there is sparse availability of in depth Pz hole design methods in the literature
- Although an improvement was seen in the combustor in one variant with the Primary zone holes in the outer liner wall, an improvement was not observed when the holes were in the inner liner wall
- Thus, it cannot be said that the Lefebvre method is a better than the NREC method since this was not always the case
- This shows that the “better” design method is dependent on the context and the arrangement within which it is applied

Acknowledgments

This study is the result of a research effort funded by Armscor in terms of Order KT471101

Thank you

Methodology: Scoring and Ranking

Scoring:

- Some aspects inherently quantitative
  - Pressure drop and annuli mass flow splits
- Scoring system to apply a quantitative value to qualitative aspects initially analysed subjectively
  - Recirculation zone,
  - Outlet, and
  - Mixing

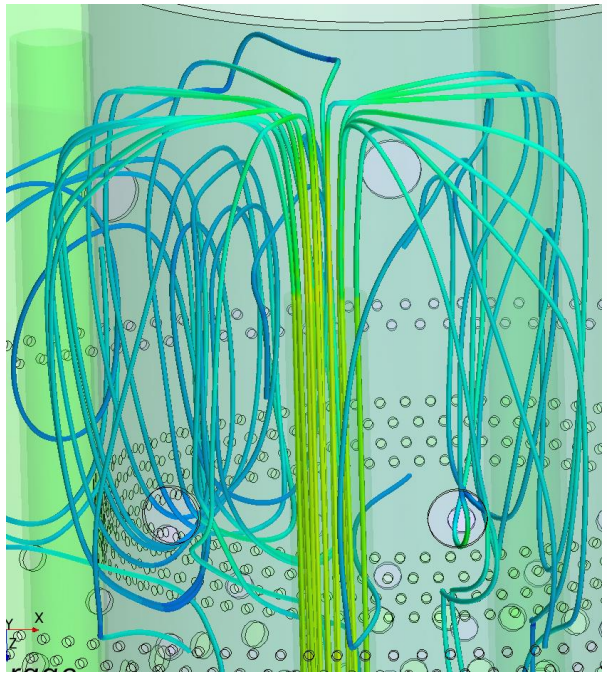
Ranking:

- Weightings and prioritising were applied in order to obtain a final ranking for the design/swirl combinations

Methodology: Scoring Sample Evaluations

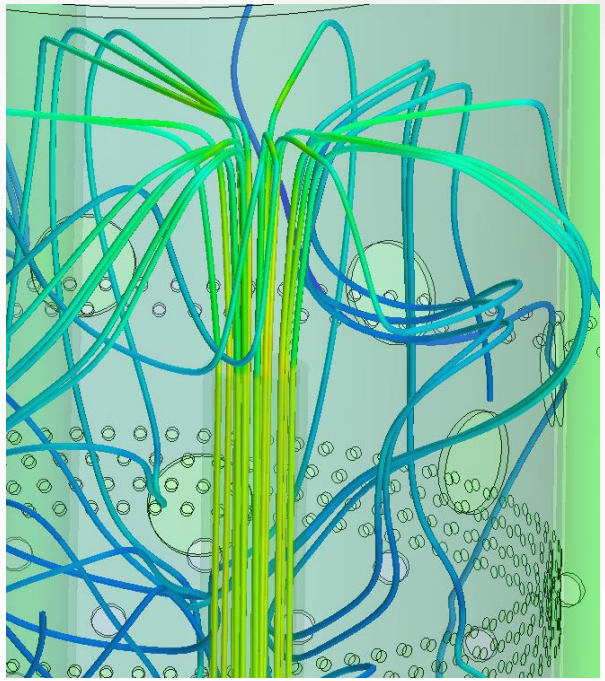
- The recirculation zone intensity, shape and position.

Best



Design L - stream tracers showing a good Rz shape. Score 8.5/10

Worst

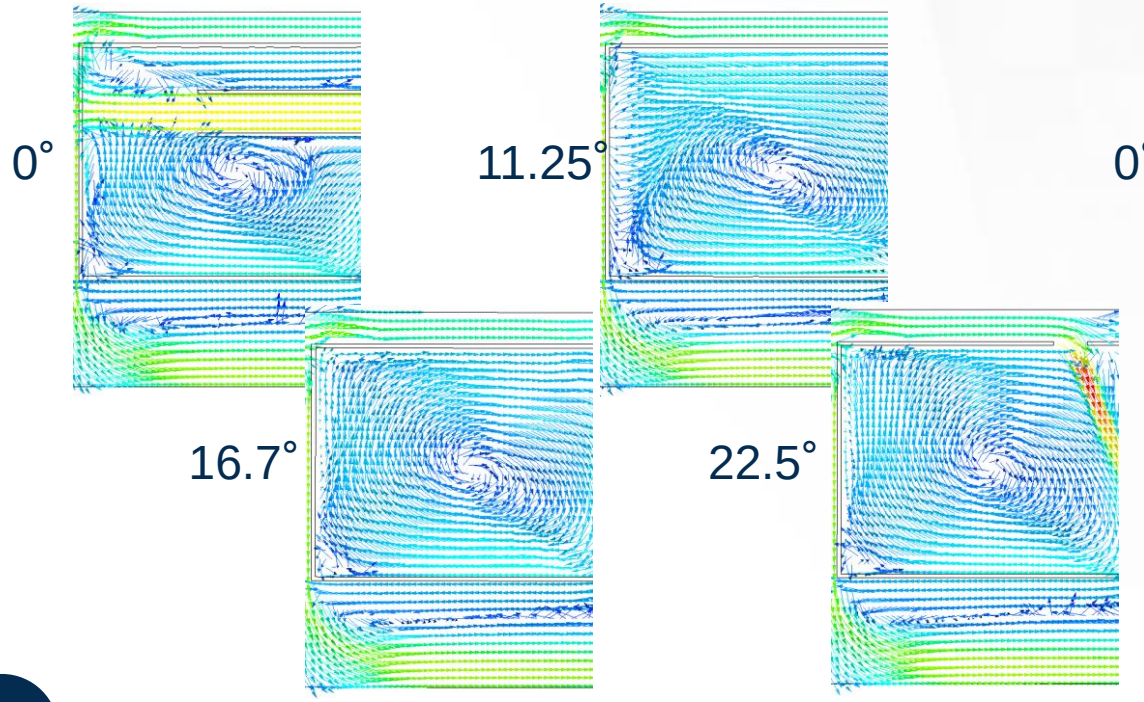


Design R - stream tracers showing a bad Rz shape. Score 4.5/10

Methodology: Scoring Sample Evaluations

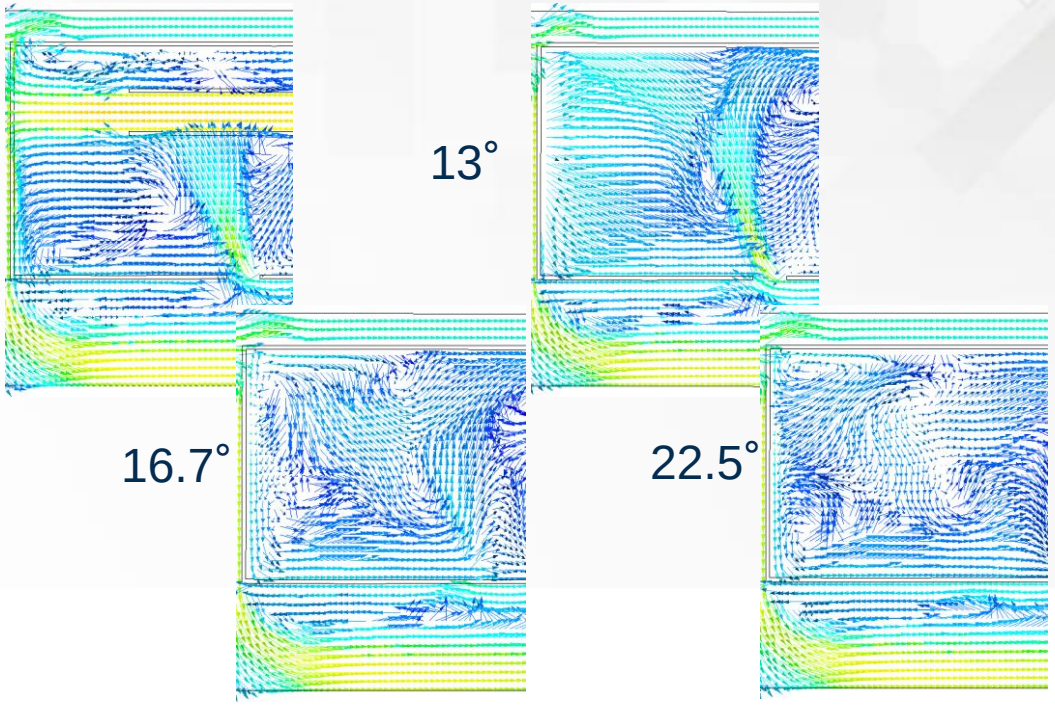
- The recirculation zone cont.

Best



Design L- longitudinal C/S vectors showing a good Rz that covers multiple slices.
Scored 9.5/10

Worst

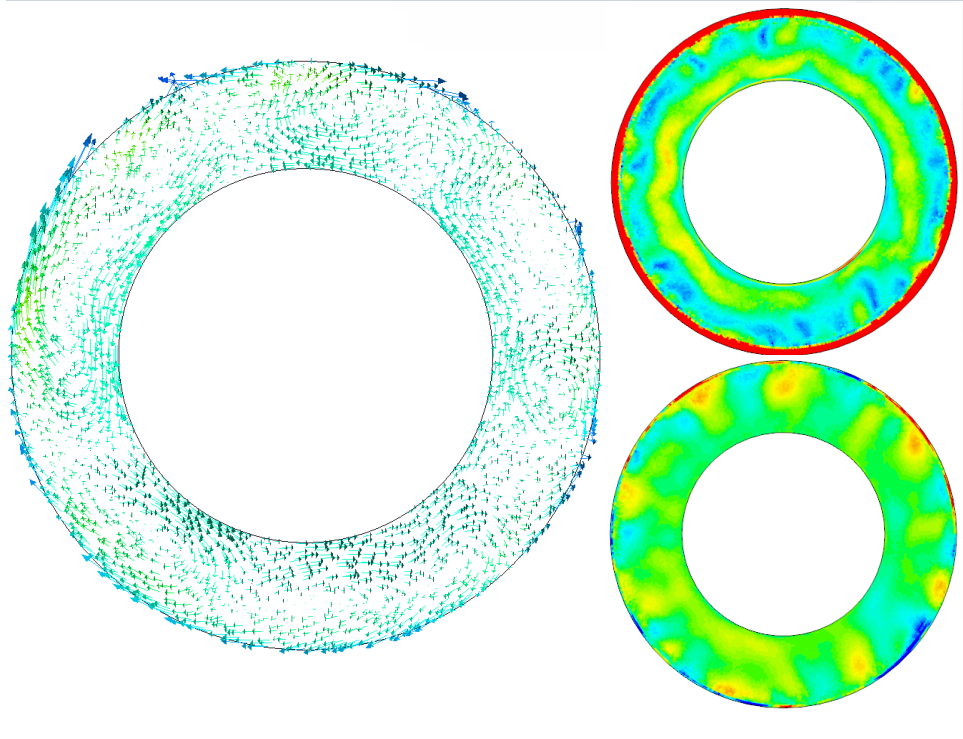


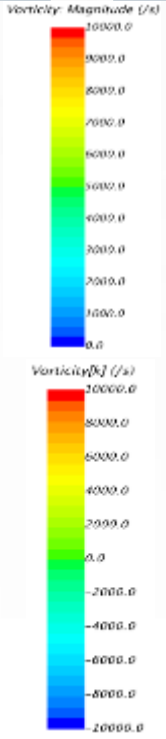
Design S - longitudinal C/S vectors showing a weak Rz that covers only one slice.
Scored 3/10

Methodology: Scoring Sample Evaluations

- Outlet plane: vorticity and the velocity vectors' uniformity and direction.

Best





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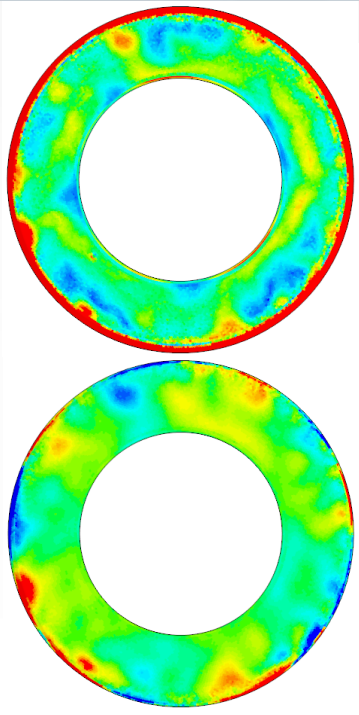
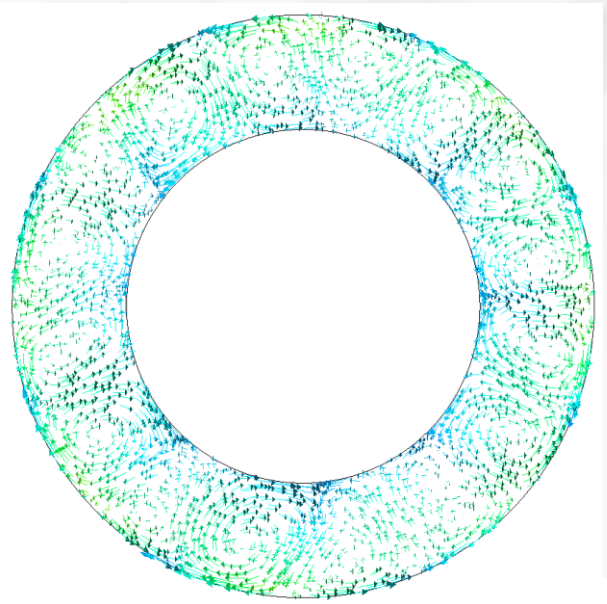




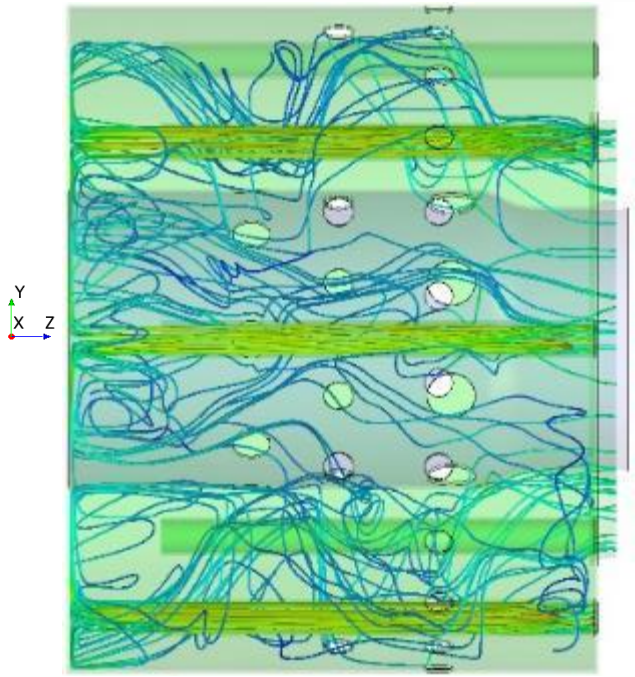
Design C - outlet plane velocity vectors showing relatively fewer vortices. Score 6/10
Design L - vorticity magnitude and vorticity about the Z-axis. Score 3/10

Design K - outlet plane velocity vectors showing a large number of vortices. Score 0/10
Design R- vorticity magnitude and vorticity about the Z-axis. Score 1/10

Methodology: Scoring Sample Evaluations

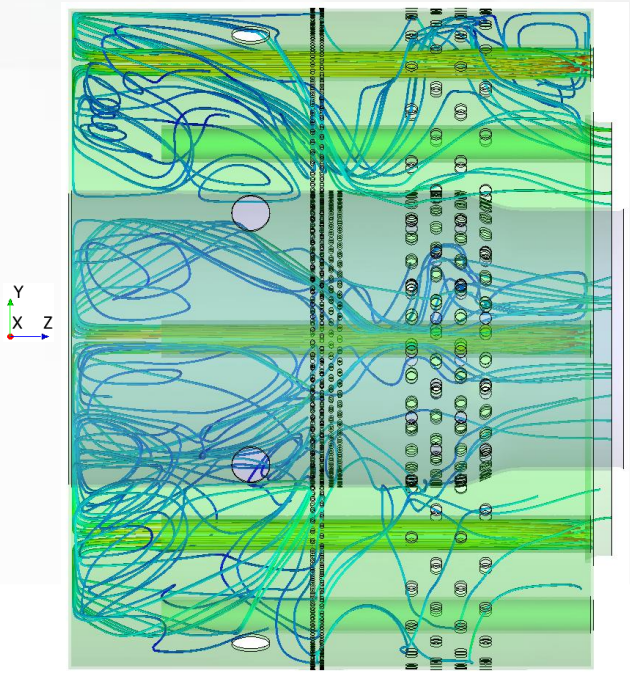
- Mixing: The tracer flow paths were evaluated for flow path length and complexity and some interpretation of the mixing might be acquired from these.

Best



Design G - stream tracers showing fairly convoluted tracer paths in the Sz & Dz regions. Score 6/10

Worst

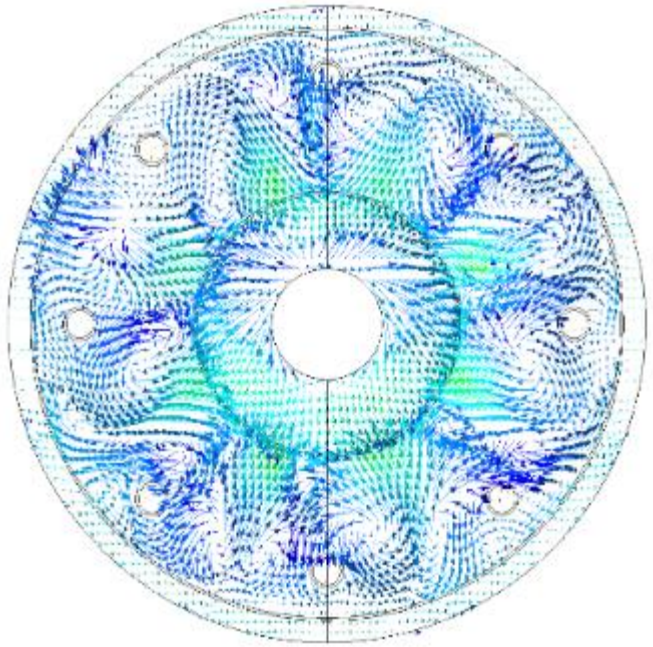


Design K - stream tracers showing flow paths that have few direction changes along the length of the Sz & Dz regions. Score 4/10

Methodology: Scoring Sample Evaluations

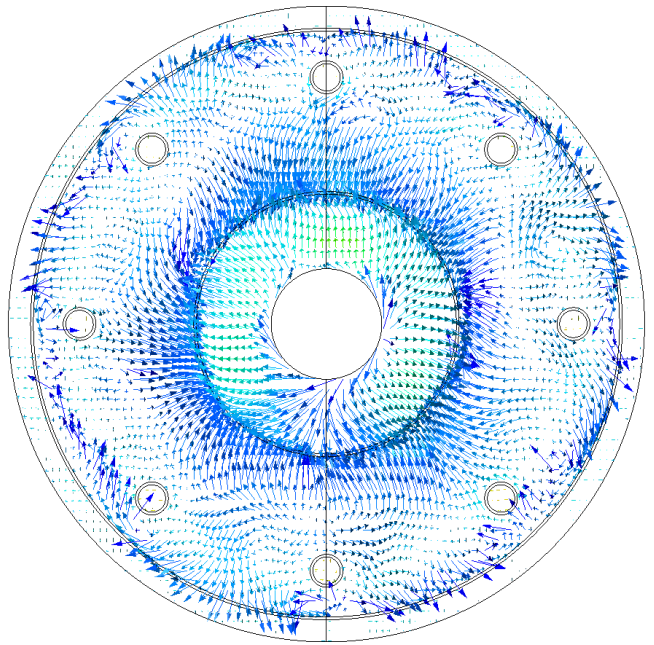
- Mixing: The velocity vector plots were evaluated for the holes' flow interactions, penetrations and influence on the overall combustor mixing through the generation of vortices.

Best



Design G - sample C/S velocity plane (after the Sz hole row) showing large, well-formed vortices.
Score 5/10

Worst



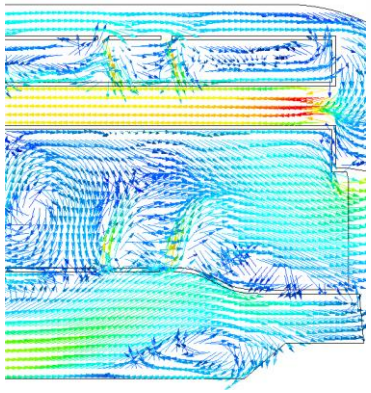
Design S - sample C/S velocity plane (after the Sz hole row) showing no vortices.
Score 0/10

Methodology: Scoring Sample Evaluations

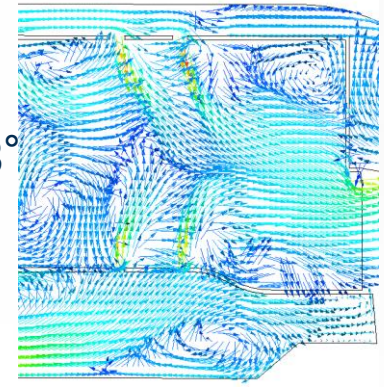
- Overall combustor mixing cont.

Best

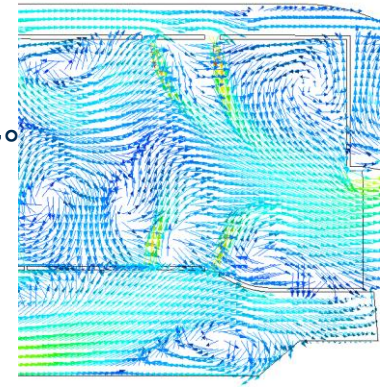
0°



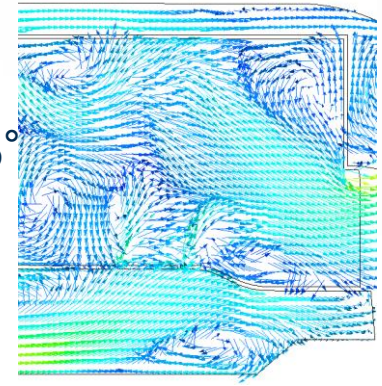
13°



16.7°



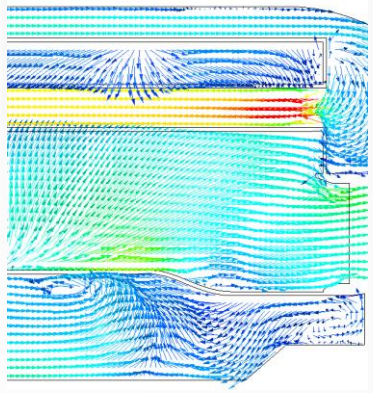
22.5°



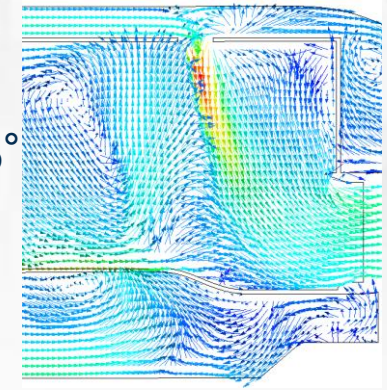
Design S - longitudinal C/S vectors showing many, intense vortices in the Sz & Dz.
Scored 7.5/10

Worst

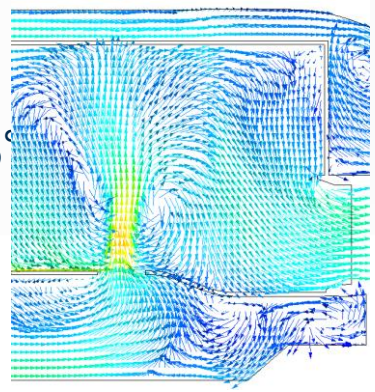
0°



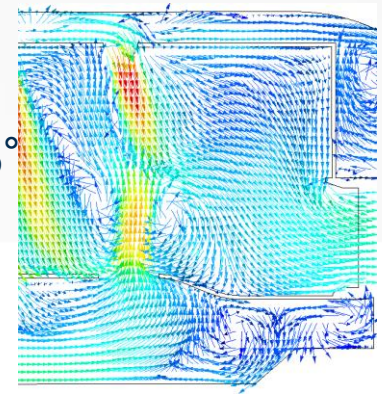
11.25°



16.875°



22.5°



Design C - longitudinal C/S vectors showing only a few, weak vortices in the Sz & Dz.
Scored 4/10

Methodology: Ranking