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# The Numerical Aerodynamic Evaluation of Geometrical Configurations of a Vaporizer Tube Micro-Gas Turbine Combustor

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## ABSTRACT

A combustor was designed for a 200N micro-gas turbine for the Model aircraft industry using the NREC design method. During the design process, there are various aspects where there are no definitive methodologies for specifying the design detail, such as the design of the hole-sets, and multiple options can be derived that can satisfy the required mass flow split and pressure drop for a particular hole-set.

For this study, the various solutions for hole-set configurations were tested using CFD before experimental development will be pursued. The three design parameters tested were 1) annular area split configuration, 2) Hole area splits and 3) Relative hole positions.

CFD simulations for a chosen 9 designs were run and the data were processed, analysed and interpreted. Some of the results such as mass flow splits and pressure drop are already quantitative in nature, however, the evaluation of the quality of the recirculation zone, mixing and outlet plane flow are of a more qualitative nature.

In order to apply a more quantitative method for choosing a preferable design, a scoring system was devised in order to apply a quantitative value to the aspects of the flow which are initially analysed subjectively. The evaluation was broken up into the relevant aspects/features, namely, Recirculation zone (Rz), Outlet and Mixing. For each feature, the designs were subjectively evaluated relative to each other and given a rating/score.

The scoring methodology for ranking combustors proved to be an effective method for evaluating the large mass of data that is generated using CFD and allowed for the use of this data to inform choices when narrowing down the mass of combustor designs that are generated in the preliminary design phase.

**Keywords:** Combustor; Computational Fluid Dynamics; Evaluation

## NOMENCLATURE

NREC	Northern Research and Engineering Corporation
CFD	Computational Fluid Dynamic
Pz	Primary zone
Rz	Recirculation zone
Dz	Dilution zone
Sz	Secondary zone
SL	Sea Level
Pzo	Outer primary zone hole-set
Szo	Outer secondary zone hole-set
Dzo	Outer dilution zone hole-set
PzV	Primary hole-set that are vaporiser tubes
Pzi,	Inner primary zone hole-set
Szi	Inner secondary zone hole-set
Dzi	Inner dilution zone hole-set
NGV	nozzle guide vanes
RST	Reynolds stress turbulence
SST	Shear Stress Transport
C/S	Cross section
alt	Altitude
Eff	Efficiency

### Symbols

$\Delta P$	Pressure drop
$\dot{m}$	Mass flow rate
d	Liner diameter
D	Casing Diameter
p	Static pressure
P	Total pressure
T	Temperature
x	Horizontal co-ordinate
y	Vertical co-ordinate
z	Axial co-ordinate
$x$	The fraction of total air required in the outer annulus

### Subscripts

3	Station at the inlet to the combustor
4	Station at the outlet to the combustor
o	Outer
i	Inner
f	Fuel

## 1.0 INTRODUCTION

A combustor was designed for a 200N micro-gas turbine using the NREC design method [1]. During the design process, there are various aspects where there are no definitive methodologies for specifying the design detail, such as the design of the hole-sets, and multiple options can be derived that can satisfy the required mass flow split and pressure drop for a particular hole-set.

Hole-set configurations were devised using the process provided in NREC [1] combined with the knowledge that the previous combustor used in the engine had a problem with the inner combustor liner burning away. It was suspected that part of the reason for this was a much lower air flow rate in the inner annulus than the outer annulus due to minimal holes in the inner liner wall. An alternative cause could also be due to annular

flow irregularities in the inner annulus such as flow separation [2]. The original combustor design had the vaporizer tubes entering from the outer annulus.

In order to approach the combustor development process systematically, it was decided that the first combustors to be built from the new designs will retain the current vaporizer tube setup with the vaporizer tubes entering from the downstream liner wall fed from the outer annulus. An alternative vaporizer tube position was designed as an option in an attempt to improve the probability of a strong recirculation zone.

The first phase of design focussed on correcting the airflow splits between the two annuli and focusing on achieving an improved Primary zone flow pattern that more closely resembles the recirculation in the theory [3,4]. Once the Primary zone flow has been improved, attempts to investigate design scenarios for the secondary and dilution zones will be performed. Secondary aspects such as combustor can rounding and tapering of the annulus areas etc. will be developed at a later stage.

For this study, the various solutions for hole-set configurations were tested using CFD before experimental development will be pursued. The three design parameters tested were 1) annular area split configuration, 2) Hole area splits and 3) Relative hole positions.

CFD simulations for a chosen 9 designs were run and the data were processed, analysed and interpreted and various aspects of it are presented in **Figure 5** to **Figure 18**. Some of the results such as mass flow splits and pressure drop are already quantitative in nature, however, the evaluation of the quality of the recirculation zone, mixing and outlet plane flow are of a more qualitative nature.

In order to apply a more quantitative method for choosing a preferable design, a scoring system was devised in order to apply a quantitative value to the aspects of the flow which are initially analysed subjectively. The evaluation was broken up into the relevant aspects/features, namely, Recirculation zone (Rz), Outlet and Mixing. For each feature, the designs were subjectively evaluated relative to each other and given a rating/score. The designs with the highest scores overall were earmarked for manufacture.

The results indicates that the hole area split seems to be dominant over the annulus area split when determining the air flow split between the inner and outer annuli. It is suspected that a discrepancy in the mass flow splits when the vaporiser tube length and position are changed could be due to there being a lack of design method for vaporiser tubes explicitly and a plunged hole model being used instead. In general none of the outlet planes were close to ideal which is likely due to the highly compromised length of the combustors in this case. Further, there seems to be an inverse relation between having a good recirculation zone and a good outlet plane.

## 2.0 DESIGN PARAMETERS

The Input conditions for the combustor design are given in **Table 1**. The combustor was designed for 5 conditions namely Take off/Max Power, High Altitude Relight, Ground Idle, Flight Idle and Cruise (SL) – Max  $\dot{m}_3$ . The parameters at each condition were devised using the cycle modelling tool GasTurb [5].

The first aspect varied was the annular area split configuration. Two options were designed:

1. 50/50% area split.
2. 65/35% area split.

This variation resulted in a variation in the inner ( $d_i$ ) and outer ( $d_o$ ) combustor liner diameters for the two split ratios.

In order to accommodate a variable annuli air flow split (and associated area split), new liner diameter equations were derived and are show below:

$$d_o = \sqrt{D_o^2 - 0.3x(D_o^2 - D_i^2)} \quad \dots (1)$$

and

$$d_i = \sqrt{D_i^2 + 0.3(1-x)(D_o^2 - D_i^2)} \quad \dots (2)$$

where  $x$  = The fraction (out of 1) of total air required in the outer annulus

The second aspect varied was the hole-set configurations and thus annular air flow splits. The following three options were designed:

1. Outer annulus: Pzo, Szo, Dzo, PzV and Inner annulus: Szi, Dzi (65/35% air flow split).
2. Outer annulus: Szo, Dzo, PzV and inner annulus: Pzi, Szi, Dzi (50/50% air flow split).
3. Outer annulus: Pzo, Szo, Dzo and Inner annulus: PzV, Szi, Dzi (50/50% air flow split).

Representative cross sectional views of the 3 hole-set configurations mentioned above of the combustor liner are shown in **Figure 1**

The third aspect varied was the hole configurations of the hole-sets with respect to one another. This aspect required some application of arbitrary rules and logical thought about the aerodynamic consequences of the choices. Considerations included:

1. The available diameters of tubing limited the vaporizer tubes to either 6 or 8 tubes for the prescribed mass flow split. In order to try get more evenly distributed aerodynamic features around the circumference of the combustor the 8 tube configuration was chosen.
2. Each hole-set calculation provides many hole-diameter/number-of-hole configurations. NREC recommends a maximum of 10 holes per hole-set row.
3. This combustor is highly constrained in the lengthwise direction and thus minimising the hole row intrusion into the material in the lengthwise direction was employed as well as attempting to reduce the number of rows per hole-set.
4. The interference (both constructive and destructive) of the hole-sets' flow with each other and the vaporizer tubes was also considered thus various design options were produced where:
  - a. Holes could be aligned with the vaporizer tubes or placed in between them to make sure they don't impinge on the vaporizer tubes and their flow isn't disrupted by the vaporizer tubes.
  - b. The number of holes per hole-set were as designed or modified to various combinations of multiples of the number of vaporizer tubes.

With regards to the primary zone and its recirculation zone, 4 different Pz hole/vaporizer tube configurations were tested:

1. Vaporizer tube from the Inner annulus with Pz holes in outer annulus *in line* with the vaporizer tubes (option 3 in **Figure 1**)
2. Vaporizer tube from the outer annulus with Pz holes in outer annulus *in line* with the vaporizer tubes (option 1 in **Figure 1**)
3. Vaporizer tube from the outer annulus with Pz holes in inner annulus *in line* with the vaporizer tubes (option 2 in **Figure 1**)
4. Vaporizer tube from the outer annulus (option 3 in **Figure 1**) with Pz holes in inner annulus *in between* the vaporizer tubes

## 3.0 METHODOLOGY

### 3.1 CFD Analysis

Due to the large number of combustor design options, it was decided to perform CFD to evaluate only 9 representative designs. Cold flow CFD runs were performed and the internal aerodynamics of the combustors were evaluated. This enabled the identifying of the preferred configurations in order to choose two designs with the most promise for manufacture.

It was suspected that Option 2 designs (see **Figure 1**) would result in the most well developed recirculation zone (Rz) since the Pz/PzV hole configuration was devised to try to enhance the Rz (while maintaining the current vaporizer design). For this reason this design was proposed as a baseline for various hole-set configuration testing and thus designs E to I were added to the list of combustors to model. Designs E to I are of the Option 2, 50/50% annulus area split, 50/50% annulus air split type configuration. The hole variations between the designs are incremental from each other and are described in the last column of **Table 2**:

For the CFD modelling, the all-purpose CFD software, STAR-CCM+, was used. The analyses were performed on a simplified model of the combustor where the flow domain excluded the diffuser and nozzle guide vanes (NGV) sections. The flow domain inlet was placed just downstream of the diffuser and the outlet just upstream of the NGV. Air entered the flow domain perpendicular to the boundary in the analyses. **Figure 2** shows the model used for the analysis of Design B. The models of all the designs were similar, with only the combustor itself changing (green part in **Figure 2**). Each model consisted of approximately 4 million polyhedral cells.

The boundary conditions corresponding to Condition 1 (Take off/Max Power) were used. The inlet temperature was specified as 501 K and remained close to that value throughout the domain (see **Figure 3**). The inlet boundary had a pressure specification of 426kPa and an inlet mass flow rate of 0.35kg/s.

The modelling approach was developed and validated by comparing results of a CFD analysis of a generic combustor for which experimental data were available [6,7]. Three turbulence models were employed to find the most suitable one: k-epsilon, k-omega (Menter SST) and the Reynolds stress turbulence (RST) model. Simulations were also carried out assuming steady state and transient flow as well as two mass flow rates: 0.056 and 0.089 kg/s (validation combustor design mass flow).

Results indicated that the simulations with k-epsilon produced flow patterns that were unrealistically stable compared to the experimental data. The simulations employing the RST model produced results that were similar to those obtained with the k-omega turbulence model but were numerically less stable, more so at the higher flow rate.

The velocity components in the x, y and z directions at various positions along the combustor were compared to values measured experimentally. The results obtained with the k-omega and RST turbulence models as well as those using the steady and transient flow assumptions were all in agreement with the experimental results. This allowed the steady state, k-omega turbulence model to be used instead of the more computationally expensive time dependent and / or RST model options without compromising accuracy.

Due to the unsteady nature of the flow, both the experimental and the CFD data had to be averaged. It was decided to average 100 simulations since averaging the results of more than 100 simulations did not improve the accuracy significantly. Typically 4000 iterations would be performed and then a simulation would be saved for averaging after every 10 iterations up to simulation 5000.

As shown in **Figure 4**, the flow speed was below Mach 0.3 (134.6m/s) almost everywhere in the solution, implying that the segregated flow solver could be used. Simulations were started with the coupled flow solver and the switch to the segregated flow solver was done later. The density specification was left at 'ideal gas' to allow for the adjustment of density using the ideal gas assumption instead of the alternative 'constant density' setting. Using the segregated solver made it possible to use a so-called 'Flow Split' boundary at the outlet, and thus the exit pressure need not be specified and could be calculated.

## 4.0 RESULTS AND DISCUSSION

### 4.1 Scoring

The evaluation was broken up into the relevant criteria/features, namely, Recirculation zone (Rz), outlet, mixing and pressure drop.

Some of the results such as mass flow split and pressure drop are inherently quantitative, however, the aspects such as the quality of the recirculation zone, mixing and the outlet plane flow are qualitative. In order to apply a more quantitative method for choosing a preferable design, a scoring system was devised in order to apply a quantitative value to the aspects of the flow which are initially analysed subjectively.

In order to analyse which designs to choose for manufacture, the designs were evaluated according to:

- The recirculation zone intensity, shape and position.
- The outlet plane vorticity and the velocity vectors' uniformity and direction.
- The tracer flow paths were evaluated for flow path length and complexity and some interpretation of the mixing might be required from these.
- The velocity vector plots were evaluated for the holes' flow interactions, penetrations and influence on the overall combustor mixing through the generation of vortices.
- Combustor pressure drop.

For each feature, the designs were subjectively evaluated relative to each other and given a rating/score.

**Figure 5** to **Figure 18** show sample evaluations of the results showing the best and worst rated representations of each of the 3 major qualitative aspects evaluated. The associated score for each feature is shown.

#### 4.1.1 Mass flow and pressure drop

**Table 3** shows the designed annulus area and mass flow split vs the CFD simulated mass flow splits ordered from least balanced to most balanced designs. The trend shows that the simulated mass flow split follows the hole mass flow split design rather than annulus area split design. This indicates that the hole area split seems to be dominant over the annulus area split.

Design A is highlighted in purple in **Table 3**. This design has the vaporiser tubes entering the combustor from the inner liner (option 3 in Figure 1). It can be seen that this move of the vaporiser tubes had an effect on the mass flow split compared to the other designs with both an area and mass flow split of 50/50. Moving the vaporiser tubes to the inner annulus changed the mass flow split by 3% from the other 50/50 designs.

When the tubes were entering from the downstream position in the outer annulus, the variation from the design mass flow split was  $\pm 5\%$ , however, when the vaporiser tubes were moved to the inner annulus and shortened significantly, the variation became  $\pm 8\%$ .

#### 4.1.2 Recirculation zone

When evaluating the designs, the recirculation zone was inspected both using the tracer streamlines as well as the velocity vector patterns in the longitudinal cross sections. The ideal recirculation zone recirculates combustion gasses back into the Rz from the downstream region to the upstream region. It should also preferably extend in the circumferential direction to allow for as large a region of recirculation as possible. In the case of the longitudinal direction vaporizer tubes, it was also preferable for the recirculation zone to primarily be positioned towards the inner radial direction rather than squashed in the outer direction between the tube and the outer casing wall.

It was found that design A caused a recirculation region with an axis  $90^\circ$  to that which is preferred. This direction of recirculation zone can still perform fuel/combustion gas mixing but is unlikely to increase the residence time of the fuel in the Pz, compared to the conventional Rz direction, and thus is unlikely to be the best choice.

In design B, the recirculation zone was fair however, it tended to get malformed and broke up into smaller recirculation zones as one moved along the azimuthal direction.

Design C and design D, despite having the same Pz configuration, had largely conflicting recirculation zone results when evaluating the longitudinal cross-sectional

vector plots. The cause of this is still unknown and further investigation would be required. The tracers of design C and design D indicate some well-formed toroidal recirculation zones forming at the end of the vaporizer tubes.

For designs E to I, the recirculation zones were fairly well formed with quite tight toroids forming around the vaporizer tubes and thus forming a well-defined recirculation zone. In these designs the inner Pz hole alignment to constructively add to the recirculation caused by the vaporizer tube appear to have performed as expected.

Considering the trajectories of the tracers, the best Rz visible was that of designs E and I while the worst was design A. The longitudinal cross-section vector plots indicated that the best Rz structure was design G whilst the worst was design A. These features can be seen in **Figure 5** to **Figure 8**. See **Table 5** for all design rankings.

#### 4.1.3 Outlet

The outlet plane was evaluated for velocity vector uniformity and direction. This was to determine whether the outlet flow conforms as closely as possible to the requirements for the NGV. Ideally, the NGV's require straight flow with a uniform velocity distribution from hub to shroud. Based on these requirements, the velocity vectors were inspected to determine if there were any vortices or residual swirl at the outlet plane.

Vorticity magnitude and the vorticity in each of the 3 directions were also used. The vorticity magnitude was used as an initial rating method where uniformity was established and as an indication of the level of residual swirl left in the flow. The main vorticity component magnitude used to determine whether the residual rotation was in the form of vortices or swirl was the axial direction vorticity i.e. about the z axis or k unit vector direction. It was found that, in general, the design that had a favourable outlet plane, had an unfavourable recirculation zone and vice versa.

When evaluating the outlet using the velocity vectors, the best design was design C whilst the worst design, showing the largest amount of vortices were designs E and F. The vorticity magnitude indicated similar conclusions with the best design being design D while the worst again being designs E and F. These features can be seen in **Figure 9** to **Figure 12**. See **Table 5** for all design rankings.

#### 4.1.4 Mixing

The mixing of the combustion gasses with the "cold" flow from the annuli downstream of the primary zone is the mechanism with which the combustion process is meant to be completed as well as the mechanism with which the flow is conditioned for the NGV [4]. The increased mixing in the dilution zone (Dz) serves to condition the temperature distribution (pattern factor) at the outlet. Due to the short length of the combustor, this conditioning is solely due to the mixing from the jets.

Three mechanisms were used to evaluate the amount of mixing occurring from the CFD results: The amount of vortices downstream of the Pz in the longitudinal C/S velocity vectors. The lengths and complexity of the tracer flow paths in the Sz & Dz regions and the number and size of the vortices in the combustor C/S velocity vector plots.

When evaluating the longitudinal velocity vector plots, the best designs were designs H and I while the worst was design A. The tracer paths indicated that the best mixing was in designs A and G while the worst were designs B and F. The velocity vectors on the combustor cross-sectional planes indicated that the best designs were designs A and B while the worst was design I. These features can be seen in **Figure 13** to **Figure 18**. See **Table 5** for all design rankings

### 4.2 Overall ranking

Once all of the feature categories were evaluated through the various means (vectors, tracers, vorticity) and a score was given for each design using each evaluation means (see **Table 4**), a series of weightings and prioritising were applied in order to obtain a final design choice.

First, within each category a weighting was required to be applied to each means, to arrive at a single score for each design in each category. Each category should add up to

1 due to the weighting based on the prioritising between categories to be done later. The logic for the intra-category weighting is described below.

#### 4.2.1 Recirculation zone

Due to the difficulty in interpreting the longitudinal vectors i.t.o. the three dimensional realm, a higher weighting was given to the rating based on the tracers.

#### 4.2.2 Outlet

Since the presence of outlet vorticity was similarly detectable in both the vector and vorticity plots, the vorticity plots had a quantitative quality to it and was thus less subjective. For this reason a higher weighting was given to the vorticity rating.

#### 4.2.3 Mixing

Since mixing due to vortices in the longitudinal direction is preferable over mixing due to vortices in the C/S direction, priority was given to the higher scoring mixing in the longitudinal direction. Further, since three dimensional mixing within the whole combustor volume was more readily interpreted using the tracers compared to the C/S vector plots, a higher rating was assigned to the tracers than the C/S vectors. These weightings can be seen in the 3<sup>rd</sup> last row in **Table 4**.

The next step required the prioritising of the individual feature categories w.r.t. each other and thus an inter-category prioritising and then weighting was applied. The reasoning behind how the weighting was devised is as follows: For a combustor, the Rz is the most important thing to get right and thus has the highest priority. Following that, i.t.o. the engine function, an extremely detrimental outlet plane velocity profile could hinder the engine performance by hindering the turbine functionality. Further, the Mixing contributes to the combustor reaching a more ideal/theoretical functionality while the pressure drop should be minimised, however, increased pressure drop can contribute to the improved functionality of the combustor in the form of increased turbulence intensity and thus improved mixing and functionality. For this reason, a lower pressure drop is desired but not the highest priority due to an advantage to be gained through it. The feature prioritising and weighting are given in the 2<sup>nd</sup> last and last rows in **Table 4**, respectively **Table 5** shows the design ranking within each test.

Once the weightings are applied, the final scores provide a ranking for the various designs. This ranking is shown in **Table 6**.

Upon evaluating the CFD results, there are a few other aspects that appear in various designs that one might want to try and eliminate in future designs. In this case, these features were noted but not used as criteria for elimination due to them subtly influencing the main criteria relevant to a combustor design.

A few of the features that fall in this category are:

1. In designs C & D, the outer annulus primary zone jet penetrates so far into the combustor that it impinges on the secondary zone jet on the opposite, inner annulus wall. It can be seen in the stream tracer data that the inner Sz jet still has mass flow entering the combustor, however, the flow is immediately split apart and moves around the Pz jet. Part of the reason for this could be attributed to the larger mass flow in the outer annulus for these two designs since they are the ones with the 65/35 mass flow split design. This could be solved by offsetting the Sz jets w.r.t the outer Pz jets and thus allowing for the utilization of the Sz jets for combustor flow pattern manipulation. An example of this feature can be seen in **Figure 19**.
2. The flow in the inner annulus, after the inner dilution zone hole, is hugely disrupted and has a large amount of swirl and intrusion in the upstream direction in the annulus. This type of flow disrupts the smooth entrance of the annulus air into the Dz holes as well as increases the combustor pressure loss without reaping the benefits (in the form of mixing) within the combustor liner from the pressure drop. This is most prominent in designs E to I. An example of this feature can be seen in **Figure 20**.

3. In most designs there were some stream tracers that would travel in the azimuthal direction around the annuli for a long time before entering the combustor liner. Also in most of the combustors there is a large amount of recirculating flow in the outer annulus end before the vaporiser tube entrances. This too increases the combustor pressure loss without the benefits of mixing within the combustor liner from the pressure drop. An example of these features can be seen in **Figure 21**.

## 5.0 CONCLUSION

The annulus air flow split is closer to the area ratio of the inner and outer annulus holes than the inner and outer annulus areas. This indicates that the hole area split seems to be dominant over the annulus area split when determining the air flow split between the inner and outer annuli.

The variation in the mass flow splits when comparing the two positions of the vaporiser tubes could be due to the chosen discharge coefficient used to design the vaporiser tubes. There is no known guideline for this value and the design process for a plunged hole was used during the design.

In general, it was found that the design that had a more favourable outlet plane, had an unfavourable recirculation zone and vice versa. This could indicate that the outlet plane condition is highly sensitive to the Pz condition and possibly less sensitive to the other zones subsequent to the primary zone. However, this effect might be more prevalent in this highly length constrained combustor case due to the length being significantly shorter than the theoretical design would require. It should be noted however that none of the designs scored above 6/10 for the outlet plane and thus none of the designs provides an ideal outlet plane velocity field.

The scoring methodology for ranking combustors proved to be an effective method for evaluating the large mass of data that is generated using CFD and allowed for the use of this data to inform choices when narrowing down the mass of combustor designs that are generated in the Preliminary design phase.

Despite the CFD indicating non-ideal flow for various aspects for these combustor designs, the designs are deemed adequate to proceed to manufacture due to the highly constrained nature of this particular engine. The combustor length is  $\pm 45\%$  of the theoretical design length and diameter constrained to  $\pm 67\%$  of the theoretical design diameter and thus non-ideal combustor flow and performance is expected.

## ACKNOWLEDGMENTS

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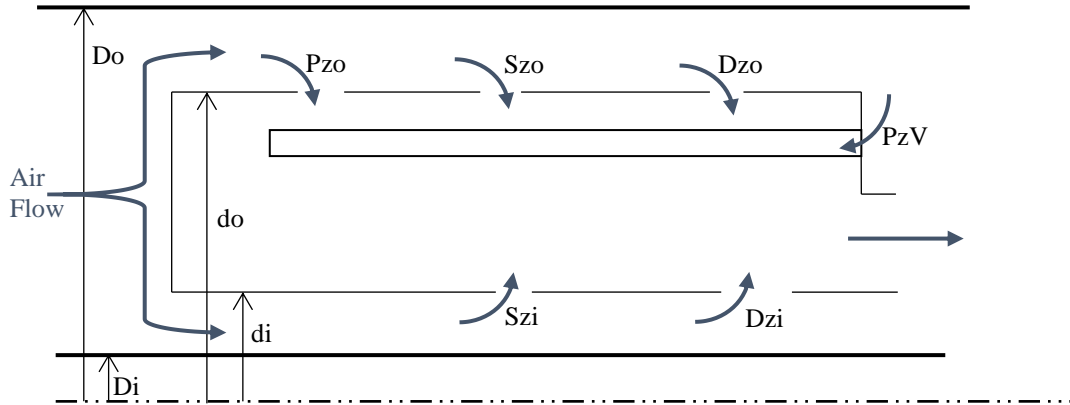
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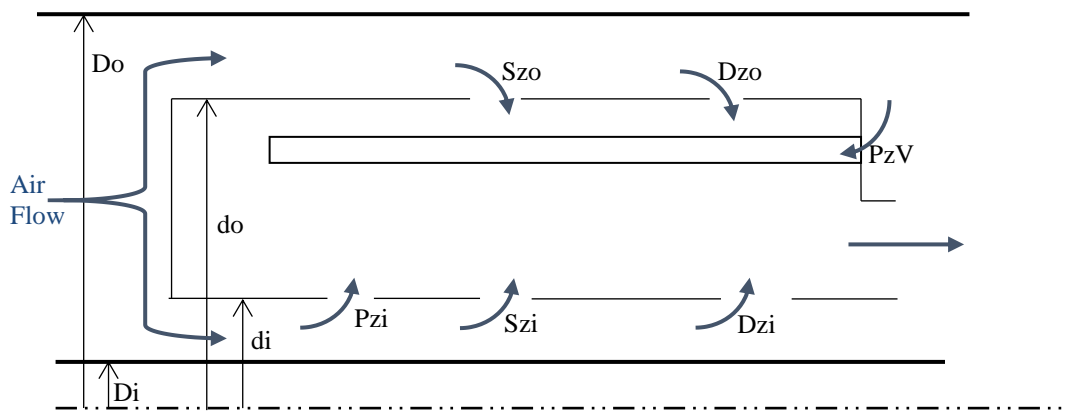
## APPENDIX

**Table 1:**  
The Input values for the combustor design [8,9,10]

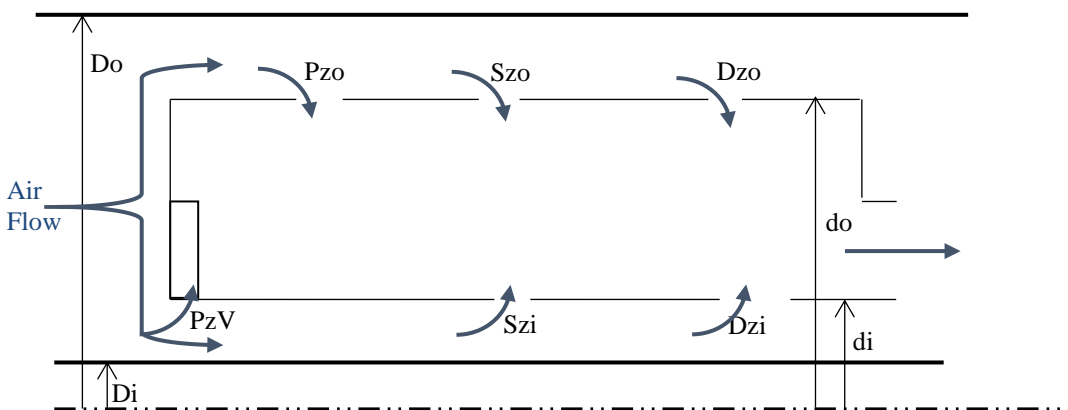
Ref. No.	Condition	Compressor outlet data							Turbine inlet data	Combustor				
		Mach No.	alt	$p_3$	$P_3$	$T_3$	$\dot{m}_3$	$\dot{m}_f$	$T_4$	$P_4/P_3$ [11]	$\Delta P/P$ [11]	$P_4/P_3$ [1]	$\Delta P/P$ [1]	Eff
			m	Pa	Pa	K	kg/s	kg/s	K					%
1	Take off/Max Power	0	0	425589	425608	501.29	0.35	0.00666	1171	0.94	0.06	0.94	0.06	0.95
2	High Altitude (relight)	0.2	2 500	75705	75708	274.08	0.057	0.00149	904	0.97	0.03	0.94	0.06	0.65
3	Ground Idle	0	0	123625	123629	309.23	0.08	0.00204	1184	0.98	0.02	0.94	0.06	0.91
4	Flight Idle	0.4	2 500	181798	181806	373.99	0.149	0.00209	897	0.96	0.04	0.94	0.06	0.95
5	Cruise (SL)-max $\dot{m}_3$	0.6	0	542825	542848	536.14	0.431	0.00756	1153	0.94	0.06	0.94	0.06	0.95



Option 1



Option 2



Option 3

Figure 1: Cross section of the combustor liner showing the various hole-set configuration options 1 to 3

**Table 2:**  
The design choices of the analysed designs.

Design Aspect: →	(1)		(2)			(3)
	Annular Area Split (outer/inner %)		Hole-set Configuration & Annular Air Flow Splits (outer/inner %)			Hole configurations
Design No.: ↓	50/50	65/35	Option 1 65/35	Option 2 50/50	Option 3 50/50	Comment
Design A	✓				✓	<ul style="list-style-type: none"> <li>Holes are multiples of vaporizer tubes.</li> </ul>
Design B	✓		✓			<ul style="list-style-type: none"> <li>Hole-sets designed individually.</li> </ul>
Design C	✓		✓			<ul style="list-style-type: none"> <li>Holes are multiples of vaporizer tubes.</li> </ul>
Design D		✓	✓			<ul style="list-style-type: none"> <li>Holes are multiples of vaporizer tubes.</li> </ul>
Design E	✓			✓		<ul style="list-style-type: none"> <li>Hole-sets designed individually.</li> <li>Maximum 10 holes per row rule applied.</li> </ul>
Design F	✓			✓		<ul style="list-style-type: none"> <li>Holes are multiples of vaporizer tubes</li> <li>Pz holes in line with vaporizer tubes for constructive interference.</li> <li>Sz &amp; Dz holes in between vaporizer tubes to prevent tubes from interfering with flow and to prevent the Sz &amp; Dz air from cooling the vaporizer tubes.</li> <li>Maximum 10 holes per row rule applied.</li> <li>Increased Dz hole diameter to reduce number of Dz rows to 2 to try decrease lengthwise intrusion.</li> </ul>
Design G	✓			✓		<ul style="list-style-type: none"> <li>Holes are multiples of vaporizer tubes (Pz in line, Sz &amp; Dz offset).</li> <li>Number of Dz rows further reduced to try decrease lengthwise intrusion but hole sizes kept as designed using NREC momentum flux balancing method.</li> </ul>
Design H	✓			✓		<ul style="list-style-type: none"> <li>Holes are multiples of vaporizer tubes (Pz in line, Sz &amp; Dz offset).</li> <li>Sz holes have reduced diameter but a larger number to try improve circumferential mixing.</li> </ul>
Design I	✓			✓		<ul style="list-style-type: none"> <li>Holes are multiples of vaporizer tubes (Pz in line, Sz &amp; Dz offset).</li> <li>Sz holes have reduced diameter but a larger number to try improve circumferential mixing.</li> <li>Alternative Dz hole configuration to test mixing but hole sizes kept as designed using NREC momentum flux balancing method.</li> </ul>

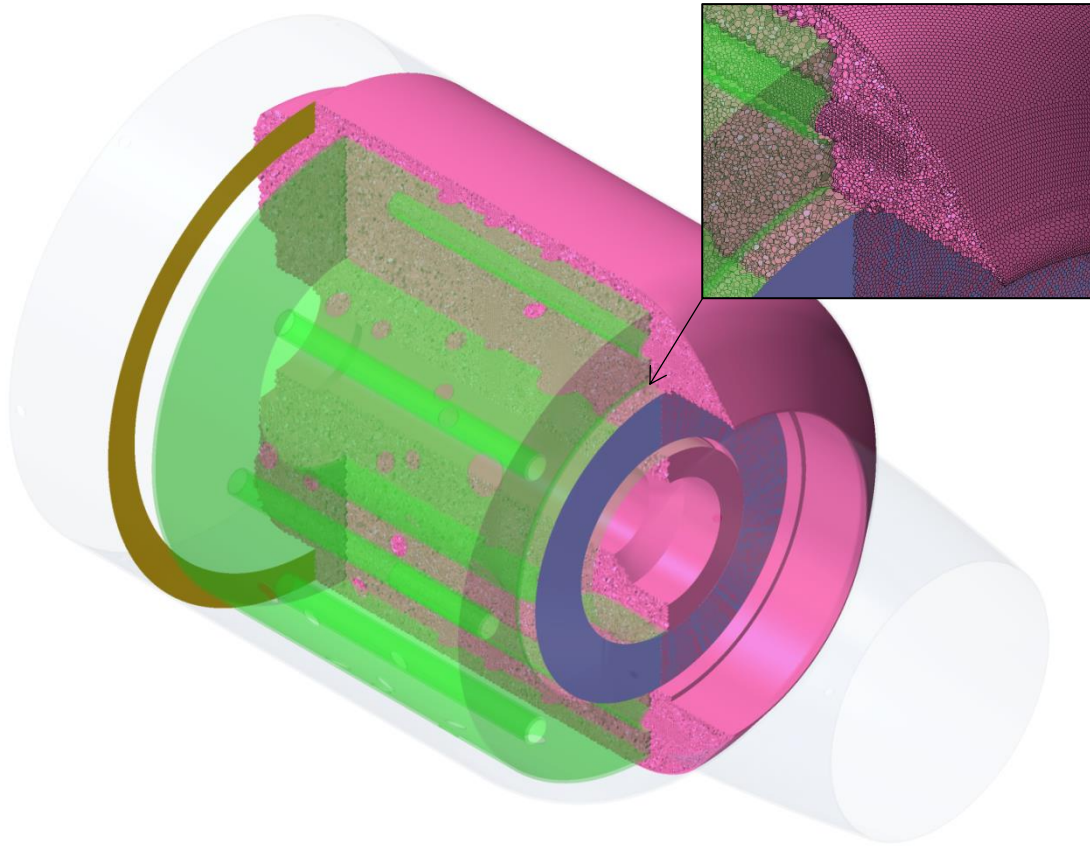


Figure 2: A cross sectional view of the mesh used (pink) with some of the geometry features showing for reference

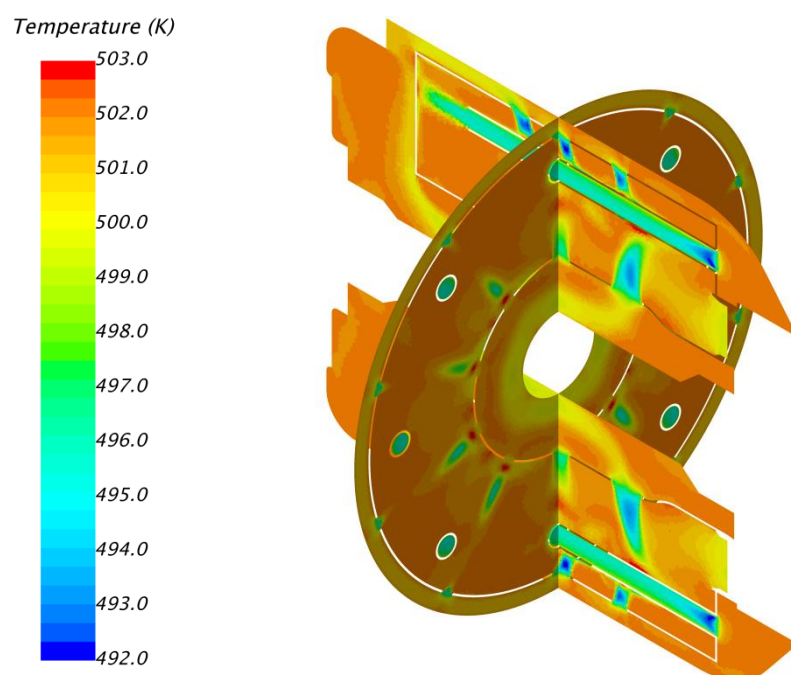


Figure 3: The temperature distribution on representative cross sectional and longitudinal planes

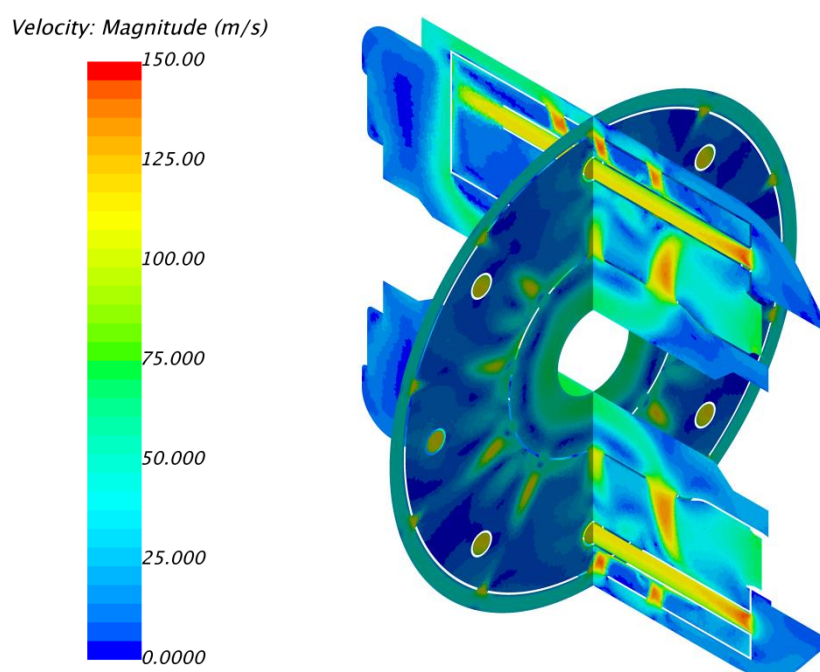


Figure 4: The velocity magnitude distribution on representative cross sectional and longitudinal planes

## Sample evaluation of the Recirculation zone aspects

**Best**

Figure 5: Design E - stream tracers showing a fairly good Rz shape. Score 7/10

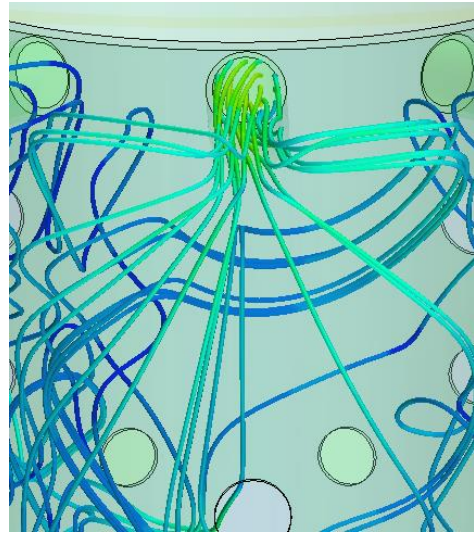
**Worst**

Figure 6: Design A - stream tracers showing a bad Rz shape. Score 1.5/10

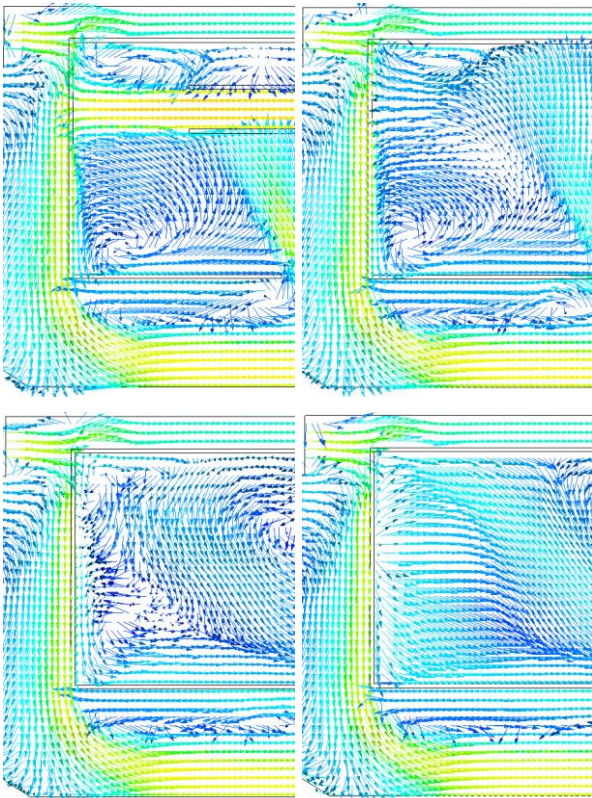


Figure 7: Design G - longitudinal C/S vectors showing a fairly good Rz that covers multiple slices. Scored 7.5/10. (slices at 0°, 7.5°, 15°, 22.5° to Y-axis)

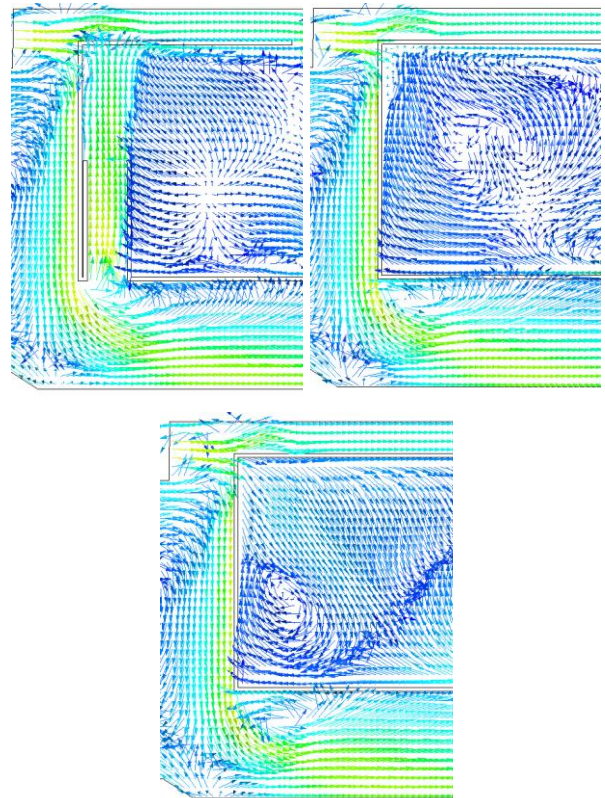


Figure 8: Design A - longitudinal C/S vectors showing a Rz that covers only one slice. Scored 1.5/10. (slices at 0°, 10°, 20° to Y-axis)

Sample evaluation of the Outlet plane aspects

**Best**

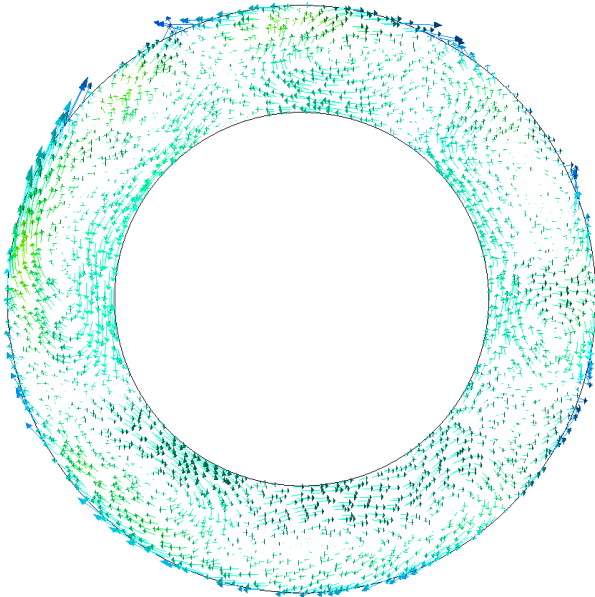


Figure 9: Design C - outlet plane velocity vectors showing relatively fewer vortices. Score 6/10

**Worst**

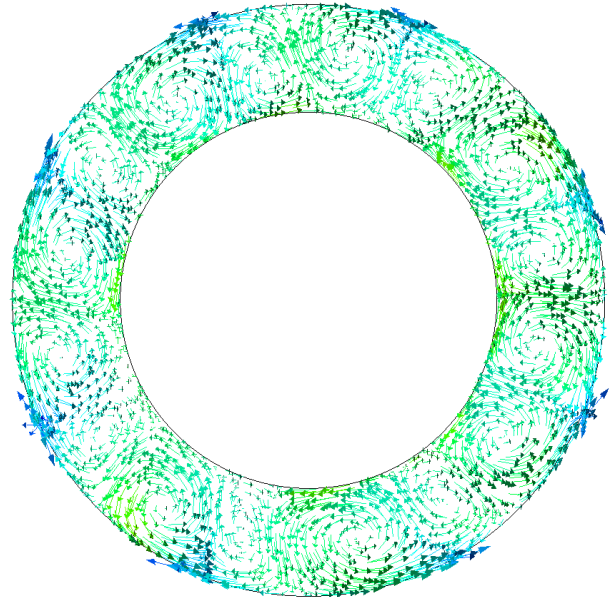


Figure 10: Design F - outlet plane velocity vectors showing a large amount of vortices. Score 0/10.

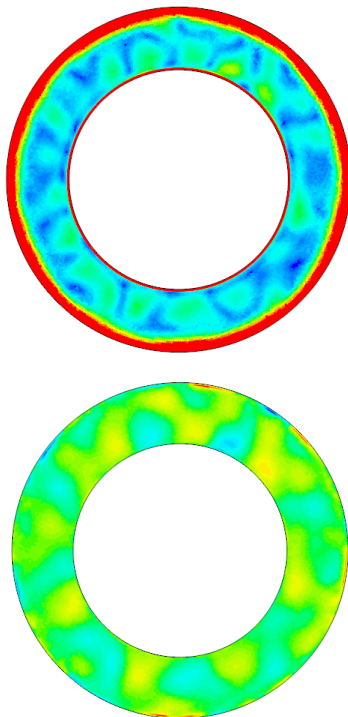


Figure 11: Design D - vorticity magnitude (Top) and vorticity about the Z-axis (k unit vector direction) (Bottom) showing a relatively low magnitude and small distribution about the 0 value for the k direction.

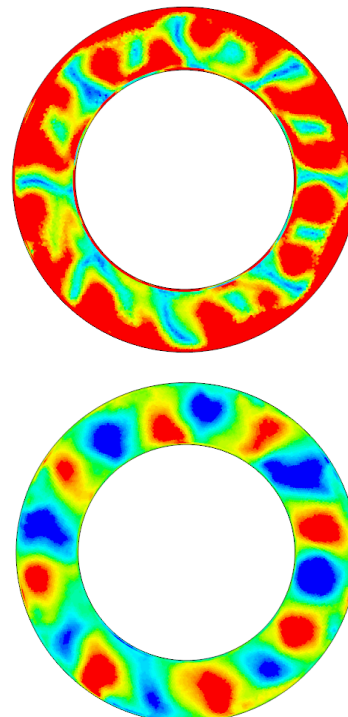
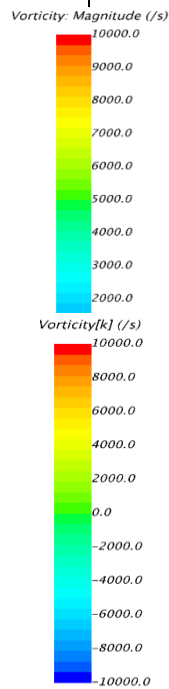


Figure 12: Design F - vorticity magnitude (Top) and vorticity about the Z-axis (k unit vector direction) (Bottom) showing a relatively high magnitude and large distribution about the 0 value for the k direction.

## Sample evaluation of the Mixing aspects

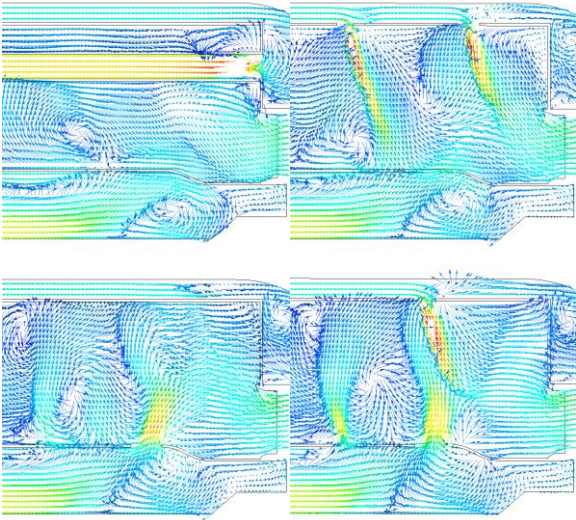
**Best**

Figure 13: Design I - longitudinal C/S vectors showing many, intense vortices in the Sz & Dz. Scored 6/10. (slices at 0°, 11.25°, 16.875°, 22.5° to Y-axis)

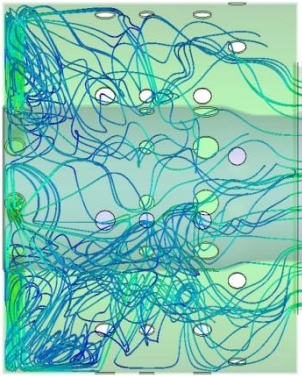


Figure 15: Design A - stream tracers showing fairly convoluted tracer paths in the Sz & Dz regions. Score 6/10

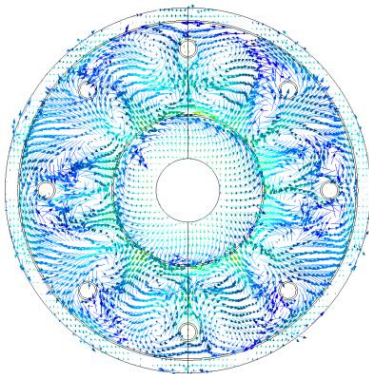


Figure 17: Design B - sample C/S velocity plane (after the Sz hole row) showing large, well-formed vortices. Score 6.25/10.

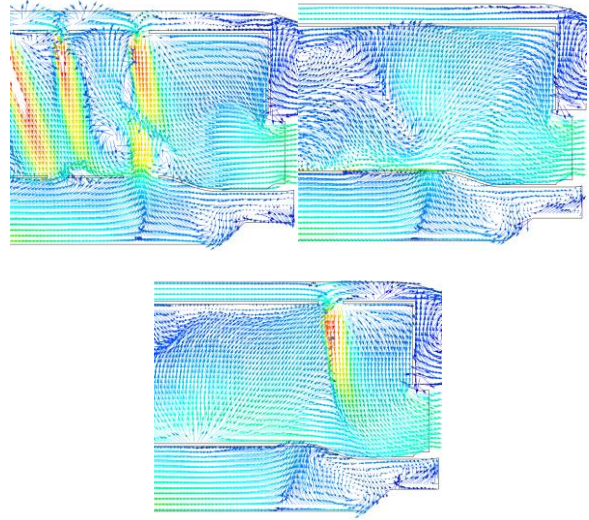
**Worst**

Figure 14: Design A - longitudinal C/S vectors showing only a few, weak vortices in the Sz & Dz. Scored 2.5/10. (slices at 0°, 10°, 20° to Y-axis)

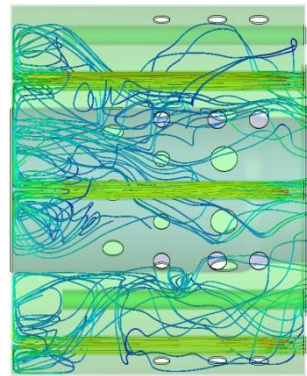


Figure 16: Design F - stream tracers showing flow paths that have few direction changes along the length of the Sz & Dz regions. Score 3/10

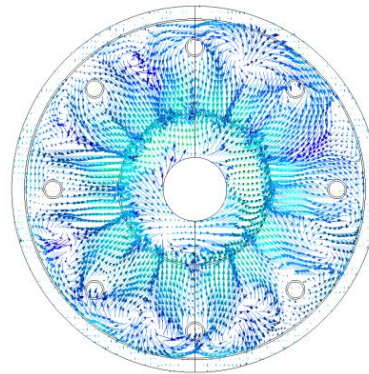


Figure 18: Design I - sample C/S velocity plane (after the Sz hole row) showing small, weak vortices. Score 2.5/10.

**Table 3:**  
The simulated annulus mass flow splits compared to the annulus design parameters

	Design				CFD		
	Annuli Area splits %		Hole Area split %		Mass flow split %		Pressure drop %
	Outer annulus	Inner annulus	Outer annulus	Inner annulus	Outer annulus	Inner annulus	
<b>Design D</b>	65	35	65	35	72	28	7.8
<b>Design B</b>	50	50	65	35	69	31	9.0
<b>Design C</b>	50	50	65	35	73	27	7.8
<b>Design A</b>	50	50	50	50	58	42	8.0
<b>Design I</b>	50	50	50	50	55	45	8.1
<b>Design E</b>	50	50	50	50	55	45	9.7
<b>Design F</b>	50	50	50	50	55	45	8.7
<b>Design G</b>	50	50	50	50	55	45	7.9
<b>Design H</b>	50	50	50	50	55	45	8.0

**Table 4:**  
The scoring for each design for the various feature categories

Design	pressure drop	Rz (tracers)	Rz (l vectors)	Outlet (vectors)	Outlet (vorticity)	Mixing (l vectors)	Mixing (tracers)	Mixing (C/S vectors)
<b>Design A</b>	8.0	1.5	1.5	1	1.5	2.5	6	6.25
<b>Design B</b>	9.0	5.5	6	1	1	3	3	6.25
<b>Design C</b>	7.8	6.5	7	6	2	4	5	4.7
<b>Design D</b>	7.8	6.5	3.5	1.5	4	4	5	5.625
<b>Design E</b>	9.7	7	7	0	0	5	5	5.3
<b>Design F</b>	8.7	5.5	2	0	0	3.5	3	5.625
<b>Design G</b>	7.9	6	7.5	1	1.5	4.5	6	5
<b>Design H</b>	8.0	6	6	1	1	6	4.5	3.6
<b>Design I</b>	8.1	7	6.5	1	1	6	5	2.5
<b>weighting within categories</b>	1	0.75	0.25	0.25	0.75	0.5	0.4	0.1
<b>feature priority</b>	3	1		2		3		
<b>feature weighting</b>	1	3		2		1		

**Table 5:**  
The design ranking table for the various feature categories tested

Ranking	Pressure drop	Rz (tracers)	Rz (I vectors)	Outlet (vectors)	Outlet (vorticity)	Mixing (I vectors)	Mixing (tracers)	Mixing (C/S vectors)
1	Design C	Design E	Design G	Design C	Design D	Design H	Design A	Design A
2	Design D	Design I	Design C	Design D	Design C	Design I	Design G	Design B
3	Design G	Design C	Design E	Design A	Design A	Design E	Design C	Design D
4	Design A	Design D	Design I	Design B	Design G	Design G	Design D	Design F
5	Design H	Design G	Design B	Design G	Design B	Design C	Design E	Design E
6	Design I	Design H	Design H	Design H	Design H	Design D	Design I	Design G
7	Design F	Design B	Design D	Design I	Design I	Design F	Design H	Design C
8	Design B	Design F	Design F	Design E	Design E	Design B	Design B	Design H
9	Design E	Design A	Design A	Design F	Design F	Design A	Design F	Design I

**Table 6:**  
The final ranking and scores for the designs tested

Ranking	Design (ordered)	Final Score [63]	Final Score [%]
1	Design C	50	79
2	Design G	44	70
3	Design D	43	68
4	Design I	43	68
5	Design E	38	60
6	Design H	36	57
7	Design A	26	41
8	Design B	22	35
9	Design F	13	21

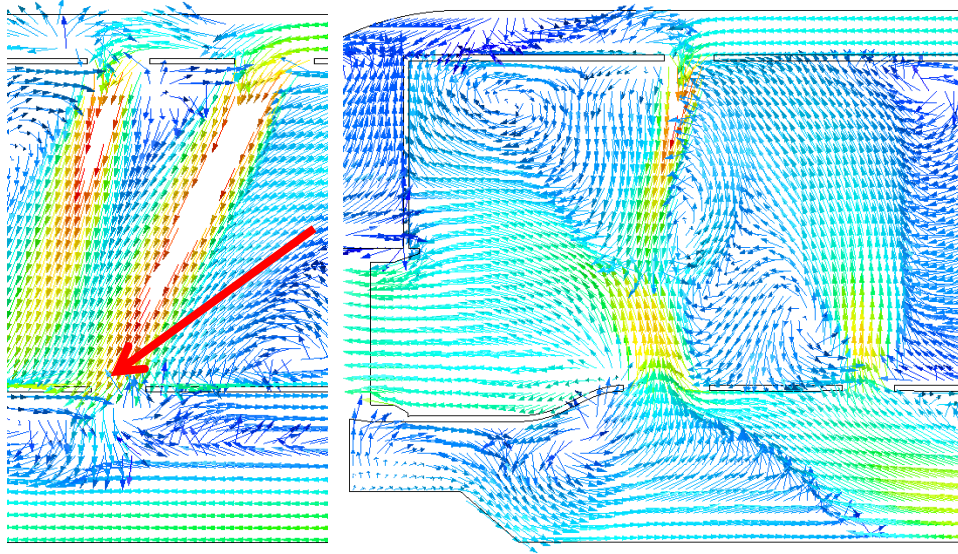


Figure 19: Design C - showing the Pz hole impinging on the opposite Sz hole

Figure 20: Design H - showing the inner annulus air flow path disruption

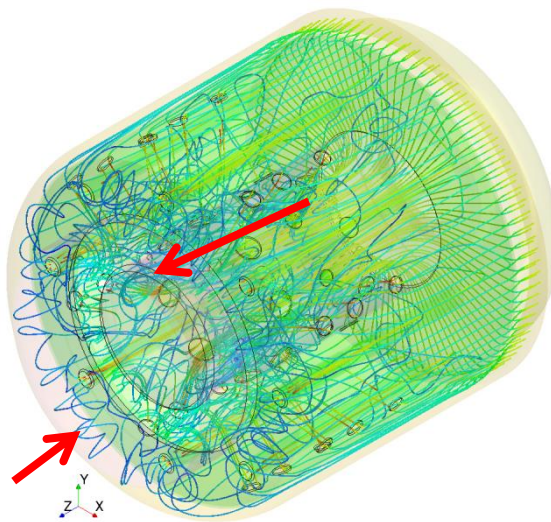


Figure 21: Design E - showing the long flow paths followed by the tracers in the annuli