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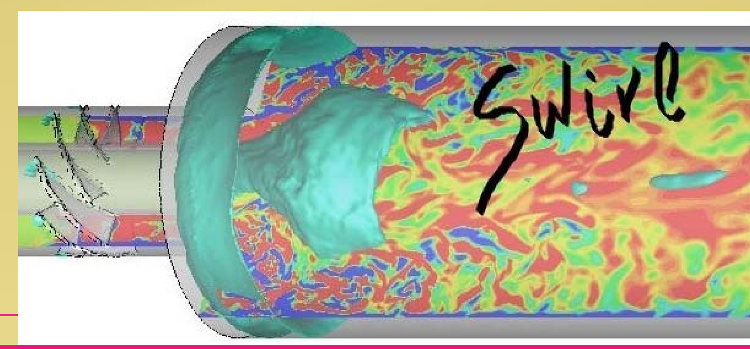

NUMERICAL STUDY OF MIXING IN SWIRLING COAXIAL JETS. AN APPLICATION OF LARGE EDDY SIMULATION.

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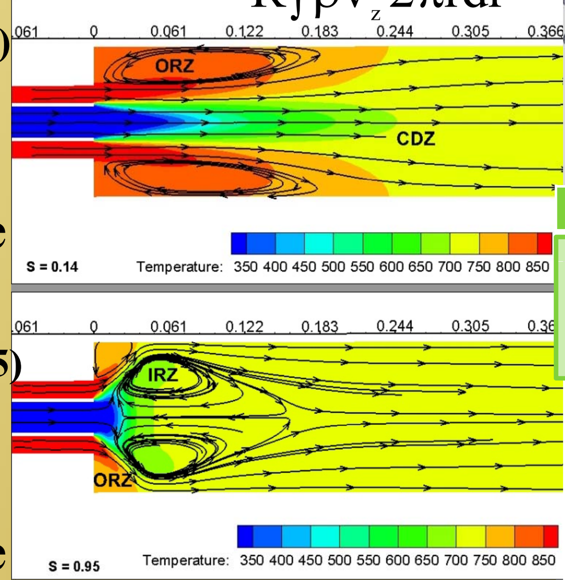
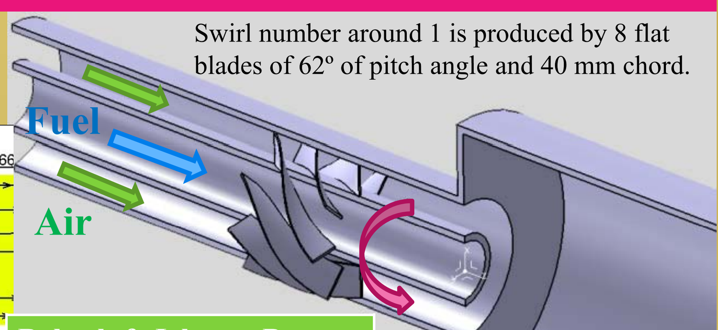
1 Physical model

Flow Pattern based on Swirl no. $S=\frac{\int \rho(rv_\theta)v_z 2\pi r dr}{R\int \rho v_z^2 2\pi r dr}$

Low-swirl injector (S < 0.5)
- Central Divergence Zone
- Shear Layer
- Outer Recirculation Zone

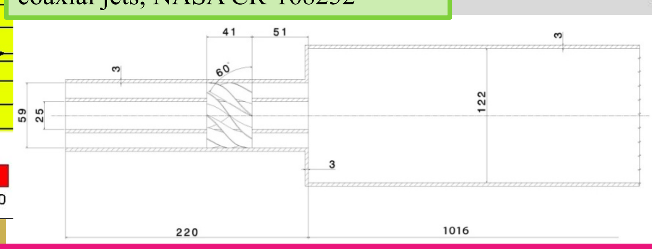
High-swirl injector (S > 0.5)
- Inner Recirculation Zone
- Shear Layer
- Outer Recirculation Zone





Roback & Johnson Burner

Roback R., Johnson B.V. (1983) Mass and momentum turbulent transport experiments with confined swirling coaxial jets, NASA CR-168252

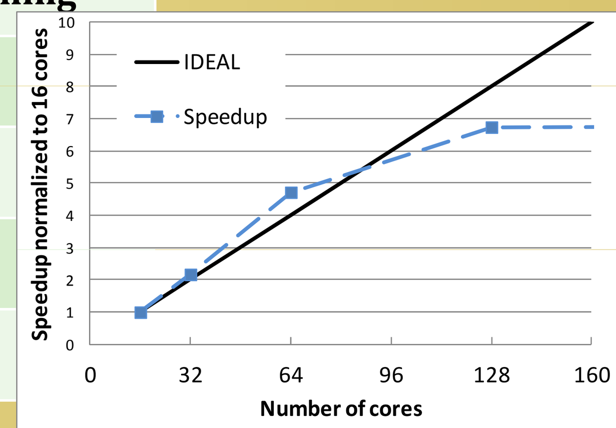


2 Numerical Model & Scalability Analysis

	Fuel	Oxidizer
Injection	Central Nozzle	Annular Nozzle
Composition	CH_4	22% O_2, 78% N_2
Temperature (K)	300	900
Velocity (m/s)	0.66	1.54
Turbulence intensity (%)	12	7.5
Specific Heat(J/kg/K)	Polynomial function of temperature	
Thermal Conductivity (W/m/K)	0.0332	0.0242
Viscosity (kg/m/s)	$1.087.10^{-5}$	$1.7894.10^{-5}$
Molecular Weight (kg/kmol)	16.04303	28.996

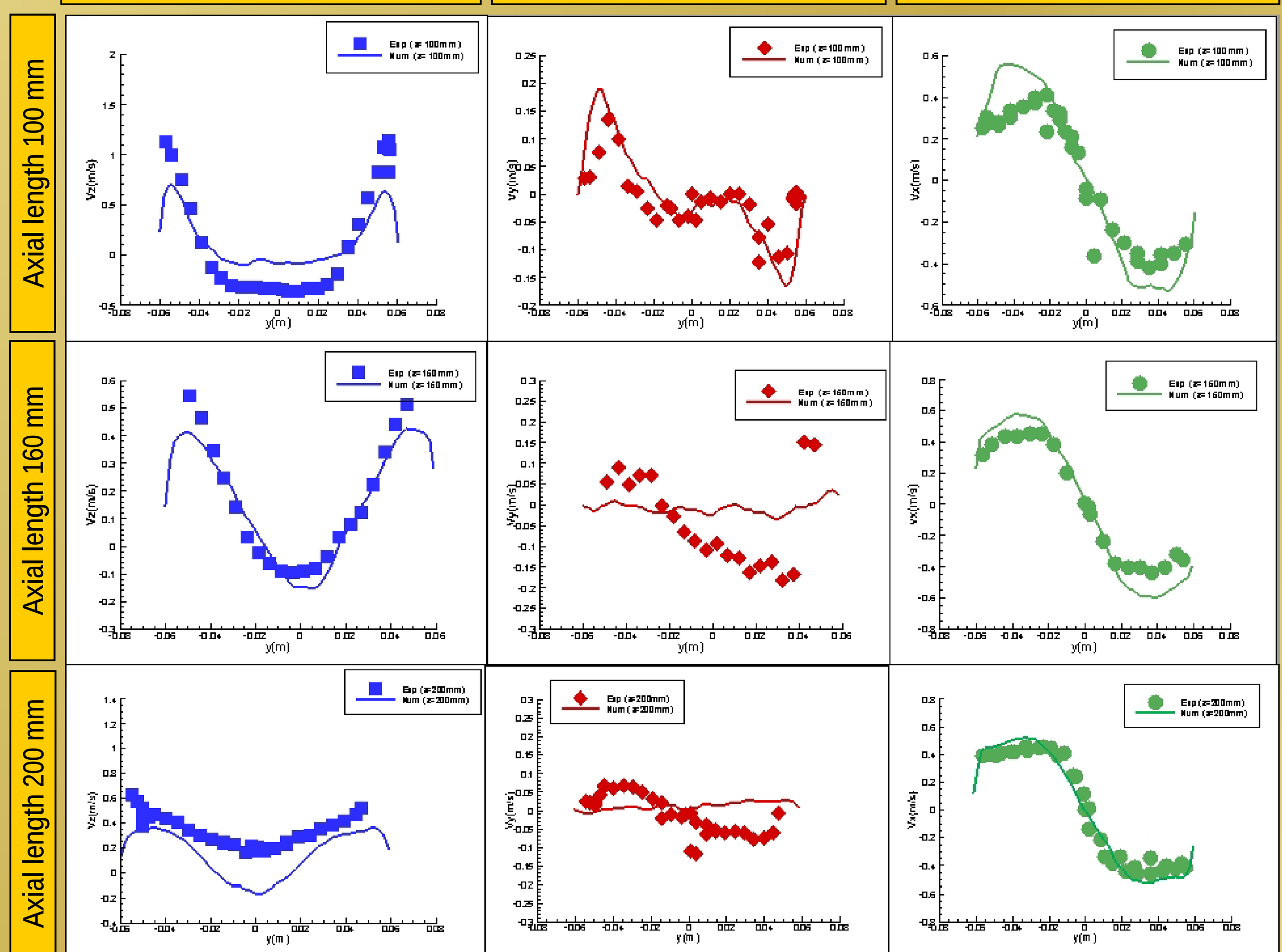
Geometry	3D
Mesh	10 Million Hexahedral cells
Spatial resolution:	test chamber (Δ~d/190) central nozzle (Δ~d/40) annular nozzle (Δ~d/46)
Scheme for velocity	Total Variation Diminishing
P&V coupling	PISO
Solver for pressure	Geometric-Algebraic Multi-Grid
Multigrid	1000 cells In Coarsest Level
Temporal resolution:	10^{-5} s/time step

The scalability performance for non reactive cases provided an optimum of 64 processors.



3 Validation with experimental data for Swirl no. 1

Velocity profiles V[m/s] vs radial length [m] Experimental (symbols) Numerical (solid lines)



The NASA report by Roback and Johnson provides experimental data on different lines of the test chamber for the isothermal case.

4 Large Eddy Simulations (LES)

Prerequisites: $\Delta y^+ = 1$ and van Driest's wall damping function
Space decomposition for minimum transfer of information among processors

Smagorinsky Model

Explicit LES equations are obtained by applying a low-pass filter with width Δ to the Navier Stokes equations.

$$\frac{\partial \rho \bar{u}_i}{\partial t}+\frac{\partial \rho \bar{u}_j \bar{u}_i}{\partial x_j}=-\frac{\partial \bar{p}}{\partial x_i}+\frac{\partial \bar{\sigma}_{ij}}{\partial x_j}+\frac{\partial \bar{\tau}_{ij}^{sgs}}{\partial x_j}$$

The unknown sub-grid stress Tensor is predicted by the Smagorinsky model as a function of the strain tensor $\bar{S}_{ij}$

$$\bar{\tau}_{ij}^{sgs}=2\mu_{sgs}\bar{S}_{ij}$$

With the sub-grid stress viscosity $\mu_{sgs}=\rho(C_s\Delta)^2\sqrt{2\bar{S}_{ij}\bar{S}_{ij}}$

Implicit_LES (ILES)

On ILES models, the filter width Δ is related to the mesh size Δ_i, then no subgrid model is applied. Since the subgrid stress tensor has a dissipative nature, this role is played by the numerical error.
The numerical error is controlled using different kind of limiters and schemes, such a TVD limited looking for good accuracy.

Selective Scale Discretization (SSD)

The separation of the scales is performed using a high-pass filter. The laplacian filter has the expression:

$$u'_i=-\frac{\partial}{\partial x_j}\left(\frac{\Delta_i}{\pi}\right)^2\frac{\partial u_i}{\partial x_j}$$

Two source terms are added on the RHS of the momentum equation as forces

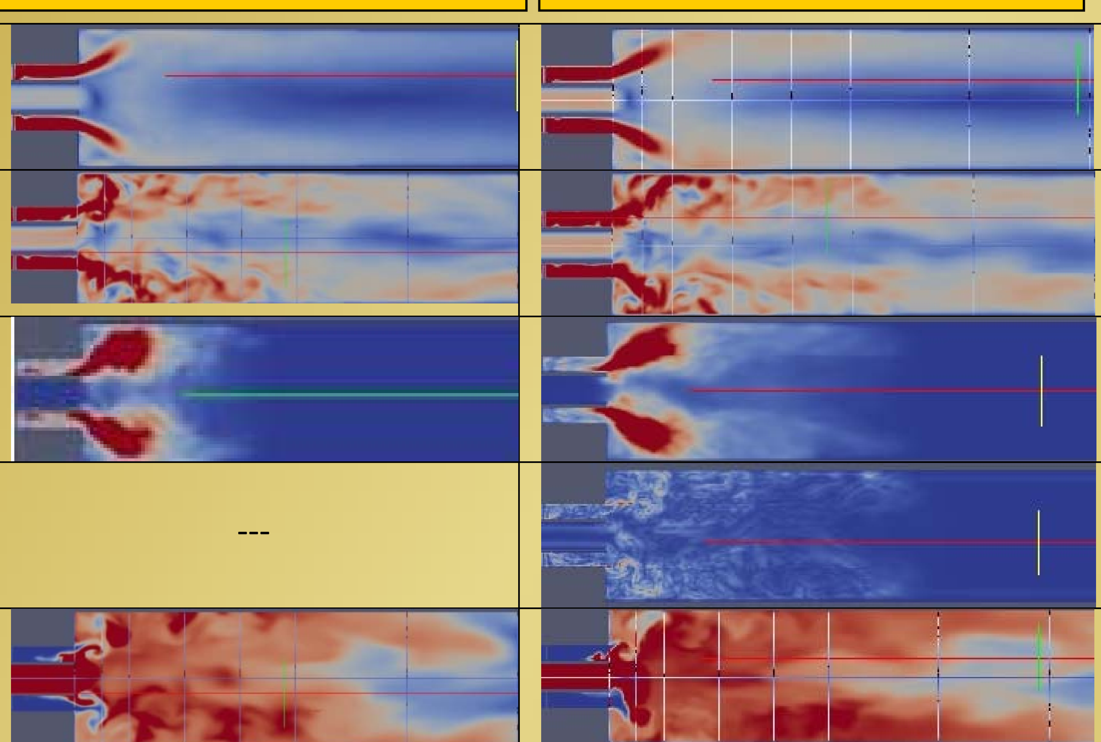
Where the fields u'_{1i} and u'_{2i} are equal. Each term must be solved with different schemes of high and low order.

$$f_{m,i}=-\frac{\partial}{\partial x_j}[u_j u'_{1i}]+\frac{\partial}{\partial x_j}(u_j u'_{2i})$$

5 Non Reactive Flow Pattern

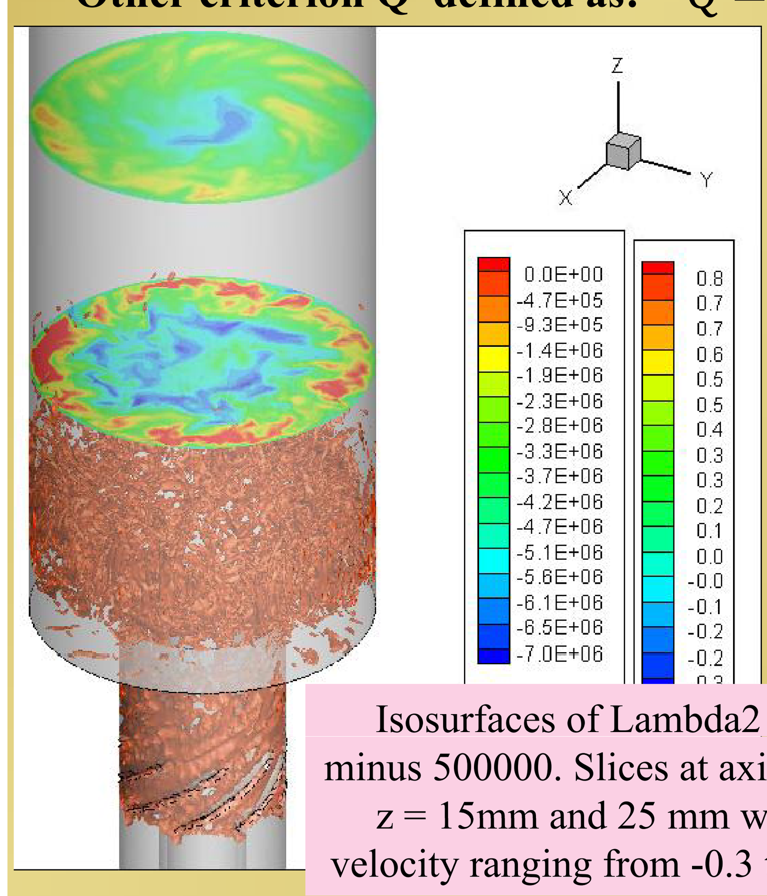
Results for Swirl no. 1

	I-LES	ILES-SSD
UMean		
U		
Uprime2Mean<0.5		
Source of SSD<0.05	---	
Ps		

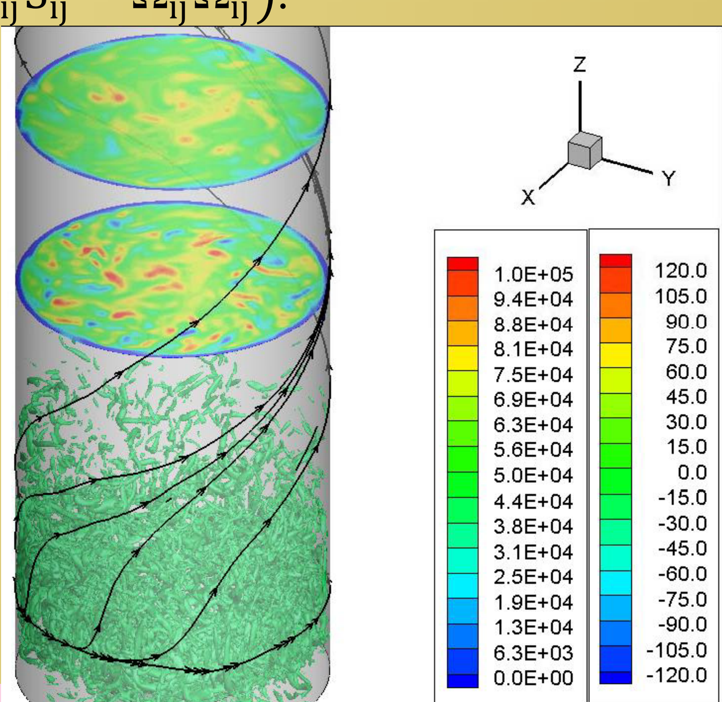


VORTEX KERNELS

Criteria to visualize the vortex kernel may be lambda2 (λ_2) lower than 0 or positive values of Q, both calculated from the strain and rotation tensors
Lambda2 is defined as the intermediate eigenvalue of the tensor $S^2+\Omega^2$
Other criterion Q defined as: $Q=-\frac{1}{2}(S_{ij}S_{ij}-\Omega_{ij}\Omega_{ij})$.



Isosurfaces of Lambda2 equal to minus 500000. Slices at axial positions z = 15mm and 25 mm with axial velocity ranging from -0.3 to 0.8 ms^{-1}.

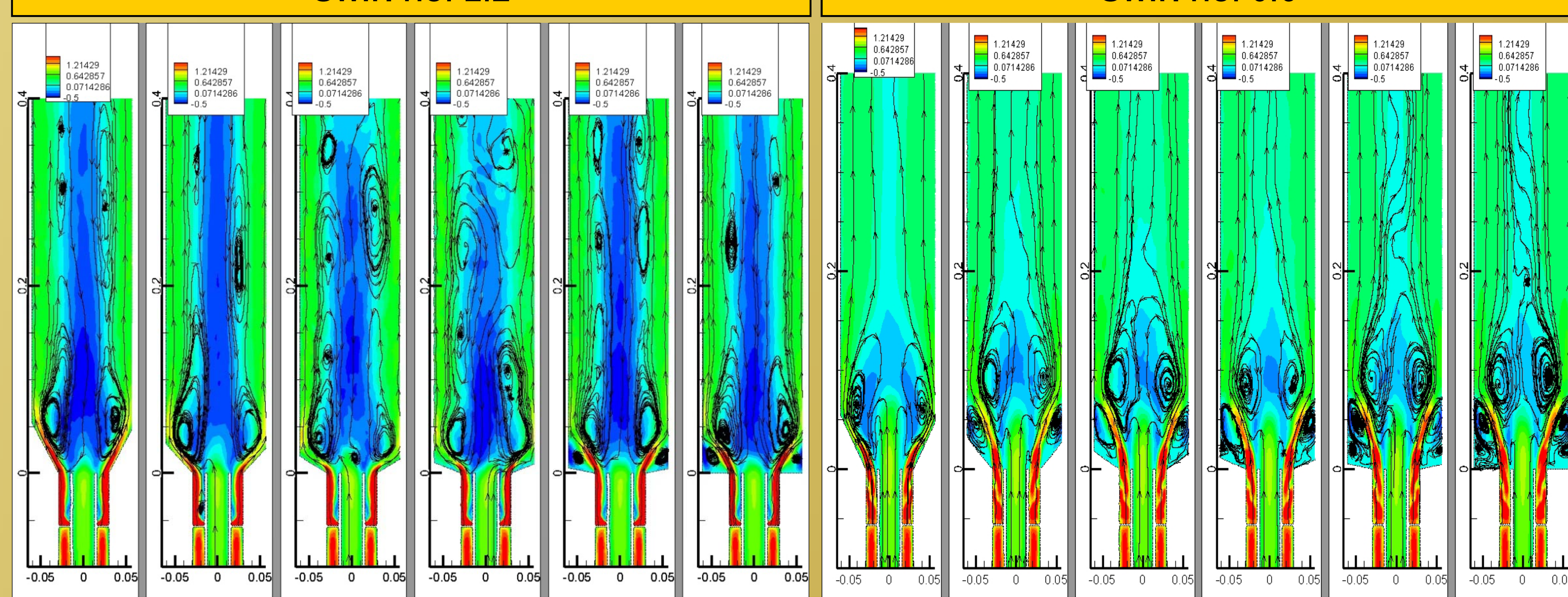


Isosurfaces of Q equal to 30000. Slices at axial positions z = 17.5mm and 25 mm with axial vorticity ranging from -120 to 120 s^{-1}. Peripheral stream lines.

6 Influence of conical diffuser

Averaged Axial Velocity with Diffusers 60º, 90º, 120º, 140º, 160º and no-Dif.

Swirl no. 1.2 | Swirl no. 0.6



Strong swirl numbers produce larger IRZ and smaller ORZ than mild swirls. Diffusers prevent the formation of counter-rotating vortex rings (**Taylor-Couette instabilities**) for mild swirls and the ORZ for strong swirls.

7 Frequency Domain Analysis

Energy spectrum

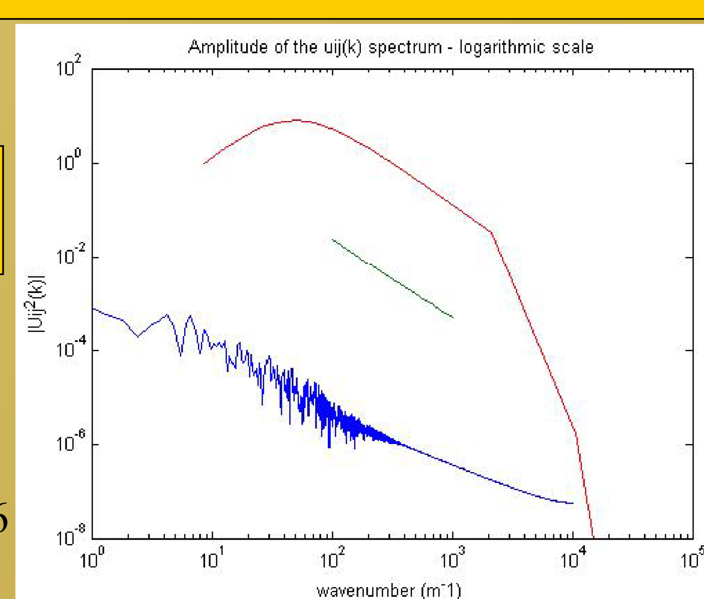
$$E(\kappa)=f_L f_\eta 1.5\,\varepsilon^{2/3}\,\kappa^{-5/3}$$

Taylor's hypothesis of frozen turbulence.

Taylor-scale and turbulence Reynolds no. let identify Kolmogorov scale

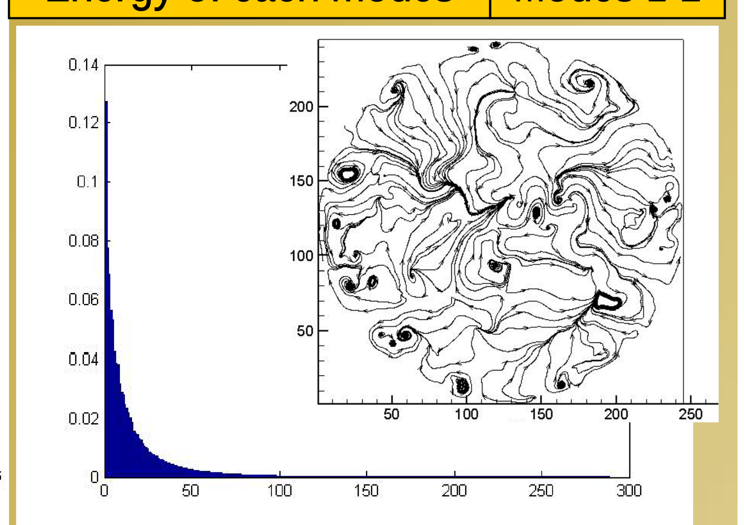
$Re_L = 2400 \Rightarrow Re_\lambda = 126$

$\eta = 0.17$ mm



Proper Orthogonal Decomposition

Energy of each modes | Modes 1-2



Conclusions

- **LES was performed to model the interaction of swirling jets. SSD is a challenging approach to model flows.**
- **Averaged fluid field was validated with experimental results provided by Roback and Johnson.**
- **The analysis on the frequency domain let identify energetic vortex structures using POD.**
- **Strong swirl numbers produce larger IRZ and smaller ORZ than mild swirl numbers.**
- **Diffuser prevents or reduces the ORZ**

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REFERENCES: http://www.researcherid.com/rid/L-9473-2014
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