Flow Structure Investigations in a "Tornado" Combustor

Igor Matveev
***Applied Plasma Technologies*, Falls Church, Virginia, 22046**

Serhiy Serbin
***National University of Shipbuilding*, Mikolayiv, Ukraine, 54025**

Thomas Butcher and Narinder K. Tutu
***Brookhaven National Laboratory*, Upton, L.I., NY, 11973-5000**

4th International Energy Conversion
Engineering Conference and Exhibit

Objectives

- **Improvement of an atmospheric pressure "Tornado" Combustor prototype based on innovative Reverse Vortex approach**
- **Theoretical and experimental investigations of the working processes in the Tornado Combustor under non-reacting conditions:**

  - study the vortex behavior, including the low and high cold air flow rate modes

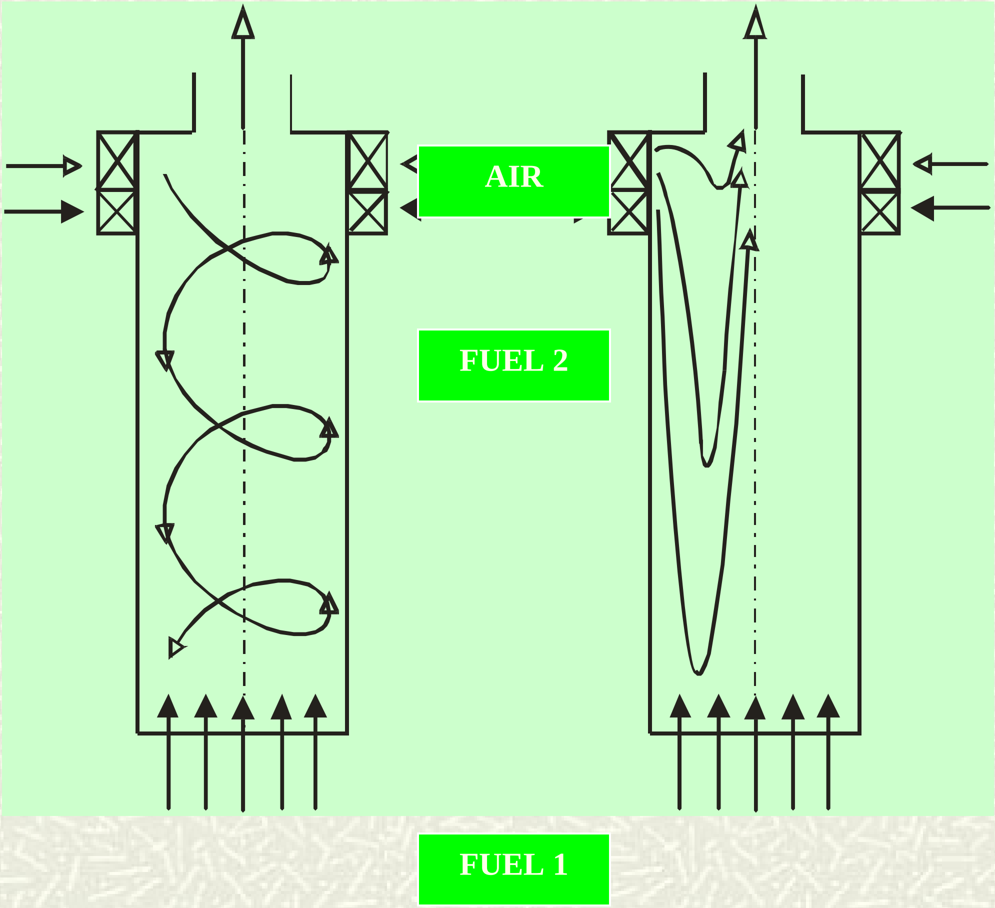
  - measure the mean axial and swirl velocity components and their respective fluctuations using laser Doppler velocimetry system

  - evaluate existing turbulence models (k-ε, RNG k-ε, LES), and select the best ones for precise process description

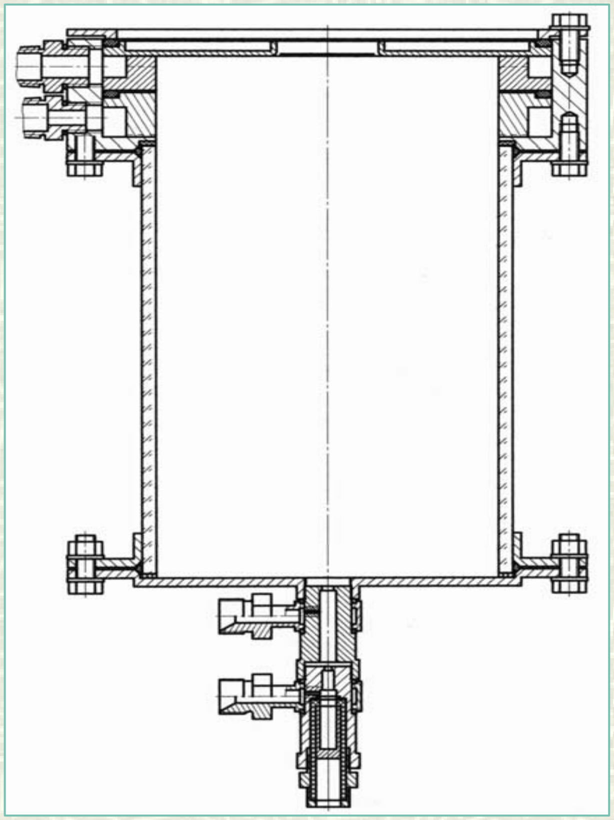
Contents

- **Aerodynamic Scheme and Combustor Design**
- **Mathematical Modeling**
- **Experimental Setup for the LDV Tornado Measurements**
- **CFD Calculations Under Isothermal Non-combusting Conditions**
- **Comparison with Calculated and Measured Data**
- **Conclusions**
- **Future Works**

Aerodynamic Scheme and Combustor Design



Aerodynamic scheme of the reverse vortex flow

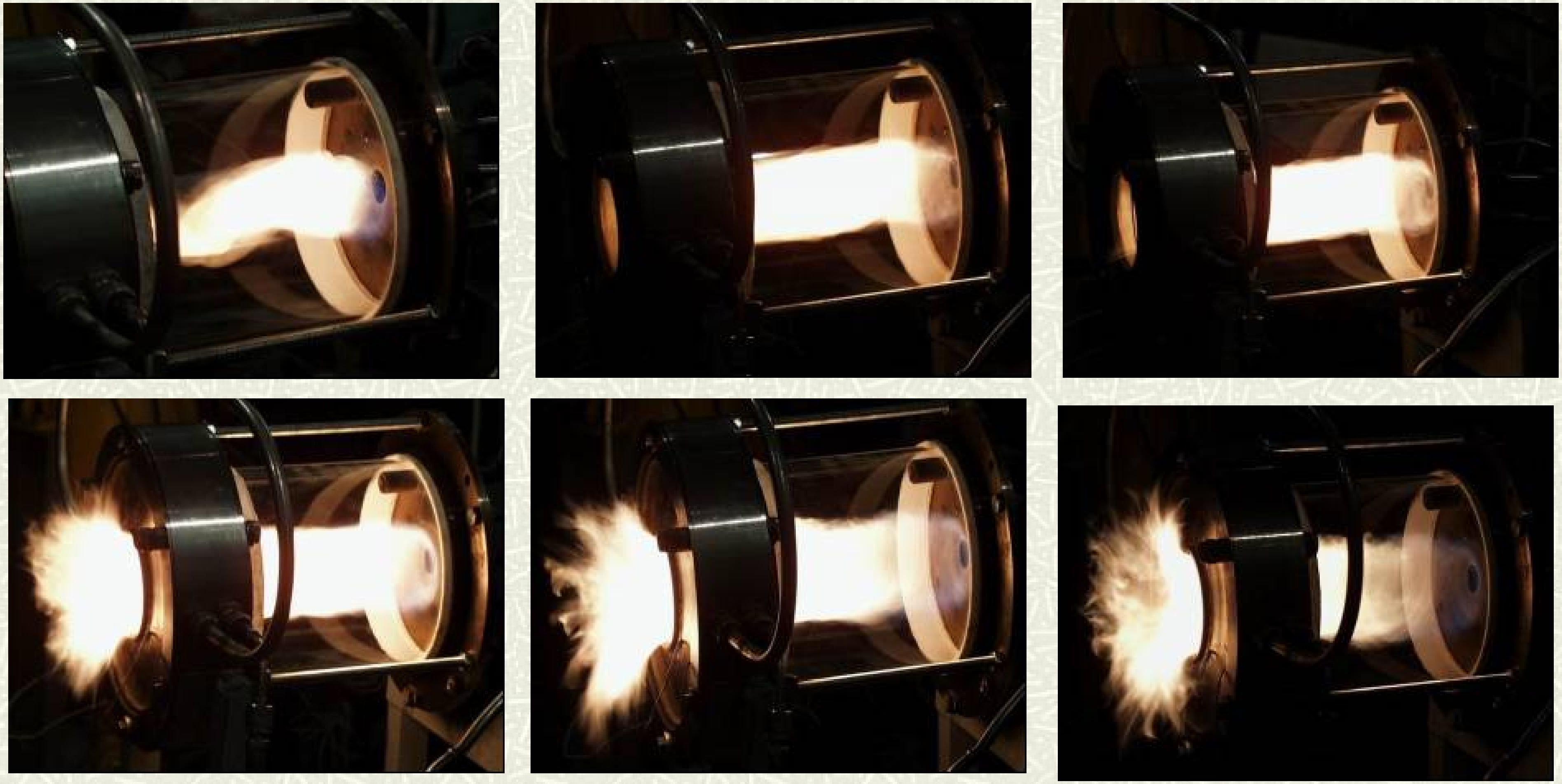


Design of the atmospheric pressure RVC

The main idea of the reverse-vortex stabilization is to direct an outlet of the flame or plasma spatial arc (in future) along the axis to the side of the swirl generator. Initially the cold gas flows along the wall to the closed end of the cylindrical vessel, and turbulent micro-volumes of this cold gas, which lost their kinetic energy near the wall, migrate radially towards the center. As a result, the cold gas comes into the hot zone from all sides, except the outlet side, and no significant recirculation zone is formed.

Preliminary “Tornado” tests

G_a = 17.56 g/s   Central fuel injection (exit nozzle 72 mm)



A complete atmospheric pressure combustor system, ID = 145 mm, internal volume of 4 liters has been designed, manufactured and preliminary tests have been completed on natural gas with air flow up to 20 gram per second. It demonstrated extremely wide range of operation parameters with lean flameouts by 0.03, maximum wall temperature of about 240 °C at the exhaust gases temperature point of about 1400 °C.

Mathematical Modeling

For modeling of physical processes inside the Tornado cold combustor a generalized method has been used, based on numerical solution of the combined conservation and transport equations for turbulent system. The RNG model is more responsive to the effects of rapid strain and streamline curvature than the standard *k*-ε -model.

1. RNG *k*-ε -model

Equation for conservation of mass

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = S_m$$

Equation for conservation of momentum

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot (\tau_{st}) + \rho \vec{g} + \vec{F}$$

Stress tensor

$$\tau_{st} = \mu[(\nabla \vec{v} + \nabla \vec{v}^{T}) - \frac{2}{3} \nabla \cdot \vec{v} I$$

Transport equations for the RNG *k*-ε-model

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}(\alpha_k \mu_{eff} \frac{\partial k}{\partial x_j}) + G_k + G_b - \rho \varepsilon - Y_M + S_k$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j}(\alpha_\varepsilon \mu_{eff} \frac{\partial \varepsilon}{\partial x_j}) + C_{1\varepsilon} \frac{\varepsilon}{k}(G_k + C_{3\varepsilon} G_b) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} - R_\varepsilon + S_\varepsilon$$

Additional term in the ε equation

$$R_\varepsilon = \frac{C_\mu \rho \eta^3 (1 - \eta / \eta_0)}{1 + \beta \eta^3} \frac{\varepsilon^2}{k}$$

Equation for turbulent viscosity

$$d\left(\frac{\rho^2 k}{\sqrt{\varepsilon \mu}}\right) = 1.72 \frac{\hat{v}}{\sqrt{\hat{v}^3 - 1 + C_v}} d\hat{v}$$

Mathematical Modeling

Turbulent flows in “Tornado” combustor are characterized by eddies with a wide range of length and time scales. The largest eddies are typically comparable in size to the characteristic length of the mean flow. The smallest scales are responsible for the dissipation of turbulence kinetic energy. Therefore in some cases for definition of instantaneous velocities inside “Tornado” and its comparison with LDV data the large eddy simulation (LES) model has been used. It is assumed that momentum, mass, energy, and other passive scalars are transported mostly by large eddies. Small eddies are less dependent on the geometry, tend to be more isotropic.

2. LES model

Filtered variable

$$\bar{\phi}(x) = \int_D \phi(x')G(x, x')dx'$$

Filtering the Navier-Stokes equations

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho \bar{u}_i) = 0$$

$$\frac{\partial}{\partial t}(\rho \bar{u}_i) + \frac{\partial}{\partial x_j}(\rho \bar{u}_i \bar{u}_j) = \frac{\partial}{\partial x_j}(\mu \frac{\partial \sigma_{ij}}{\partial x_j}) - \frac{\partial \bar{p}}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j}$$

Stress tensor

$$\sigma_{ij} = [\mu(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i})] - \frac{2}{3}\mu \frac{\partial \bar{u}_l}{\partial x_l}\delta_{ij}$$

Subgrid-scale stress

$$\tau_{ij} - \frac{1}{3}\tau_{kk}\delta_{ij} = -2\mu_t \bar{S}_{ij}$$

Rate-of-strain tensor

$$\bar{S}_{ij} = \frac{1}{2}(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i})$$

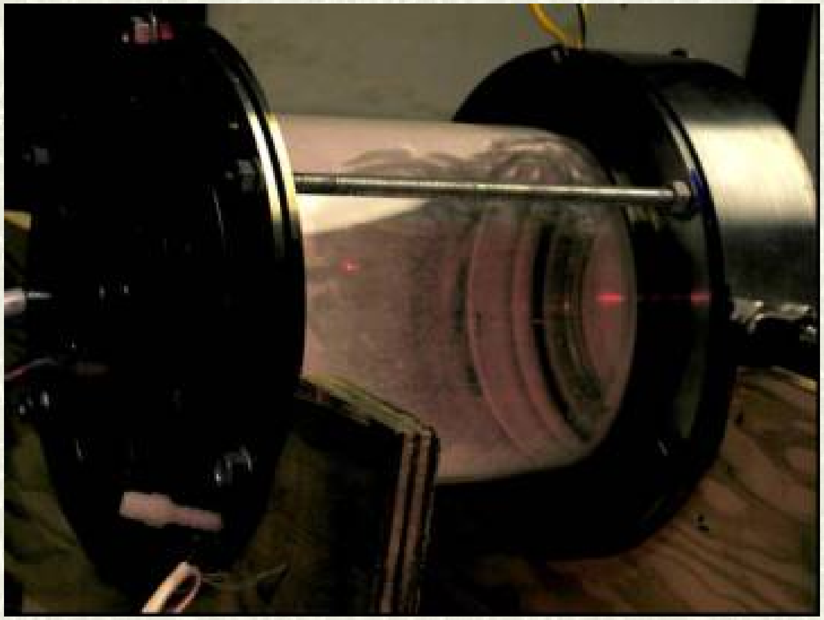
Smagorinsky-Lilly eddy-viscosity

$$\mu_t = \rho L_S^2 |\bar{S}| \qquad |\bar{S}| = \sqrt{2 S_{ij} S_{ij}} \qquad L_S = \min(\mathrm{K}d, C_S V^{1/3})$$

EXPERIMENTAL SET UP FOR THE LDV TORNADO MESUREMENTS

LDV system consists of: Laser, Detector, and Optics Module, and Digital Burst Processor

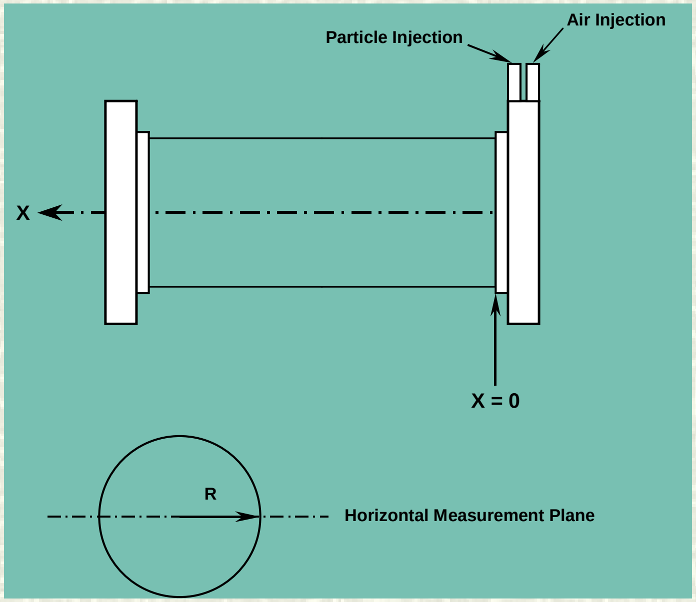
The Tornado Combustor, the LDV probe, the particle generator, and the traversing mechanism



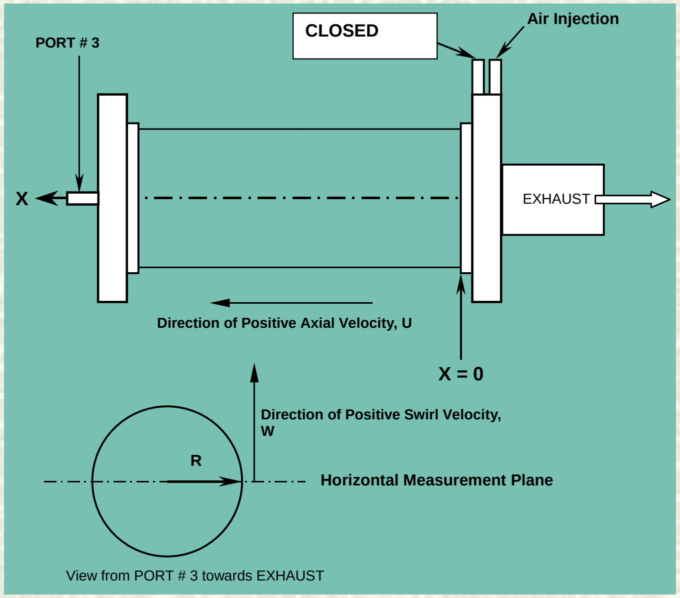
A close-up of the Tornado Combustor with the laser beam ON

The laser has a wavelength of 685 nm and a power of 50 mW (25 mW for each of the two beams). The Burst Processor contains the electronics to process the signals from the LDV probe. It is controlled from a desktop personal computer via proprietary LDV software, and the processed data is transferred to the PC. A 350-mm focal length lens is connected to the front end of the LDV probe. It outputs two laser beams that are 50 mm apart at the exit of the lens. To enable the measurement of the direction of the velocity component, the frequency of one of the beams is shifted by 40 MHz by the Bragg cell in its path. The measurement volume (the location at which the instantaneous velocity is measured) formed by the region of intersection of the two laser beams is an elongated ellipsoid 3.8-mm in length with minor axes of 0.3 mm and 0.1 mm.

EXPERIMENTAL SET UP FOR THE LDV TORNADO MESUREMENTS



Definition sketch for coordinate system at air flow rate 2.15 g/s



Definition sketch for coordinate system at air flow rate 8.1 g/s

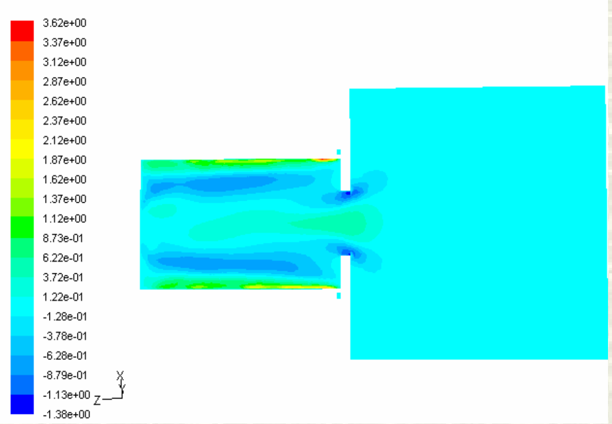
During low-flow LDV measurements air from the blower was injected at the normal "air inlet port". Particles were injected from the "fuel inlet port". The air flow rate through the particle injection port is 17 standard liters per minute for all cases. The static pressure at the air inlet port due to the blower was corresponded to an inlet air flow rate of 2.15 g/s. Even at very low flow rates, a vortex flow inside the quartz chamber has been observed. In this geometry a flow rate of less than 1 cfm seems to be enough to establish a vortex flow.

During high-flow LDV measurements air from the blower was injected at the normal "air inlet port". Particles were injected from the "fuel inlet port # 3". The air flow rate through the particle injection port is 16 standard liters per minute for all cases. The static pressure at the air inlet port due to the blower was corresponded to an inlet air flow rate of 8.1 g/s.

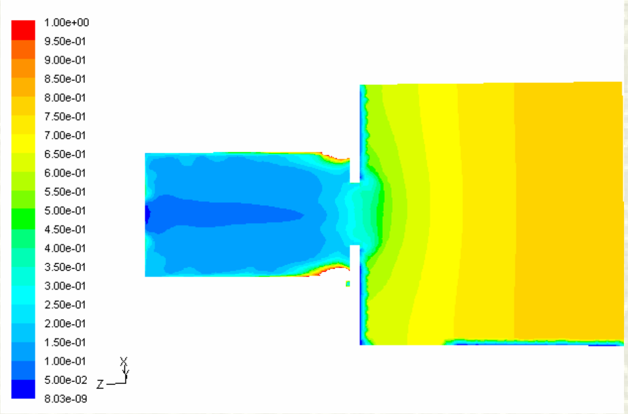
RVC Calculations Under Isothermal Non-conbusting Conditions

Air flow rate 2.15 g/s

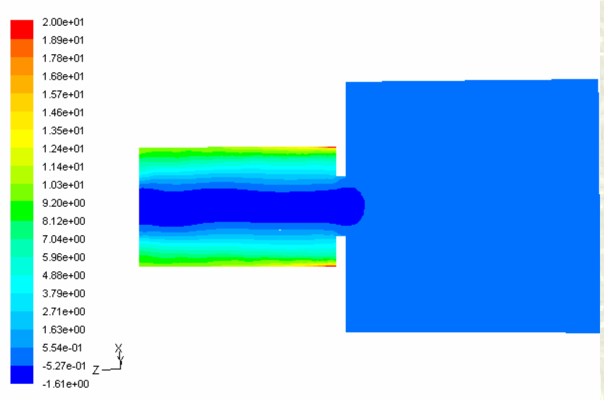
RNG k-ε turbulence model, segregated solver, steady formulation, SIMPLE method for pressure-velocity coupling, second order upwind discretization scheme for density, momentum, turbulence parameters, energy, the 3-D grid including 570988 cells



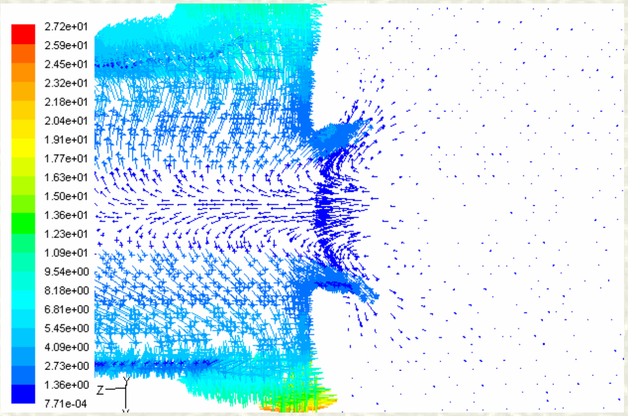
Contours of mean axial velocity, m/s



Contours of turbulence kinetic energy, m^2/s^2



Contours of static pressure, Pa

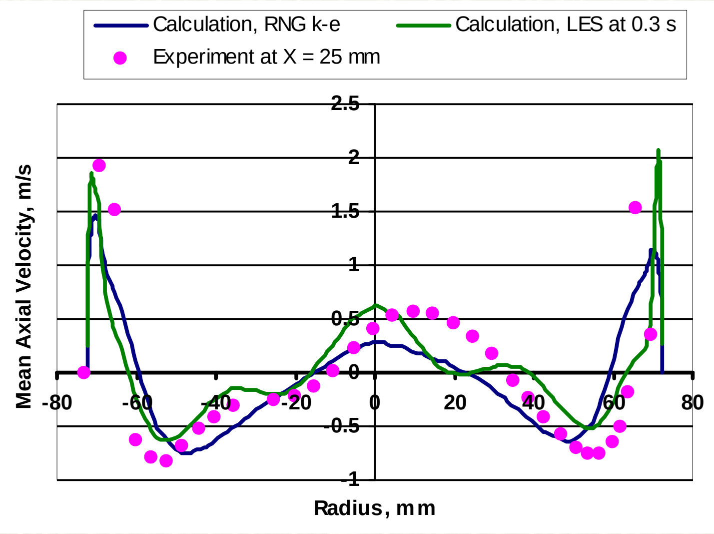


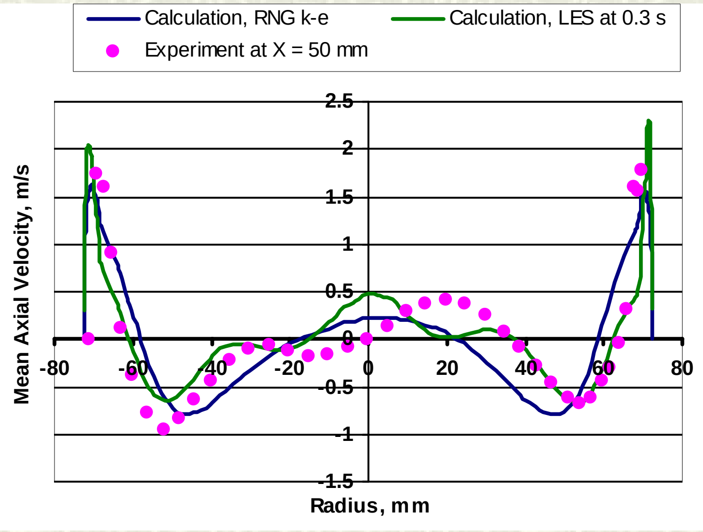
Velocity vectors, m/s

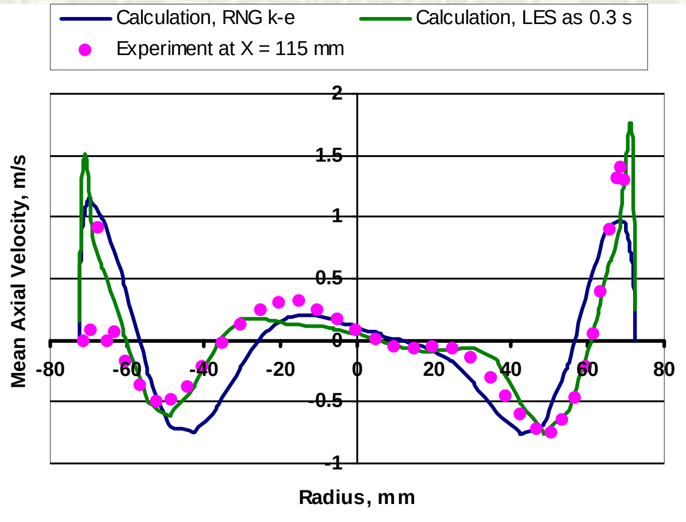
It is obvious that the presence of a vortex system inside the "Tornado" combustor causes the recirculating flow at the nozzle exit region. The velocity contours at the chamber exit are extremely non uniform thereby causing large shears in air flow

Mean axial velocity at distance X = 25, 50, 115 mm and calculated values

Air flow rate 2.15 g/s



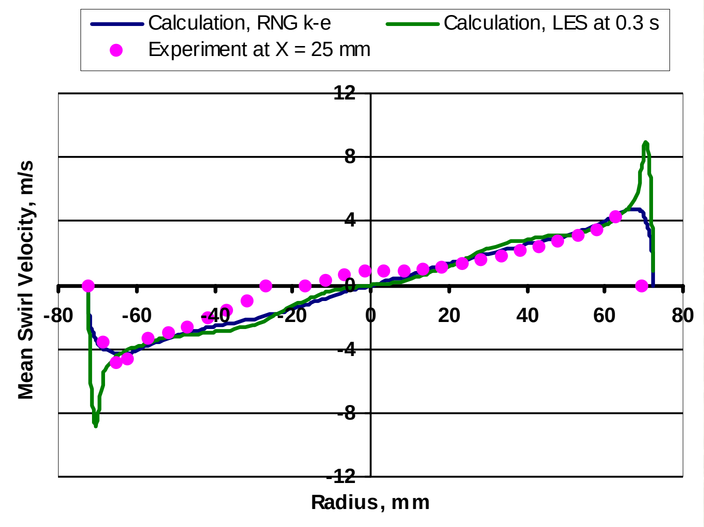


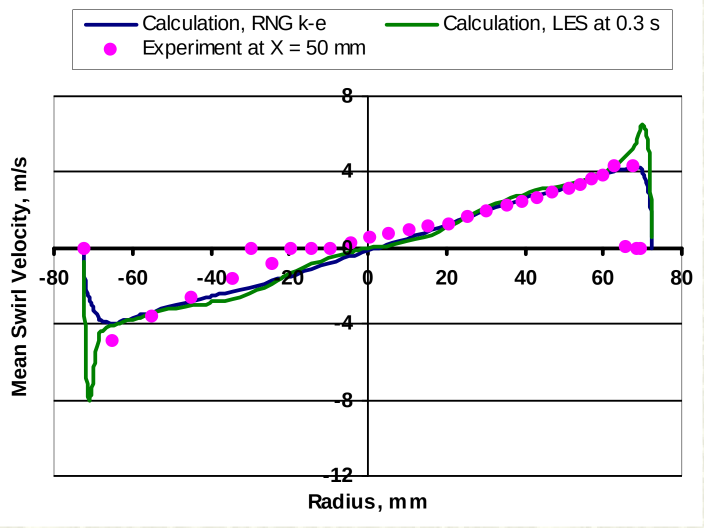


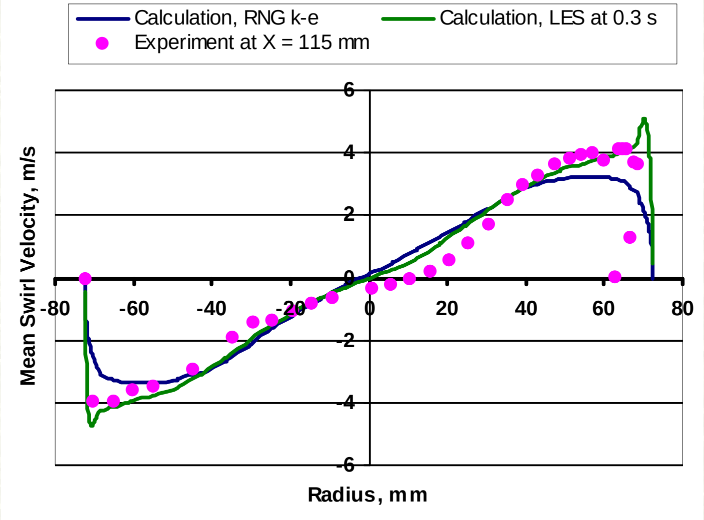
Using both the steady RNG *k*-ε-model and transient LES calculations gives good quantitative conformity with experimental data.

Mean swirl velocity at distance X = 25, 50, 115 mm and calculated values

Air flow rate 2.15 g/s





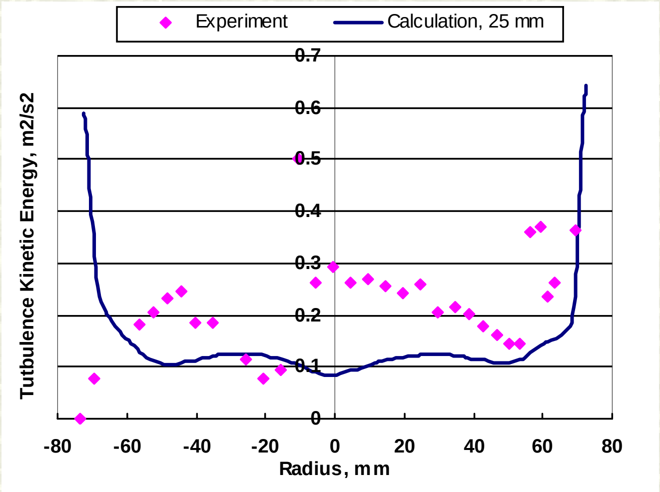


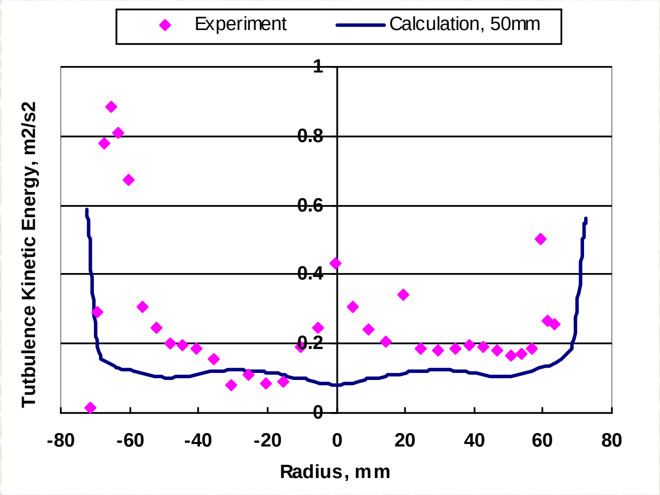
Note, that for Large Eddy Simulation we used: Smagorinsky-Lilly dynamic model, discretization: density – second order upwind, momentum – bounded central differencing, energy – second order upwind, and pressure-velocity coupling – SIMPLEC.

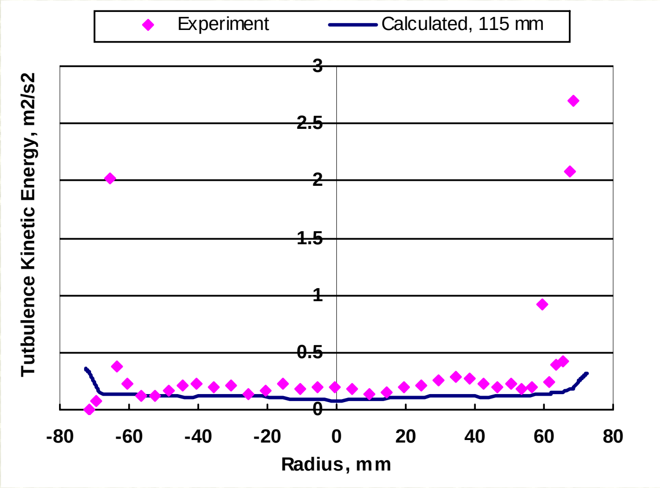
Turbulence Kinetic Energy at distance X = 25, 50, 115 mm and calculated (RNG k-ε-model) values

Air flow rate 2.15 g/s

$k = 0.5 \cdot (u'^2 + v'^2 + w'^2)$ $v' \approx 0.5 \cdot (u' + w')$





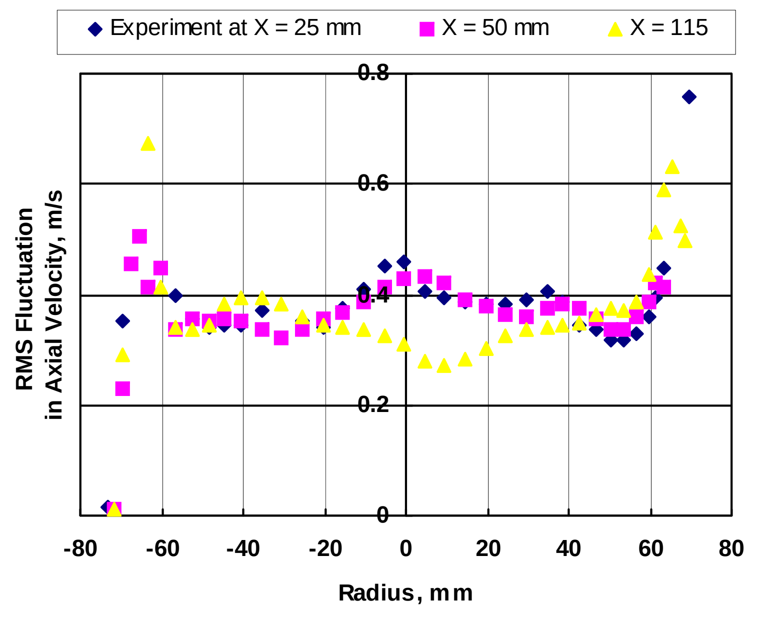


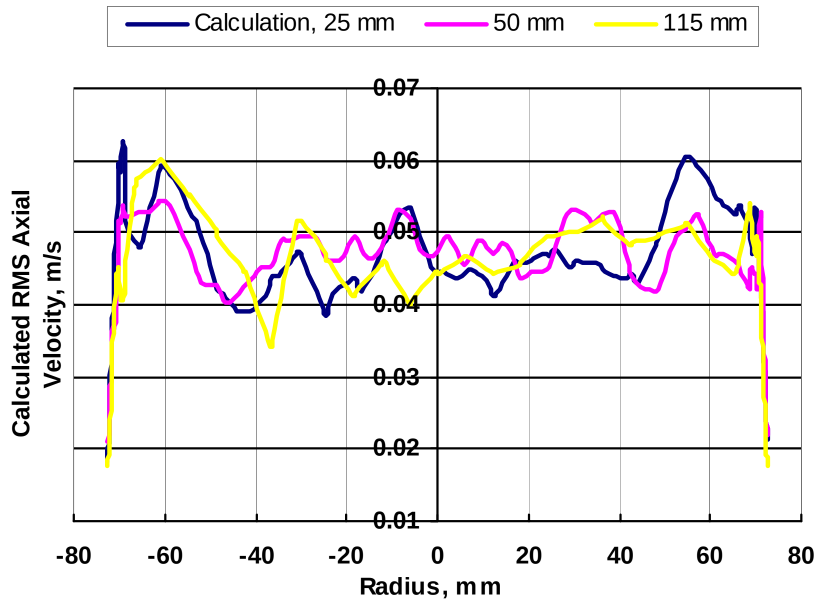
Since the vortex centerline is oscillating radially at the low flow rate of 2.15 g/s (as inferred from the LDV experimental data), this will contribute to larger velocity fluctuations as compared to the case in which the vortex axis is stable. Since for the CFD case the vortex centerline is fixed at radius *r* = 0, one would expect the measured *k* to be higher than the steady state *k* predicted by CFD. This fact agrees with data on this slide, where comparison between experimental and calculated turbulence kinetic energy profiles is illustrated.

Turbulent Axial Velocity Component Fluctuations at Distance X = 25, 50, 115 mm and calculated Root Mean Square values

RNG k-ε- turbulence model, **unsteady segregated solver with 2nd-order implicit formulation, second order upwind discretization for density, momentum, turbulence parameters, energy, and also SIMPLEC pressure-velocity coupling**

Air flow rate 2.15 g/s

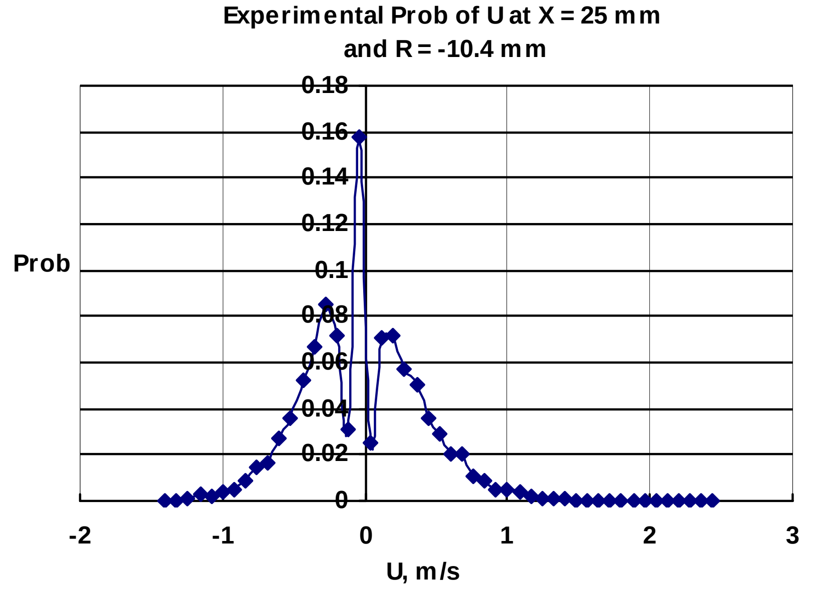


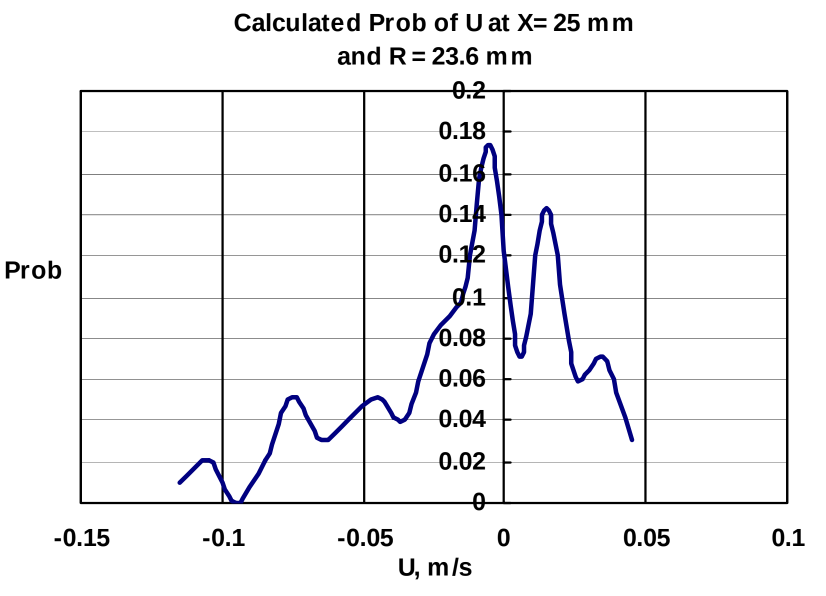


Mean experimental RSM value is near 0.4 m/s, while calculated (using unsteady RNG k-ε model) is 0.045 m/s.

Turbulent Axial Velocity Component Fluctuations at Distance X = 25 mm

Air flow rate 2.15 g/s





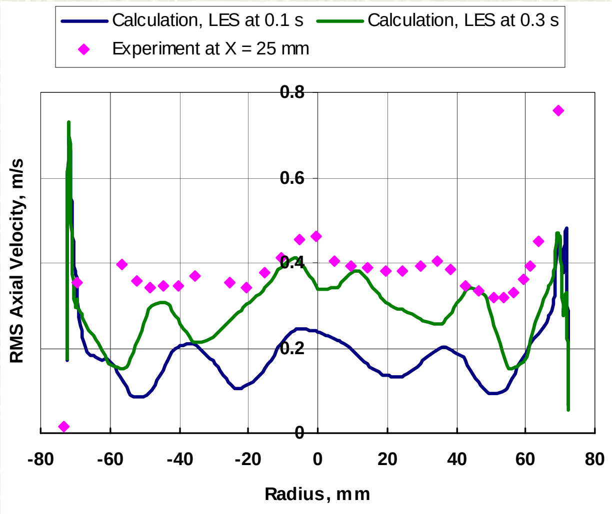
Measured Time Period = 300.0 s

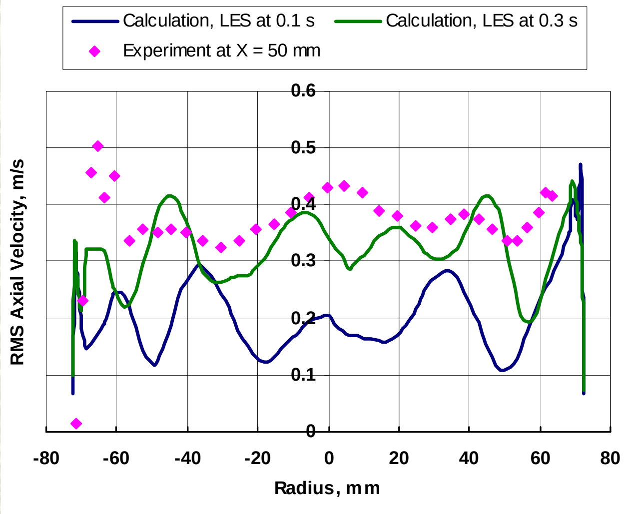
Calculated Time Period = 0.01 s

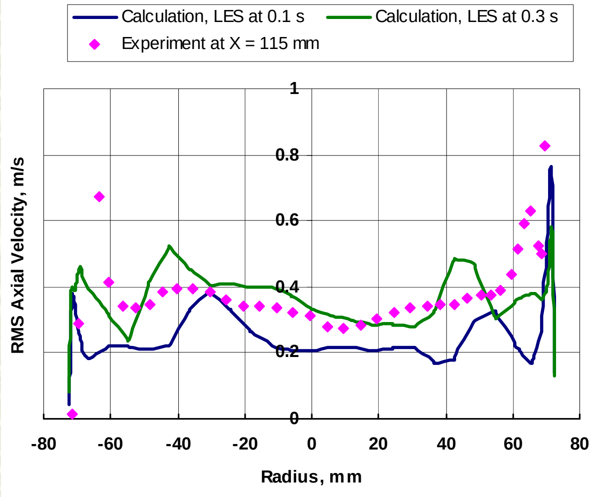
Turbulent Velocity Components Fluctuations at Distance X = 25, 50, 115 mm and calculated Root Mean Square values

Large Eddy Simulation: **Smagorinsky-Lilly Dynamic model; Discretization: Density – Second Order Upwind; Momemtum – Bounded Central Differencing; Energy - Second Order Upwind; Pressure-Velocity Coupling – SIMPLEC**

Air flow rate 2.15 g/s   Calculated Time Period = 0.1 and 0.3 s



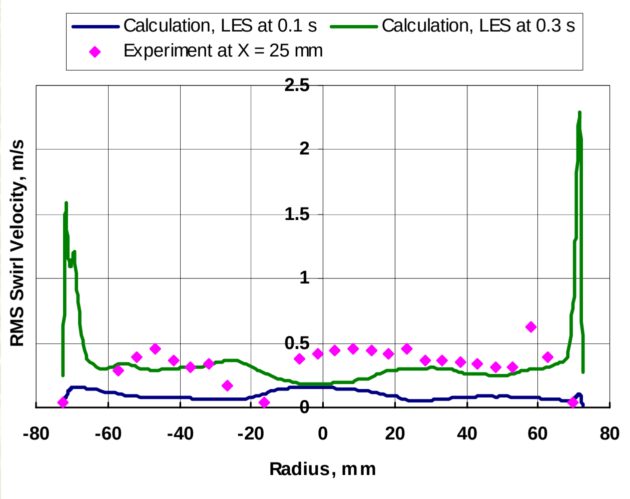


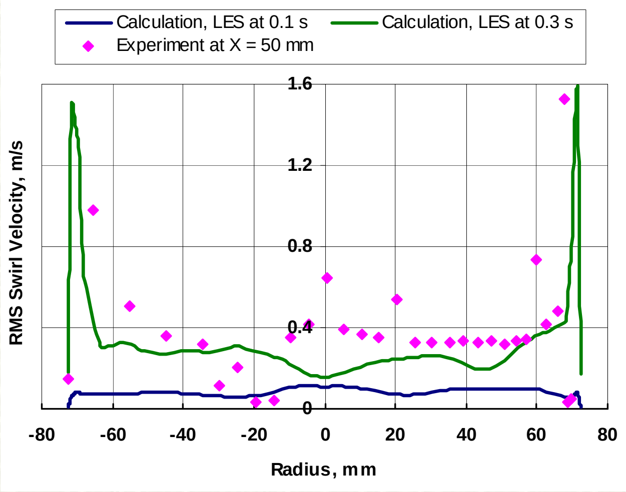


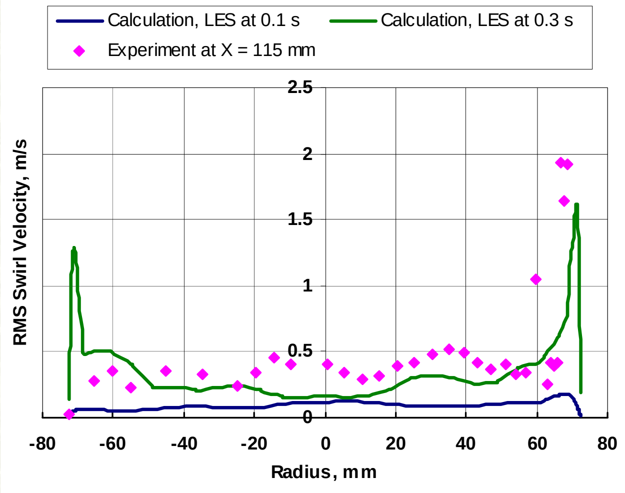
LES provides the approach in which large eddies are explicitly computed in a time-dependent simulation using the "filtered" Navier-Stokes equations. Therefore only larger eddies need be resolved. Statistics of the time-varying flow fields such as time-averages and RMS values of the velocity components can be collected during the transient simulation. Note, that the use of dynamic Smagorinsky-Lilly model assumes local equilibrium of sub-grid scales, scale similarity between the smallest resolved scales and the sub-grid scales.

Turbulent Velocity Components Fluctuations at Distance X = 25, 50, 115 mm and calculated Root Mean Square values

Air flow rate 2.15 g/s   Calculated Time Period = 0.1 and 0.3 s



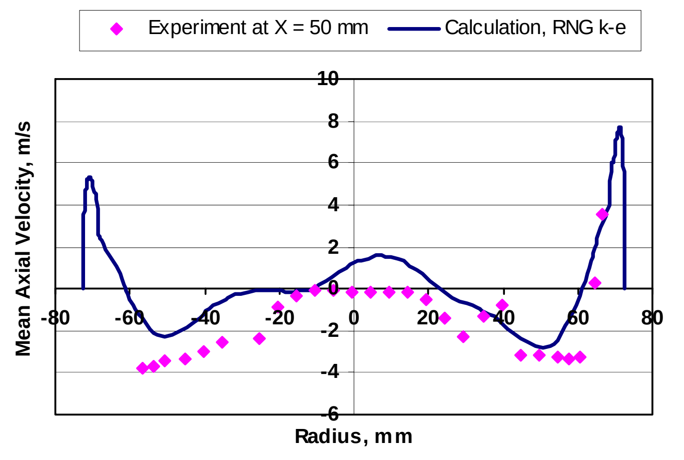


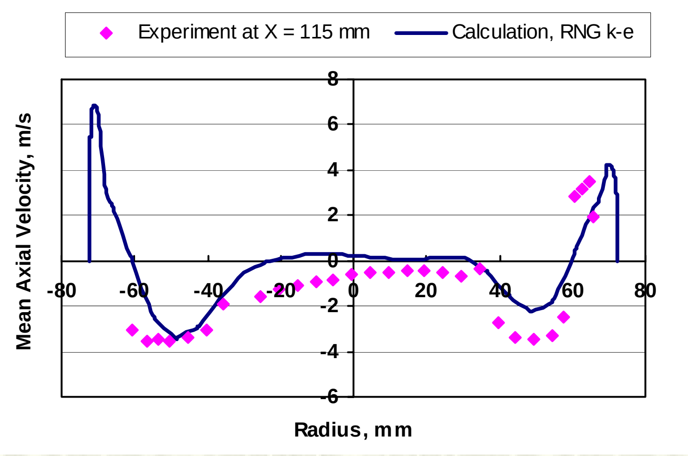


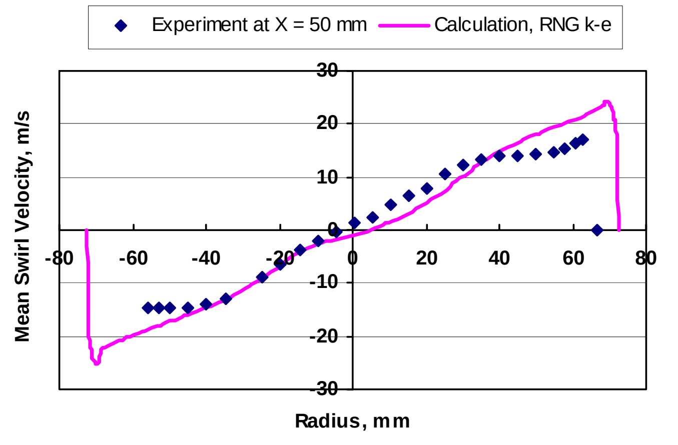
If *r* is the combustor chamber radius (*r* = 72.5 mm), W_{max} is the peak mean swirl velocity slightly away from the wall, and *t* is the time a fluid particle will take for one revolution. For air flow rate of 2.15 g/s, W_{max} is around 4 m/s and. This gives approximately *t* = 0.11 seconds. Therefore CFD LES simulation time of 0.3 seconds corresponds to about 3 revolutions of the vortex, and 0.1 second corresponds to less than 1 revolution of the air vortex. This explains why the results for the RMS axial and swirl velocity fluctuations for 0.3 seconds-calculation period are so much better than that for the calculation period of 0.1seconds.

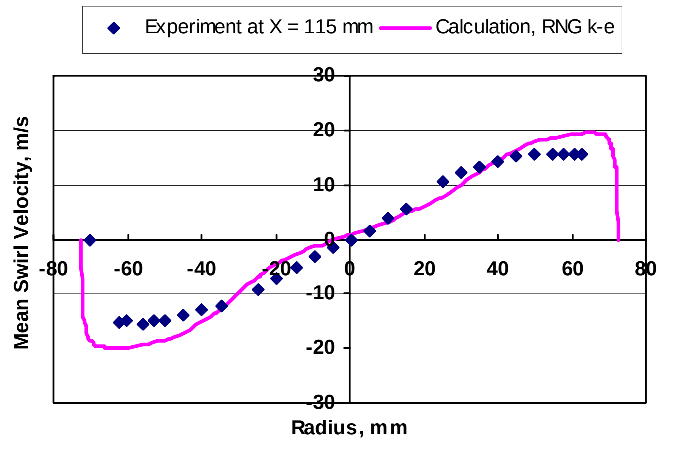
Mean axial and swirl velocities at distance X = 50 and 115 mm and calculated values

Air flow rate 8.1 g/s





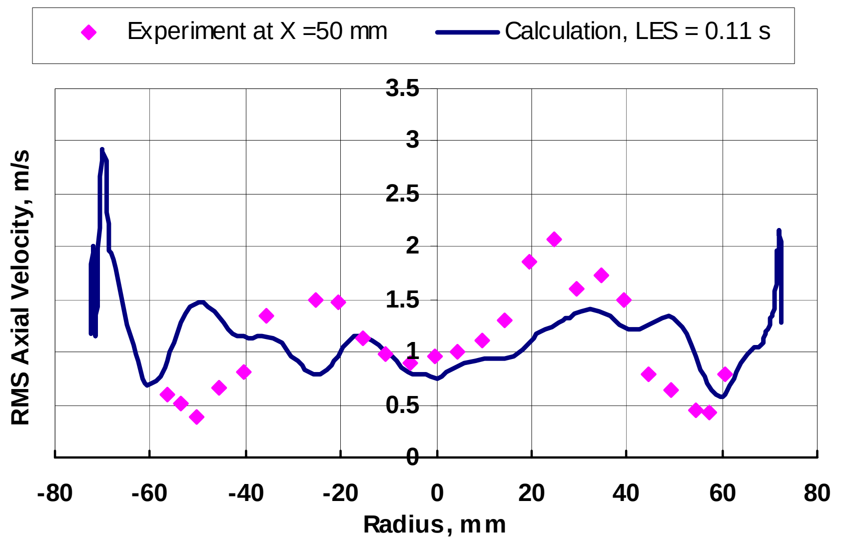


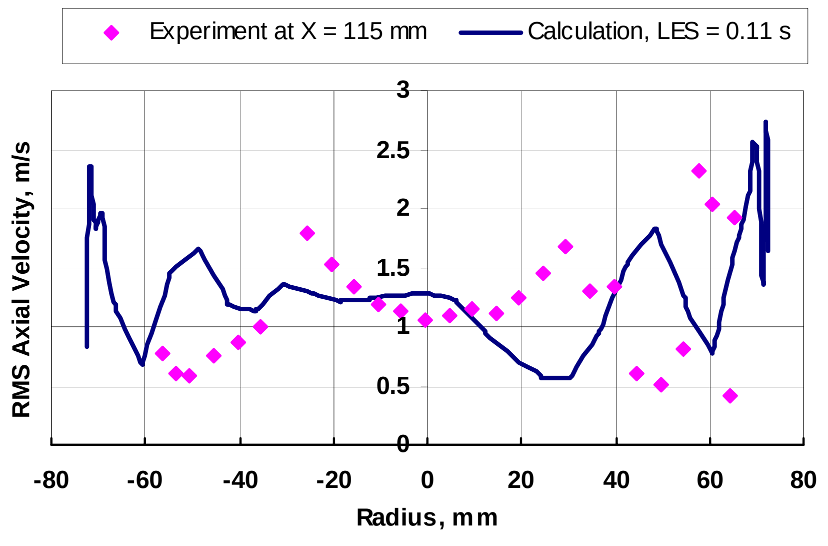


CFD calculations give more extensive inverse flow at paraxial exit nozzle area in comparison with experiment.
As shown by the swirl velocity component distributions for the high flow rate case the central air vortex is better defined.

Turbulent Velocity Components Fluctuations at Distance X = 50, 115 mm and calculated Root Mean Square values

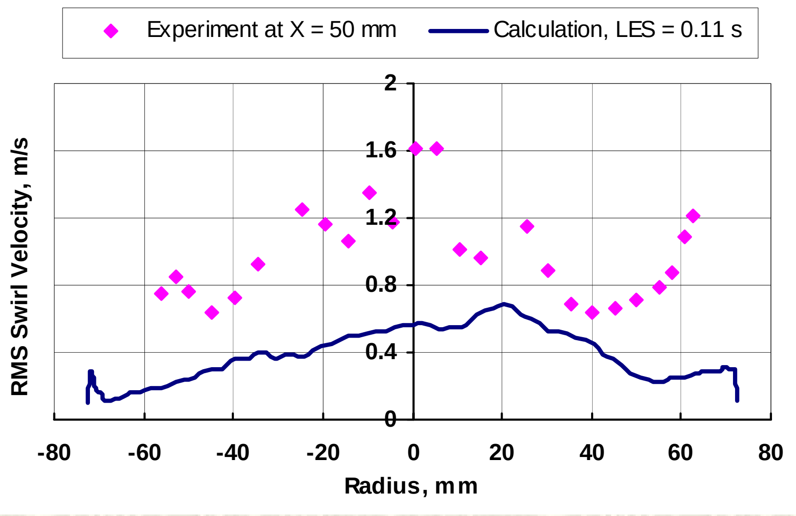
Air flow rate 8.1 g/s **Calculated Time Period = 0.11**

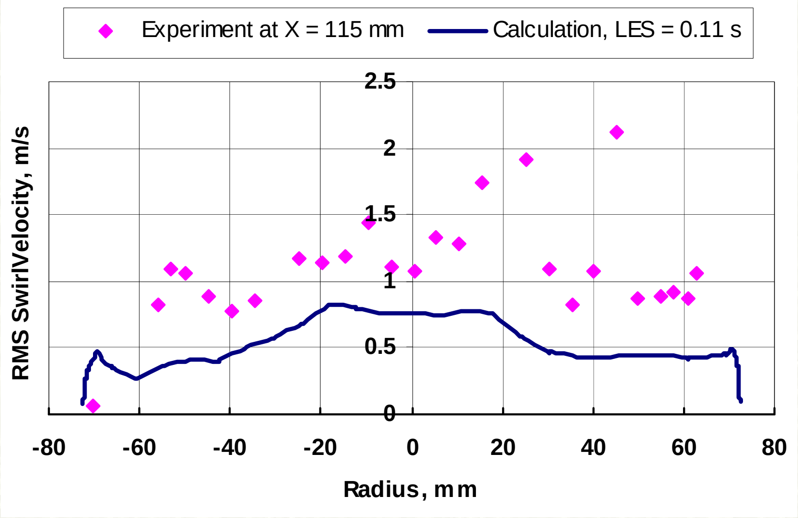




Turbulent Velocity Components Fluctuations at Distance X = 50, 115 mm and calculated Root Mean Square values

Air flow rate 8.1 g/s **Calculated Time Period = 0.11**

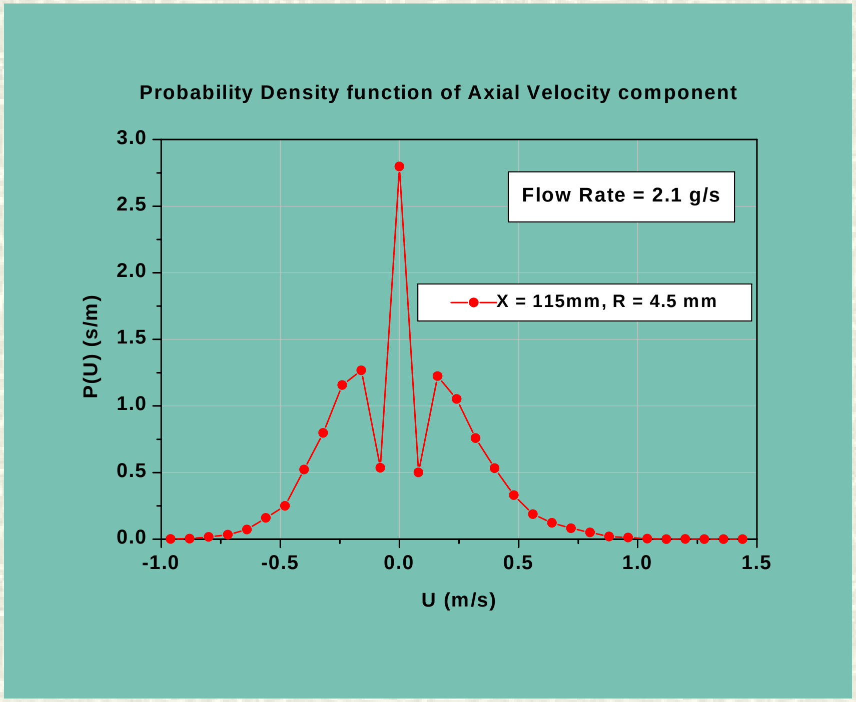




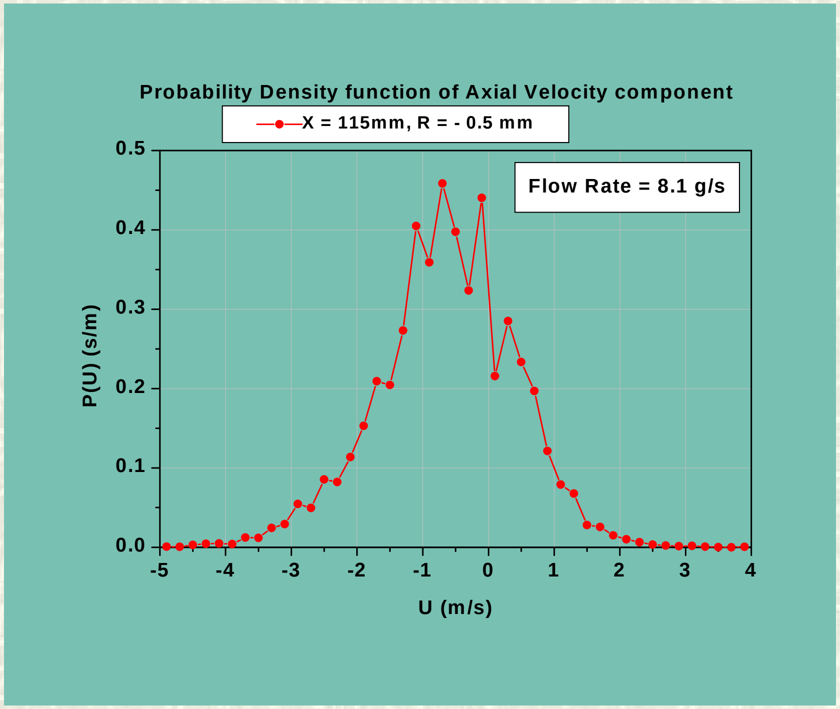
Experimental and calculated RMS velocities are shown in this slide. The measured and predicted values are of the same order of magnitude. This is a measure of the qualitative reliability of the mathematical turbulence model for the “Tornado” Combustor.

Probability Density Function (PDF) of the Instantaneous Axial Velocity Component

P(U)dU* is the probability that the instantaneous axial velocity component lies between *U* and *U + dU



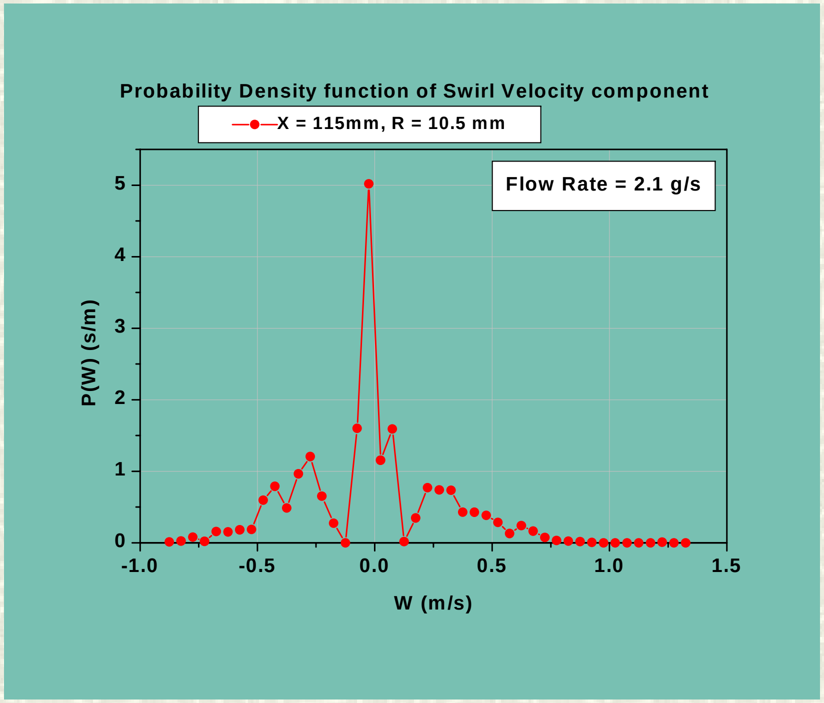
PDF of the Instantaneous Axial velocity Component near the centerline at X = 115 mm for the Low Flow Rate Case

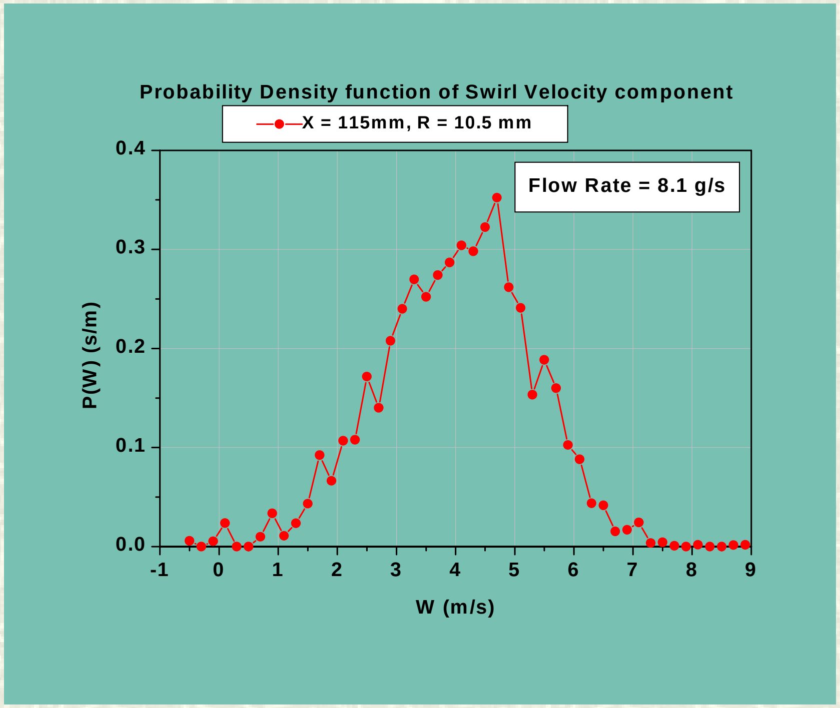


PDF of the Instantaneous Axial Velocity Component near the centerline at X = 115 mm for the High Flow Rate Case

Probability Density Function (PDF) of the Instantaneous Swirl Velocity Component

P(W)dW **is the probability that the instantaneous swirl velocity component lies between *W* and *W + dW***





PDF of the Instantaneous Swirl Velocity Component near the centerline at X = 115 mm for the Low Flow Rate Case

PDF of the Instantaneous Swirl Velocity Component near the centerline at X = 115mm for the High Flow Rate Case

These slides show very different character of axial and swirl velocities fluctuations near the centerline at low and high air flow conditions. At low flow conditions the PDFs are trimodal indicating that the vortex centerline is fluctuating radially.

Summary

- A laser Doppler velocimetry system was used to measure the mean axial and swirl velocity components and their respective fluctuations in the "Tornado" combustor under cold, non-reacting, isothermal conditions
- Experimental and theoretical investigations demonstrating the modeling opportunity for the complex aerodynamic flows without chemical reactions in the “Tornado” combustor have been conducted
- Comparison between experimental data and computed predictions using different turbulence models has been completed
- This exercise has revealed the weak sides of the existing turbulence models and has also shown the main directions for improving the mathematical model

Future Works

- **Complete laser diagnostics of the reverse vortex flows in a “Tornado” Combustor for hot conditions**
- **Improve turbulence model to increase the simulation accuracy**
- **Optimize the combustor geometric and mode parameters**
- **Combine “Tornado” Combustor with Plasma Assisted Combustion System**
- **Conduct comprehensive validation tests of the improved “Tornado” Combustor with Plasma Assisted Combustion System**

Acknowledgments

The authors would like to acknowledge Dr. Alexander Gutsol from Drexel University for his introduction into the reverse vortex flow investigations and Anna Mostipanenko from National University of Shipbuilding, Ukraine, for her mesh preparation and CFD calculations