

**2006 UTSR Industrial Internship Program**

**06/04/2006 – 08/25/2006**

**CFD Study in Air-Fuel Premixer Design  
for Gas Turbine Injector of  
A Rich-Catalytic Lean-burn (RCL®) Combustor**

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# Project Goals in Support of Air-Fuel Premixer Design of RCL Combustor

- (1) Contours of Mass fraction of Fuel ( $\text{CH}_4$ ) at the outlet
- (2) Contours of Mass fraction of Fuel ( $\text{CH}_4$ )
- (3) Contours of Velocity
- (4) Velocity Vector
- (5) Contours of Static Temperature
- (6) Contours of Turbulent Kinetic Energy
- (7) The Unmixedness Calculated by Mass Fraction of Fuel ( $\text{CH}_4$ ) and Mass Fraction of Air

# Methodology

## Three Turbulent Fluid Models

- **Standard K-Epsilon (SKE) Model Solution**
- **Re-Normalization Group K-Epsilon (RNG KE) Model Solution**
- **Reynolds Stress Model (RSM) Solution**

# Methodology

## Description of Three Turbulent Fluid Models

### → **Standard K-Epsilon Model (SKE)**

- **Isotropic structure** of the turbulent flow field (**Eddy-viscosity Models**)

### → **Re-Normalization Group K-Epsilon Model (RNG KE)**

- Highly strained flows, prediction of swirling flows, low Re flows
- Complex shear flows involving
  - ♣ Rapid strain, Moderate swirl, Vortices
  - ♣ Locally transitional flows: Boundary layer separation, Massive separation, Vortex-shedding
- Moderately complex behavior like jet impingement, separating flows, secondary flows
- **Isotropic** eddy viscosity assumption

### → **Reynolds Stress Model (RSM)**

- Free shear flows with strong **anisotropy**, like a strong swirl component
- Flows in rotating fluids, flows over curved surfaces, flow with severe pressure gradient
- Flows with sudden changes in the mean strain rate
- Flows where the strain fields are complex
- Flows with strong streamline curvature
- Secondary flow, Flows with boundary layer separation
- Buoyant flow

## Methodology

### Outline of Results for Premixer

For the **non-reacting flow**

- Standard K-Epsilon (SKE)
- RNG K-Epsilon (RNG KE)
- Reynolds Stress Model (RSM)

# Operating Conditions

## Given INLET Operating Conditions:

- Pressure = 4 atmospheres

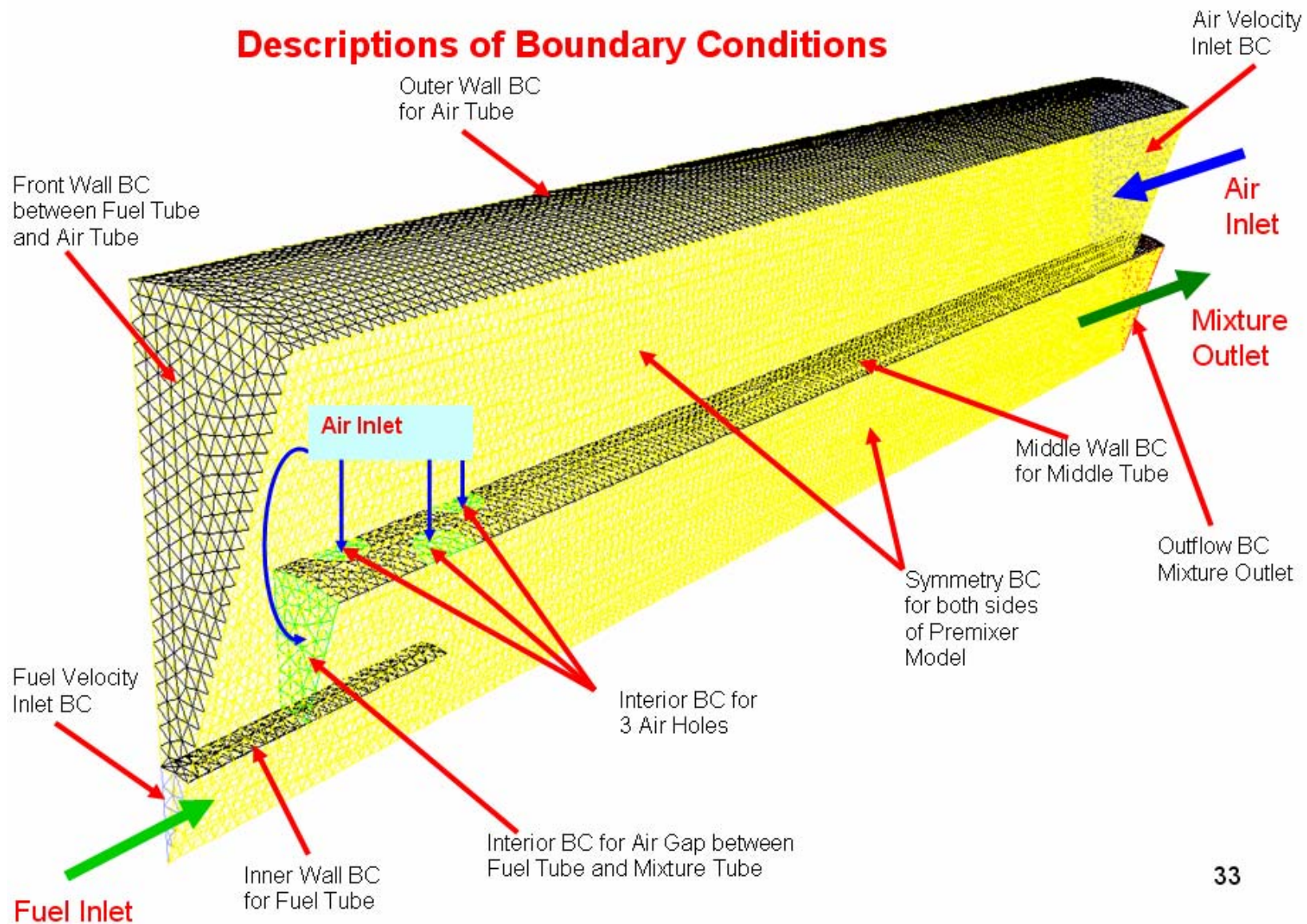
## Given INLET Boundary Conditions of Fuel CH<sub>4</sub>:

- Fuel Temperature = 25 C

## Given INLET Boundary Conditions of Air:

- Air Temperature = 578 C

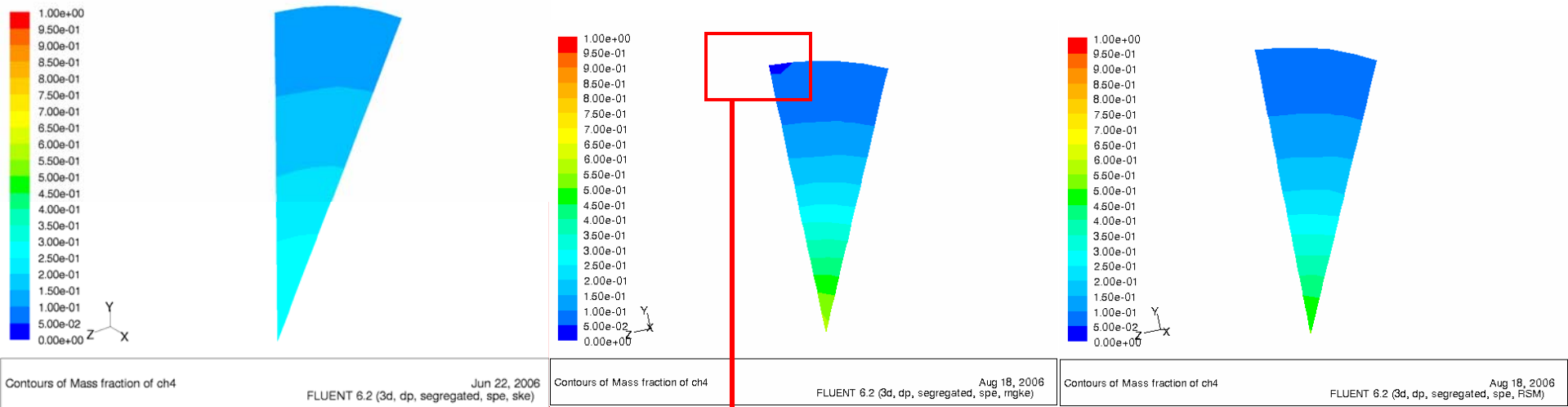
# Descriptions of Boundary Conditions (B.C.)



## **Results for Premixer – With Non-Reacting Flow**

- Standard K-Epsilon (SKE)**
- RNG K-Epsilon (RNG KE)**
- Reynolds Stress Model (RSM)**

# (1) Contours of Mass fraction of CH4 at the outlet (Non-reacting Flow)

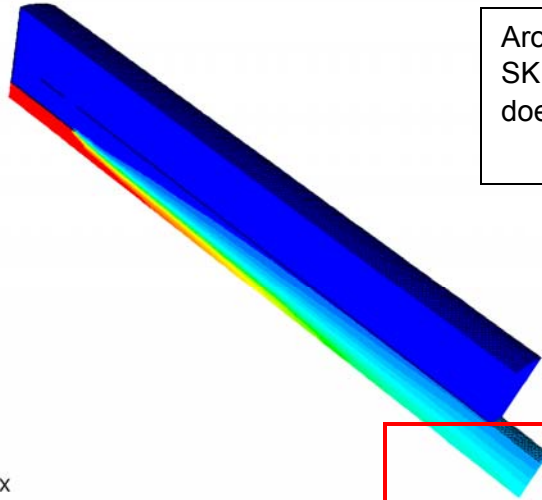
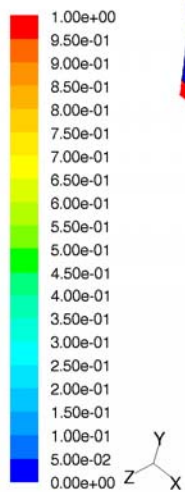


These several contours from SKE solution do not completely account for the complex structure of the flow.

These contours from RNG KE show the complicated flow patterns. This area shows that the flow has a moderate recirculation. Therefore, the mass fraction of fuel at the local area of the wall of the mixture tube is almost zero.

These contours from RSM solution show a highly recirculating flow.

## (2) Contours of Mass fraction of Fuel (CH4) (Non-reacting Flow)



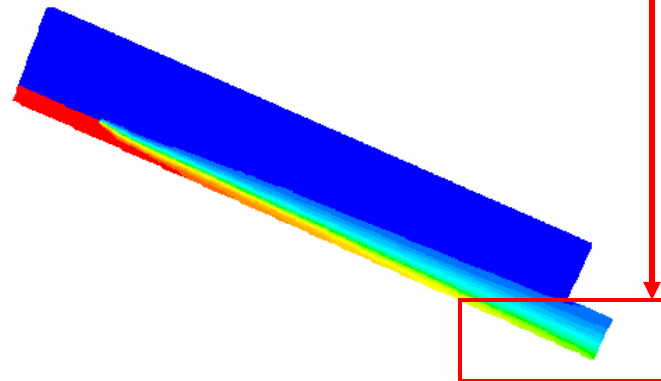
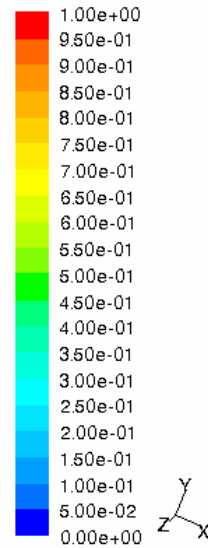
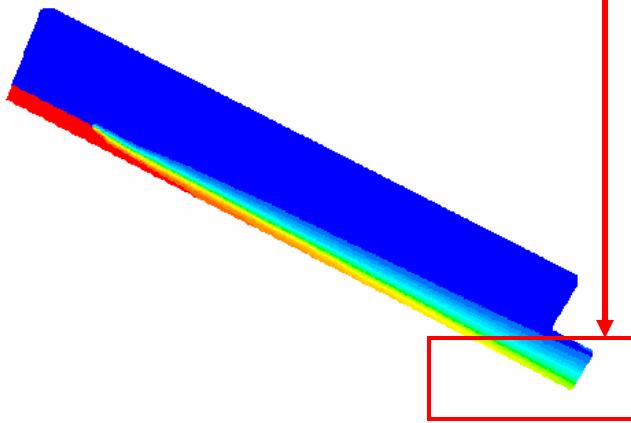
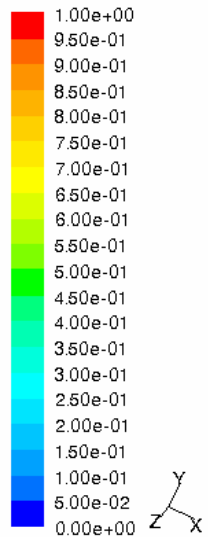
Around the center of the mixture tube, the concentration of the mass fraction of Fuel from SKE solution is very low. This SKE solution is very inaccurate because this SKE solution does not account for complex flow.

Around the center of the mixture tube, the concentration of the mass fraction of Fuel from RNG KE solution is higher than the RSM solution.

Around the center of the mixture tube, the concentration of the mass fraction of Fuel from RSM solution is lower than the RNG KE solution.

Contours of Mass fraction of ch4

Jun 22, 2006  
FLUENT 6.2 (3d, dp, segregated, spe, ske)



Contours of Mass fraction of ch4

Aug 18, 2006  
FLUENT 6.2 (3d, dp, segregated, spe, rngke)

Contours of Mass fraction of ch4

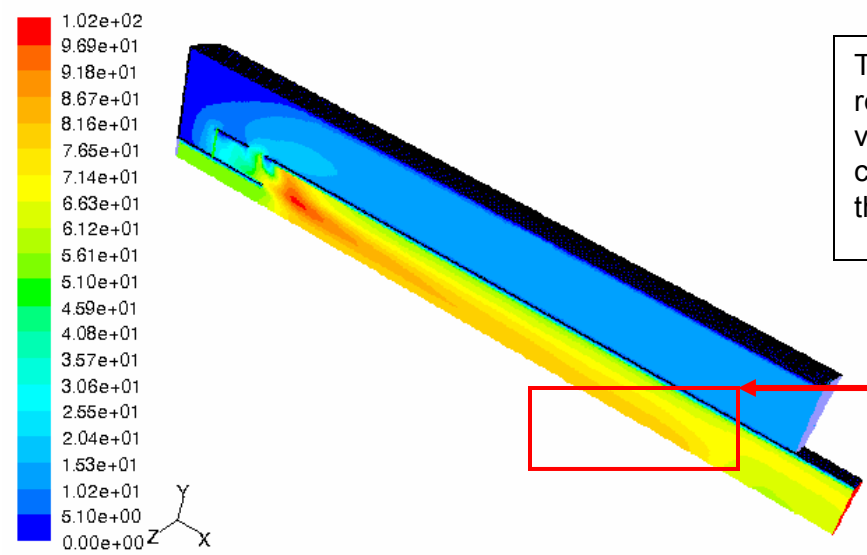
Aug 18, 2006  
FLUENT 6.2 (3d, dp, segregated, spe, RSM)

### (3) Contours of Velocity (Non-reacting Flow)

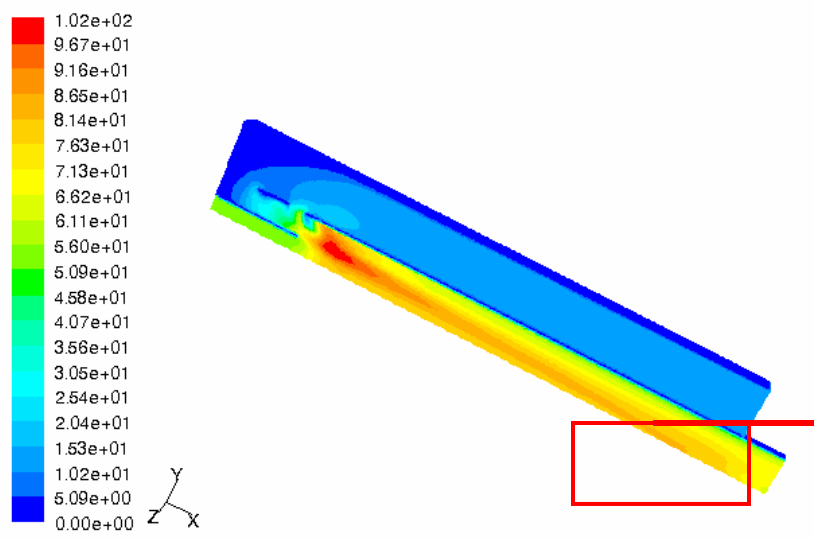
The mixing state finished before reaching the outlet. The peak velocity is **not** around the center of the premixer model at the outlet.

The mixing state extends a little further downstream, but the mixing state does not reach the outlet. The peak velocity is around the center of the premixer model.

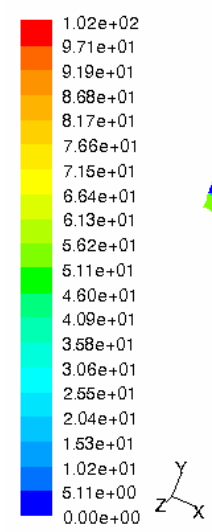
The mixing state extends until the outlet. The peak velocity is around the center of the premixer model at the outlet.



Contours of Velocity Magnitude (ft/s) Aug 21, 2006  
FLUENT 6.2 (3d, dp, segregated, spe, ske)

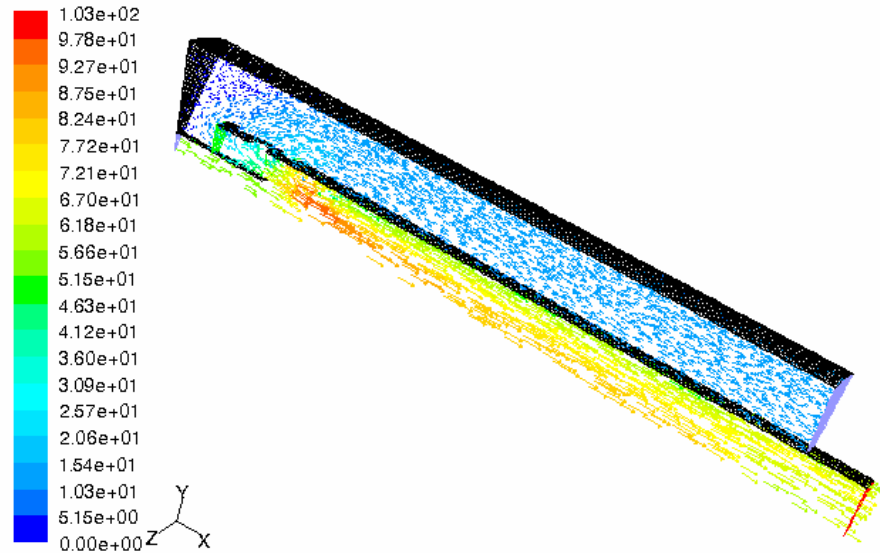


Contours of Velocity Magnitude (ft/s) Aug 18, 2006  
FLUENT 6.2 (3d, dp, segregated, spe, mgke)

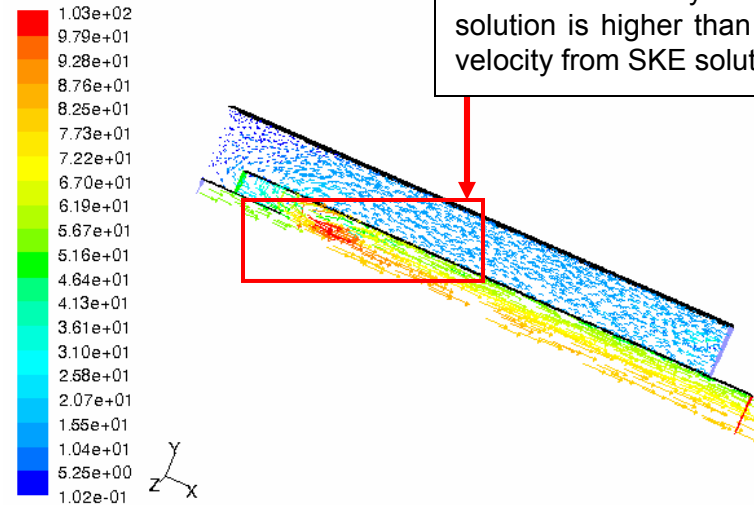
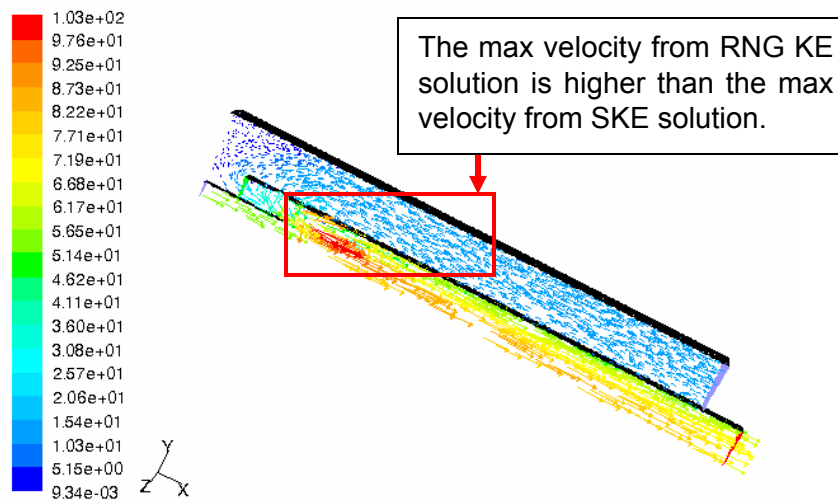


Contours of Velocity Magnitude (ft/s) Aug 18, 2006  
FLUENT 6.2 (3d, dp, segregated, spe, RSM)

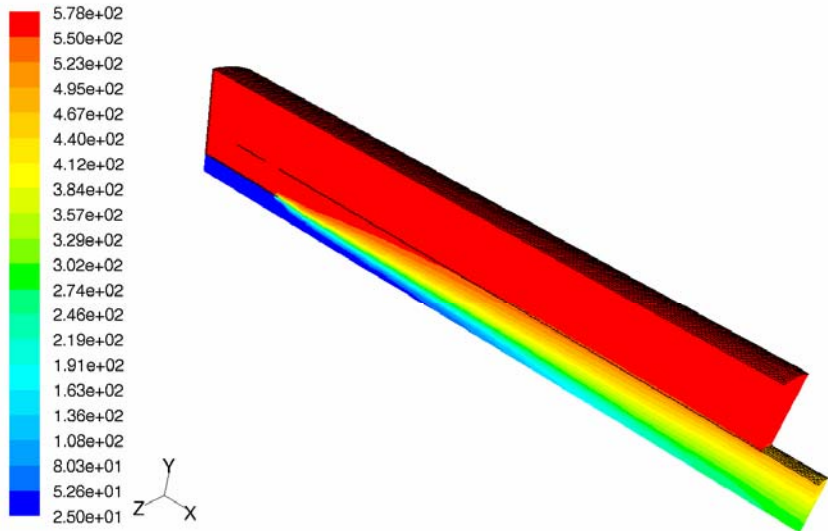
## (4) Velocity Vector (Non-reacting Flow)



The max velocity from RNG KE and Reynolds Stress Model (RSM) is higher than the max velocity from Standard K-Epsilon Model (SKE). This makes the fuel content to be extended until the exit of the mixture tube. The flow paths of velocity vector from SKE, RNG KE, and RSM seem reasonable.



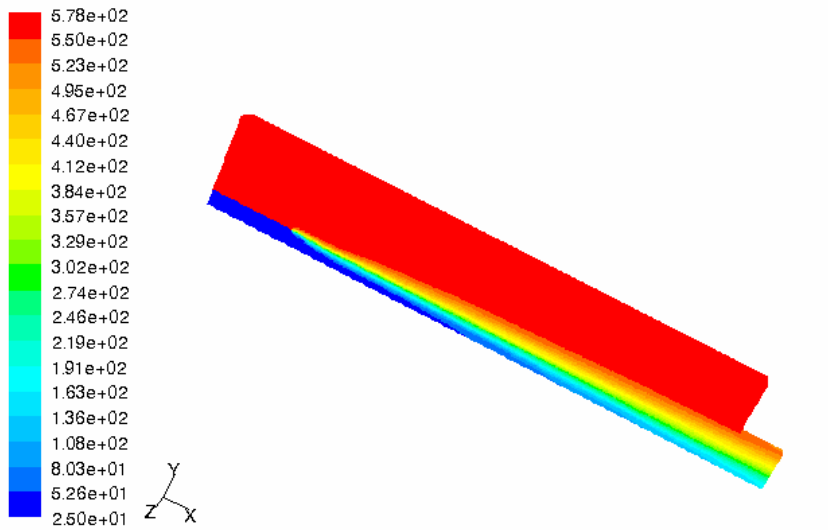
## (5) Contours of Static Temperature (Non-reacting Flow)



The static temperature profiles of the non-reacting flow from SKE, RNG KE and RSM solutions are reasonable.

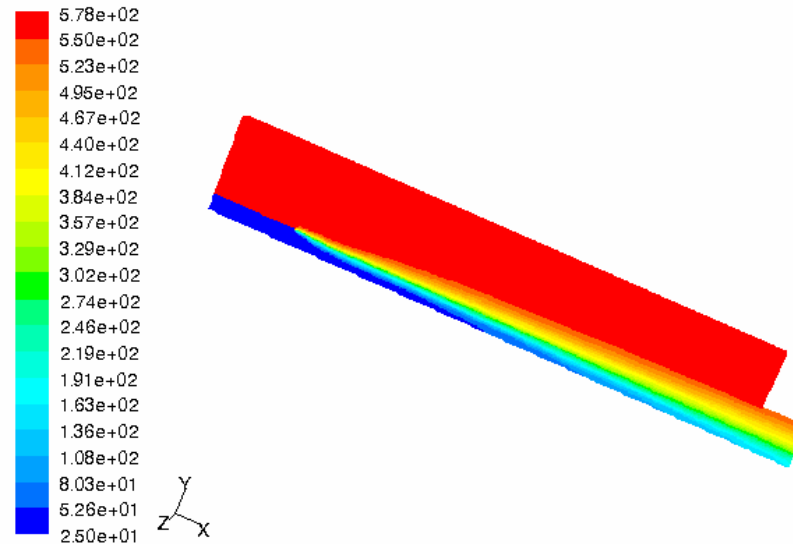
Contours of Static Temperature (c)

Jun 22, 2006  
FLUENT 6.2 (3d, dp, segregated, spe, ske)



Contours of Static Temperature (c)

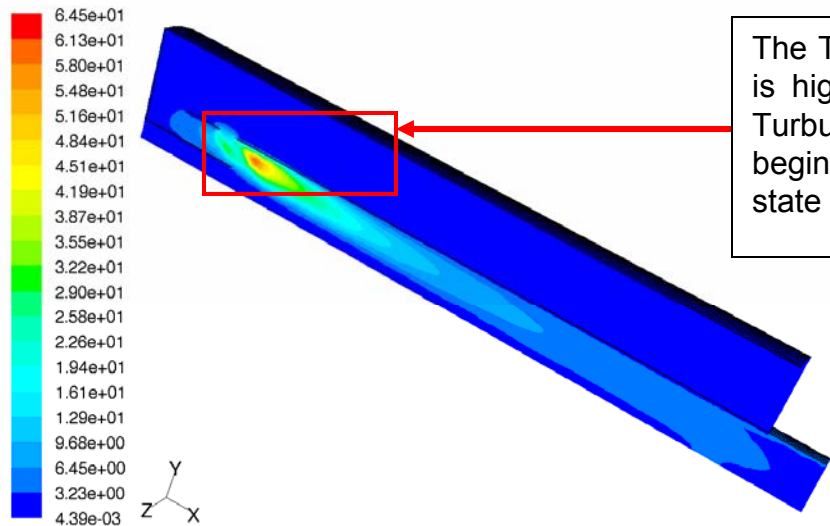
Aug 18, 2006  
FLUENT 6.2 (3d, dp, segregated, spe, rngke)



Contours of Static Temperature (c)

Aug 18, 2006  
FLUENT 6.2 (3d, dp, segregated, spe, RSM)

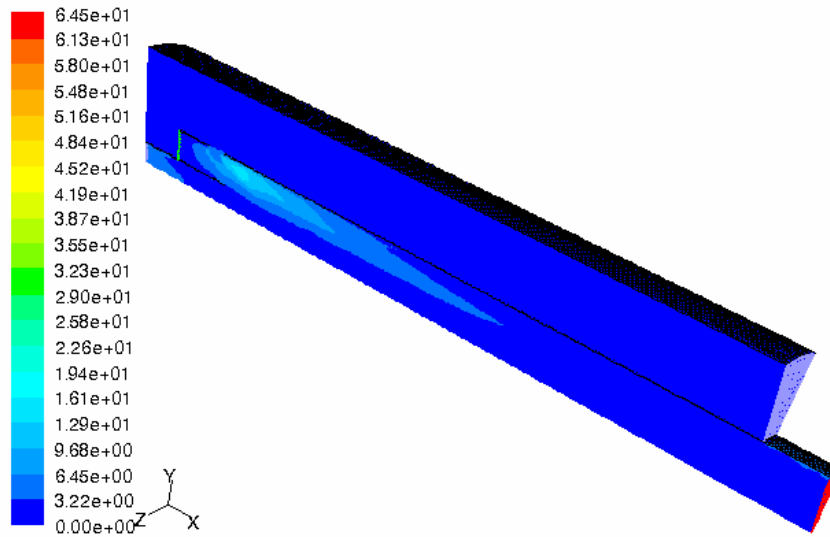
## (6) Contours of Turbulent Kinetic Energy (Non-reacting Flow)



The Turbulent Kinetic Energy around the 3 interior holes from SKE solution is higher at the beginning of the mixture tube (middle wall). The higher Turbulent Kinetic Energy intensity around three interior holes on the beginning wall of the mixture tube from **SKE** probably allows the mixing state to be finished before reaching the outlet of mixture tube.

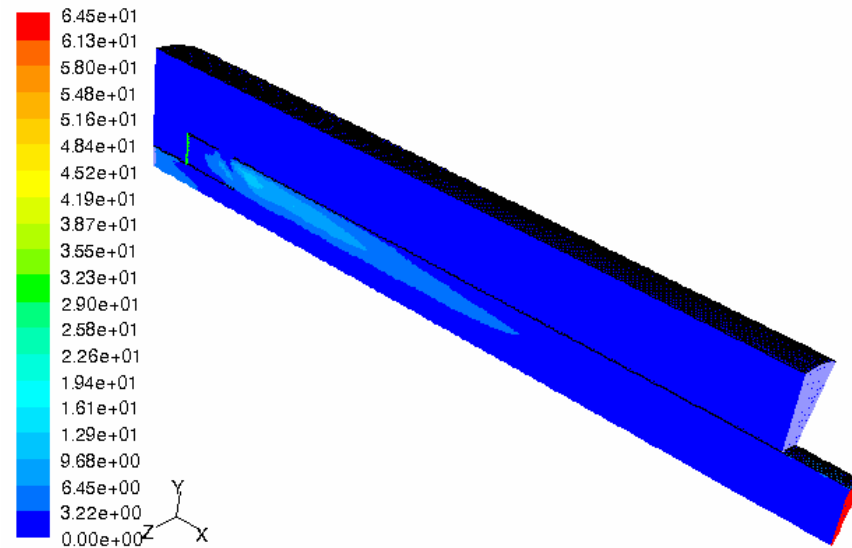
Contours of Turbulence Kinetic Energy (k) (m2/s2)

Aug 03, 2006  
FLUENT 6.2 (3d, dp, segregated, spe, ske)



Contours of Turbulence Kinetic Energy (k) (m2/s2)

Aug 21, 2006  
FLUENT 6.2 (3d, dp, segregated, spe, rngke)



Contours of Turbulence Kinetic Energy (k) (m2/s2)

Aug 21, 2006  
FLUENT 6.2 (3d, dp, segregated, spe, RSM)

## (7) The Unmixedness Calculated by Mass fraction of Fuel CH<sub>4</sub>, and Mass Fraction of Air (Non-reacting Flow)

Unmixedness from Standard K-Epsilon (SKE) Solution

	Mass Fraction of CH <sub>4</sub>	Mass Fraction of air
Unmixedness Percentage	29%	37%

Unmixedness from RNG K-Epsilon Solution

	Mass Fraction of CH <sub>4</sub>	Mass Fraction of air
Unmixedness Percentage	76%	16%

Unmixedness from RSM Solution

	Mass Fraction of CH <sub>4</sub>	Mass Fraction of air
Unmixedness Percentage	69%	14%

Having compared the unmixedness of mass fraction of fuel CH<sub>4</sub> from (SKE) Solution, RNG K-Epsilon Solution, RSM Solution, the **results of RNG K-Epsilon solution and RSM solution are very close**. The result of SKE solution is completely different with the results of RNG K-Epsilon solution and RSM solution. Therefore, the results of the unmixedness from RNG K-Epsilon solution and RSM solution are more reliable. In addition, when looking at the profile of mass fraction of Fuel CH<sub>4</sub> at the outlet, the contours of RSM solution show the better mixing state than the contour of RNG K-Epsilon solution.

In conclusion, the RSM solution probably provides the best option in simulating the premixer model of air-fuel mixture.

# Conclusions and Recommendations (1)

- If the unmixedness percentage of air-fuel mixture at the outlet is high, this will lead to higher NO<sub>x</sub> emissions.
- A design modification of the current air-fuel premixer of Injector, which should have the mixing state occurring right inside the fuel tube, is necessary.
- From contours of mass fraction of CH<sub>4</sub> in **RSM Solution**, the fuel is unmixed until the downstream of mixture tube. The fuel should be mixed at the upstream before reaching the end (the outlet) of the mixture tube.
- The current design of air-fuel premixer can be potentially improved by addition of 6 or 14 small rectangular gaps around the circumference of the fuel tube. This allows the air to get into the fuel tube right at the beginning and the mixing state will happen from the fuel tube and may finish before reaching the outlet of the mixture tube
- The new design should reach the low unmixedness percentage of air-fuel mixture at the outlet of mixture tube.

## Conclusions and Recommendations (2)

- **Re-Normalization Group K-Epsilon Model (RNG KE)** and **Reynolds Stress Model (RSM)** seem to provide approximately equal unmixedness percentage.
- The assumptions of the **RNG KE** and **RSM** are used for the effects of **curvature, highly swirling, 3-D rotating flows**.
- As a result, the **RNG KE** and **RSM** probably provides a better solution in CFD analysis of air-fuel premixer Design of Injector

# Acknowledgements

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