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Test cases for variable density flow

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ESSS

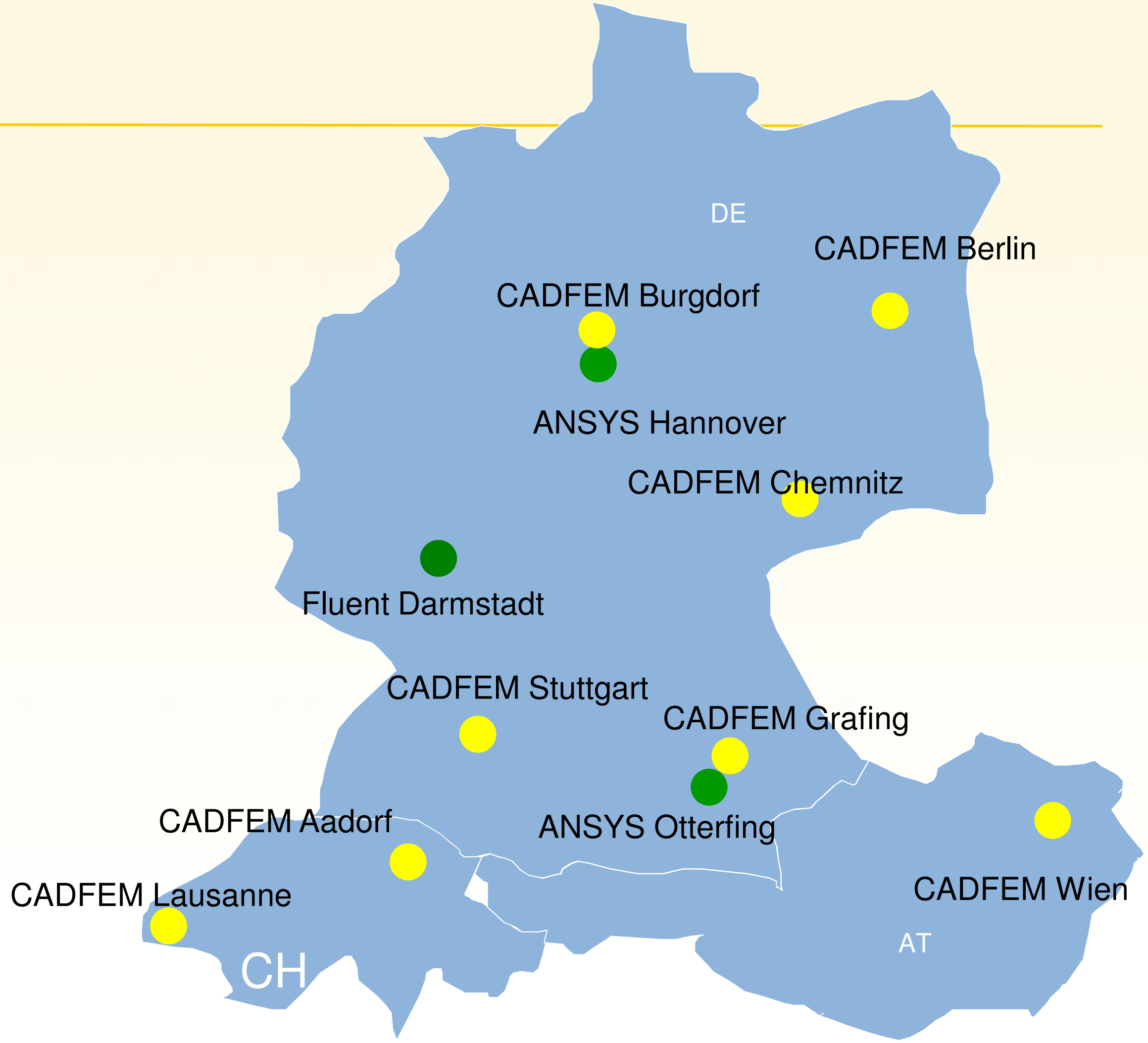
ANSYS Team Germany

CADFEM

- > 110 collaborators
- Established 1985
- Focus in FEM

ANSYS Germany

- > 114 collaborators
- Established 1990
- Focus in CFD



Motivation

- Variable density flow modeling is challenging and not well understood
- Important for many industrial flows:
  - Reactor Safety
  - Chimney Plumes
  - Internal Combustion Engines
  - High Mach Number Flows
- To better understand the effects of variable density on flows, simple test cases where selected in order to test several aspects of these flows individually

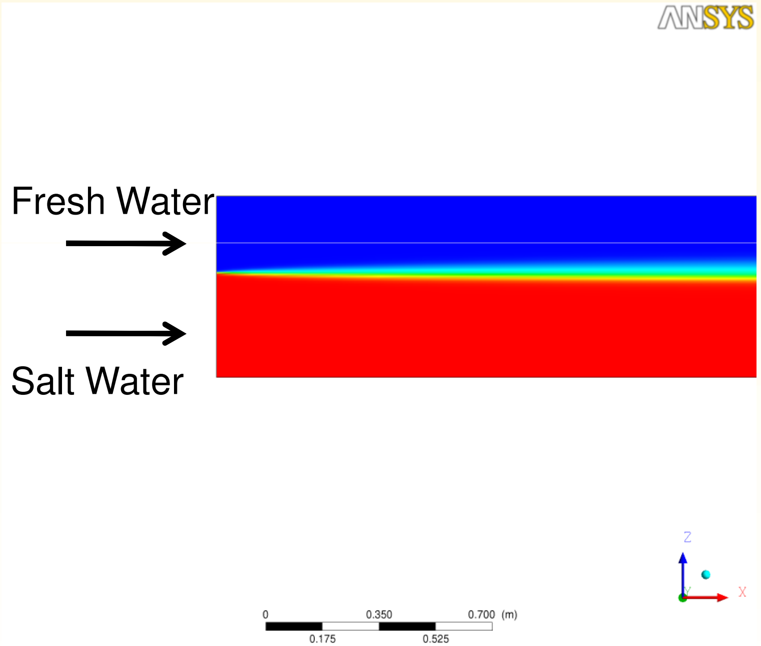
Test cases

- In this presentation:
  - Saline Mixing Layer: different density fluids
  - Differenced Heated Cavity: density variation due to heating
- The densities differences involved in both test cases are not large
- In both test cases the flow has large buoyant effects

Saline Mixing Layer

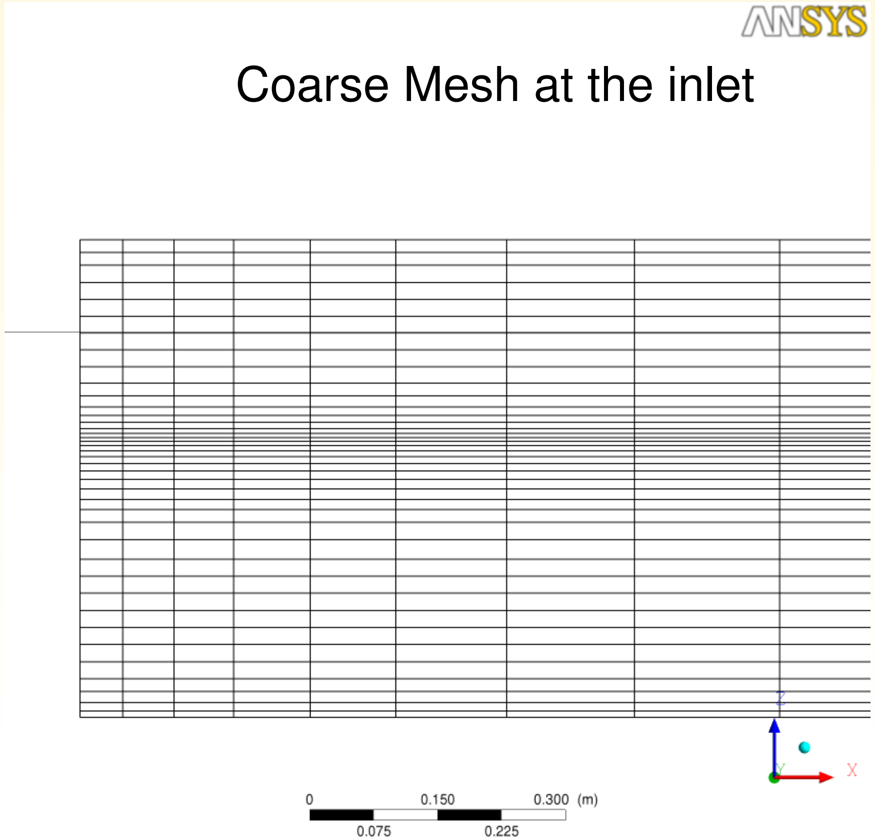
- Fluids:
  - Fresh water: ρ_1 = 1015 [kg/m^3]
  - Salt water: ρ_2 = 1030 [kg/m^3]
  - Mixture Kinematic Diffusivity:1e-9 [m^2/s]
- Inlet average velocities:
  - Fresh water inlet: U_1 = 0.52 [m/s]
  - Salt water inlet: U_2 = 0.32 [m/s]

Experiment made by Uittenbogaard [1995]



Mesh

- Coarse Mesh (Grid01):
  - Mesh suggested by Uittenbogaard [1989]
  - 8160 hexahedrical elements
- Fine mesh (Grid02):
  - Refined by a factor of 2 in each direction from Grid01
  - 32640 hexahedrical elements



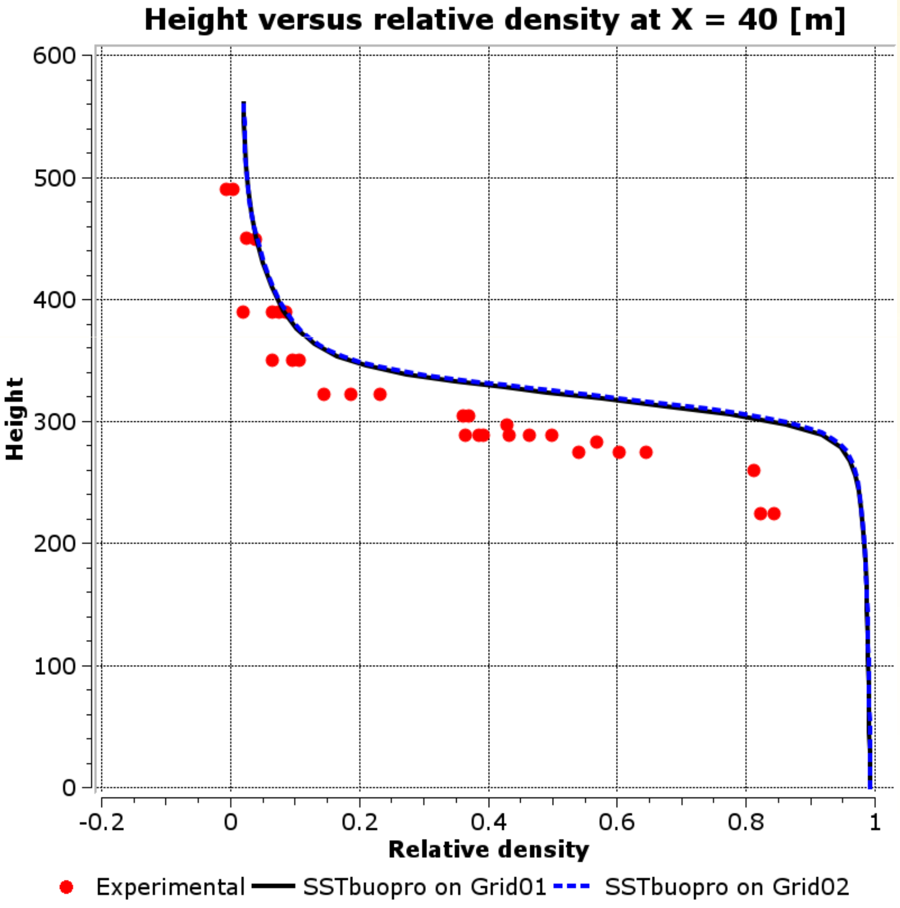
Numerical Model

- CFX 12.0 version used for simulations
- 2D Flow
- Stationary Simulation
- High Resolution advection scheme
- First order turbulence Numeric's
- Automatic Time step (0.3 seconds on both meshes)
- Full Buoyancy model
- Convergence Criteria:
  - 1e-5 RMS residuals

Numerical Model

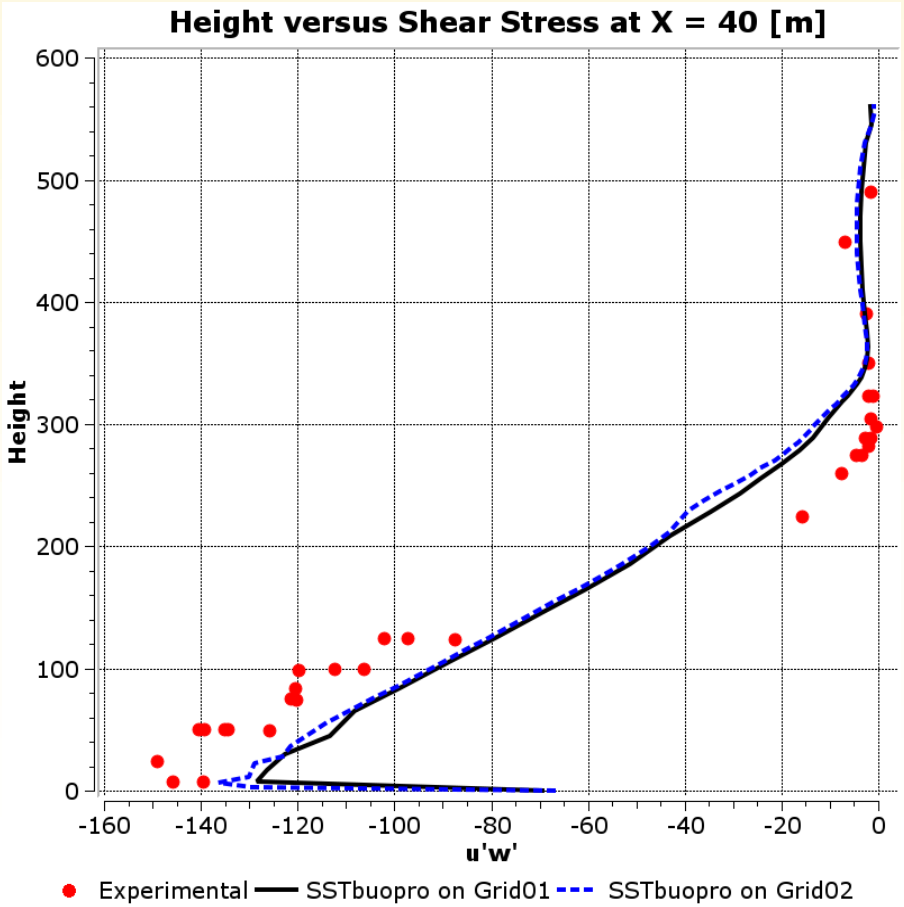
- Turbulence Models
  - SST
  - SST with buoyancy production for k (SSTbuopro)
  - K-Epsilon
  - K-Epsilon with buoyancy production for k (KEpsbuopro)

Mesh comparison



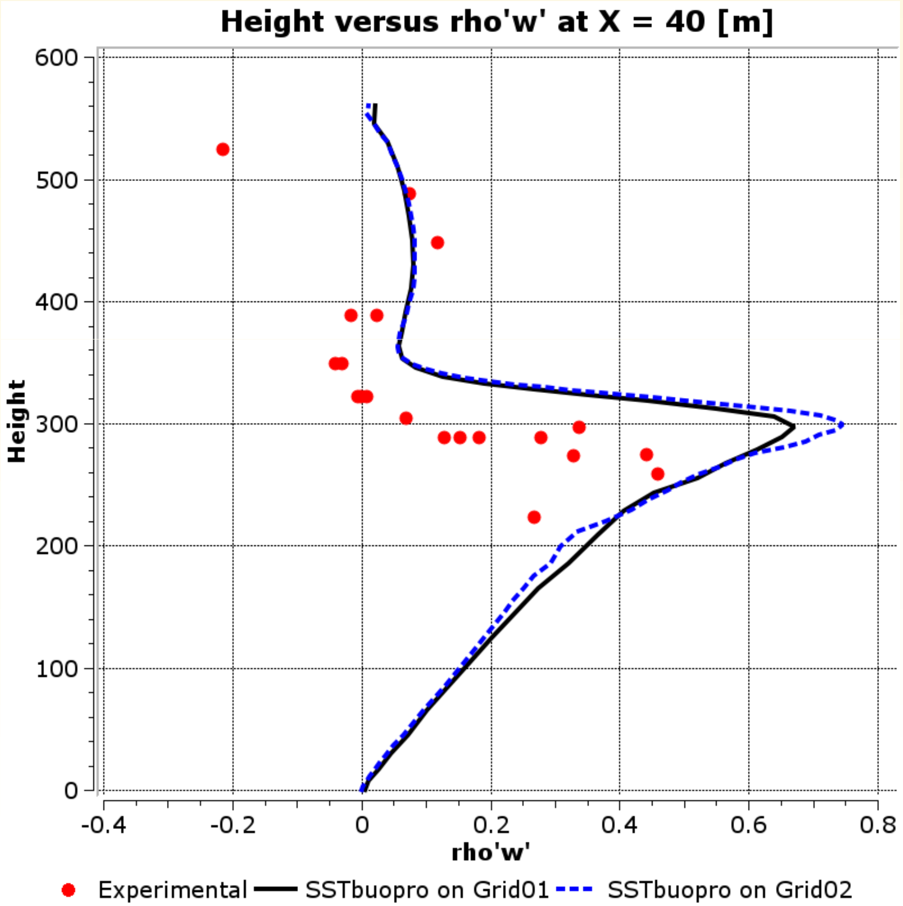
$$\rho_{rel} = \frac{\rho - \rho_{fresh}}{\rho_{salt} - \rho_{fresh}}$$

Mesh comparison



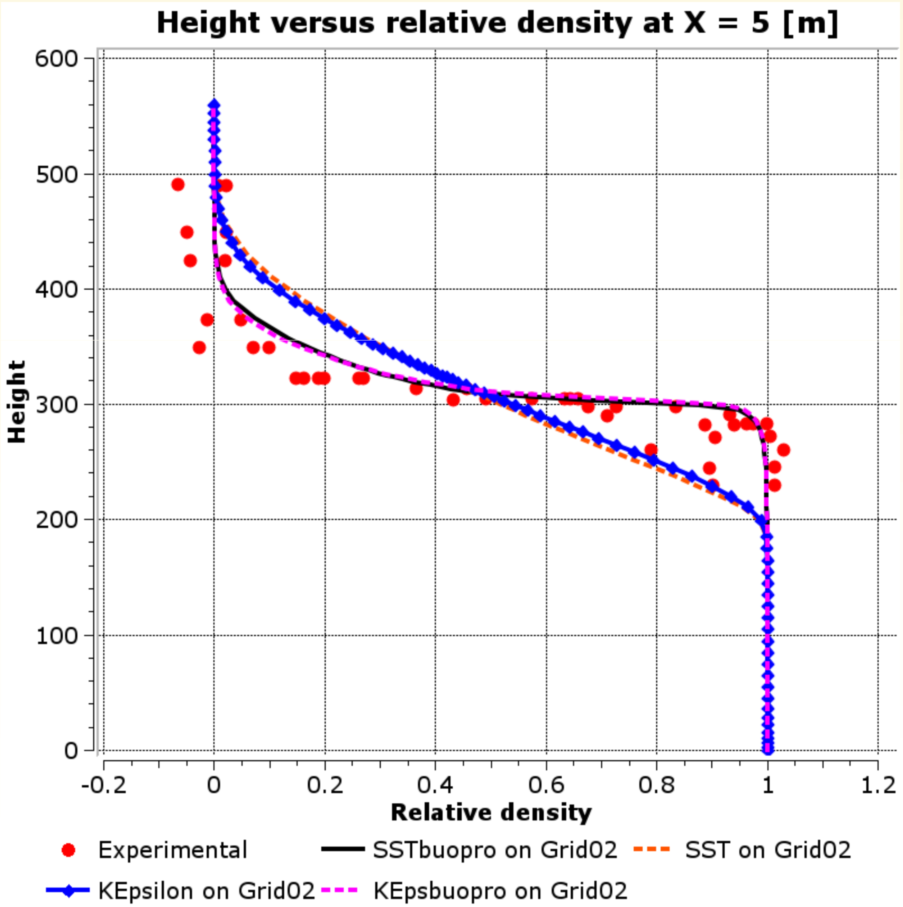
$$u'w' = -\left(\frac{\mu_t}{\rho}\right)\left(\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z}\right)$$

Mesh comparison



$$\rho' w' = -\left(\frac{\mu_t}{\rho . Sch}\right)\left(\frac{\partial \rho}{\partial z}\right)$$

Model comparison



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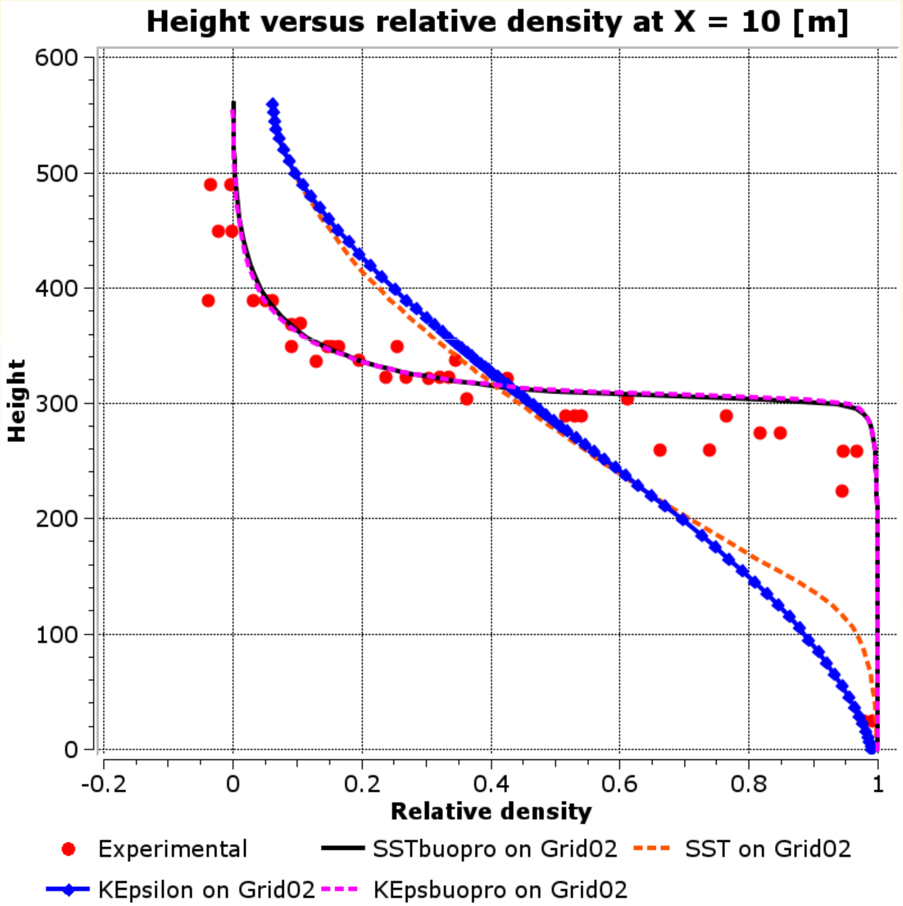
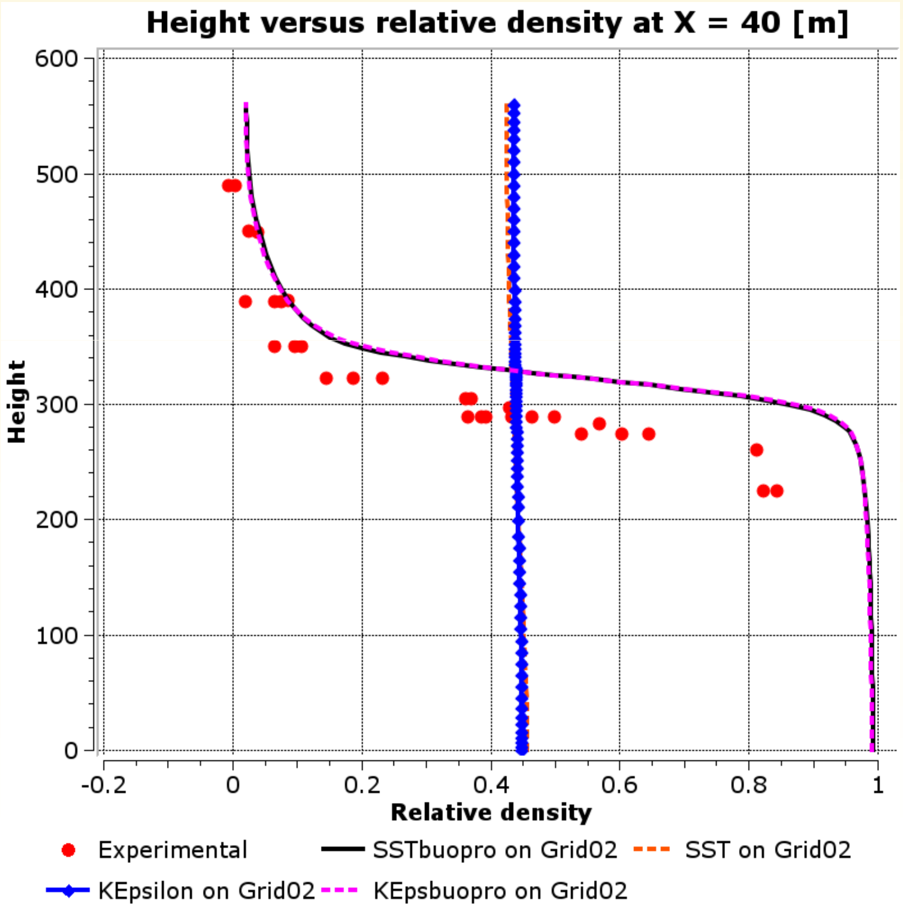
Model comparison



$$\rho_{rel} = \frac{\rho - \rho_{fresh}}{\rho_{salt} - \rho_{fresh}}$$

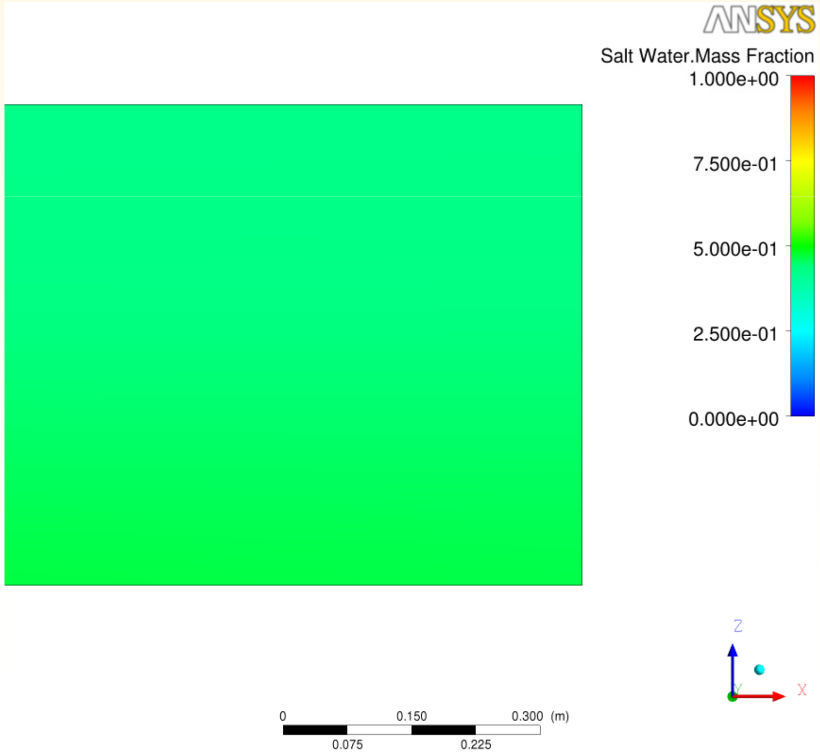
Model comparison



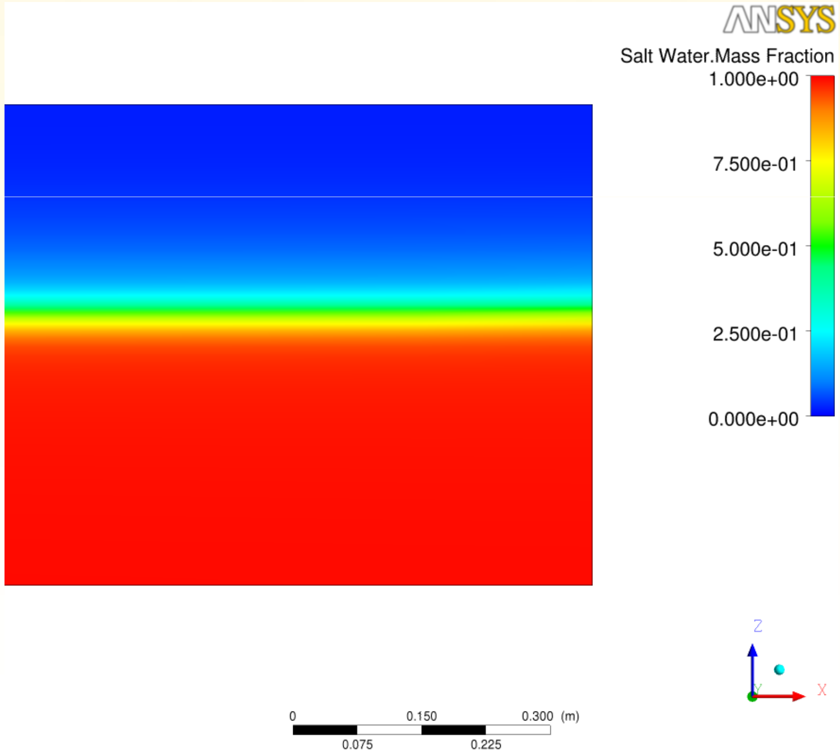
$$\rho_{rel} = \frac{\rho - \rho_{fresh}}{\rho_{salt} - \rho_{fresh}}$$

Model Comparison - Salt Water Mass Fraction at the outlet

SST

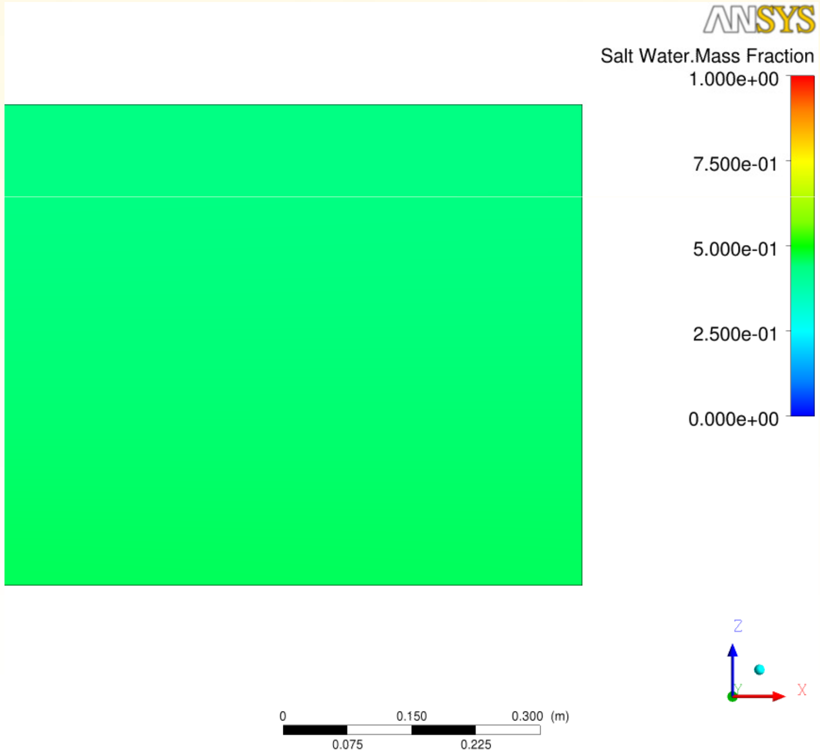


SST with Buoyancy production for the k equation

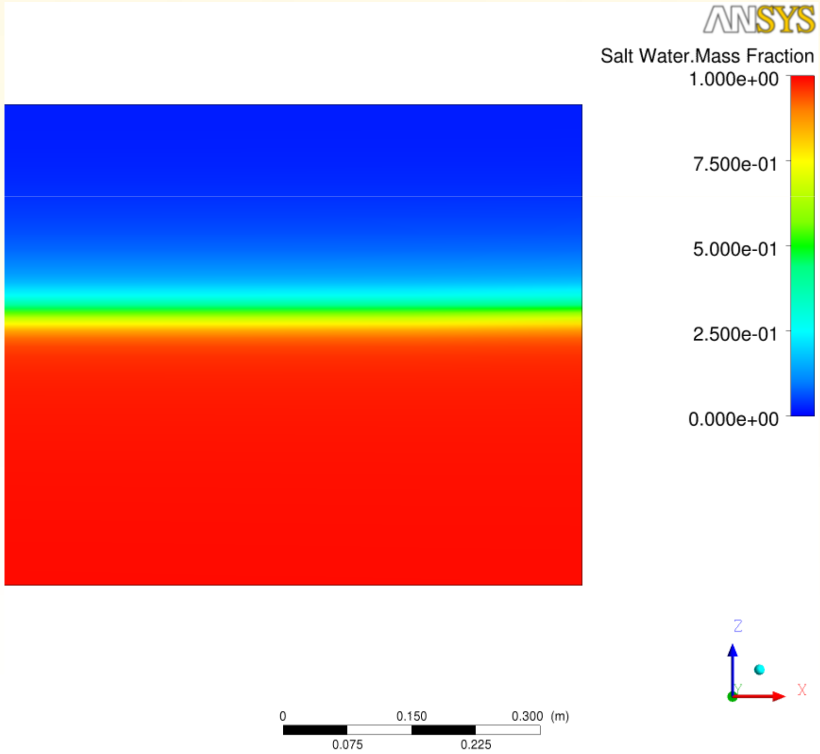


Model Comparison - Salt Water Mass Fraction at the outlet

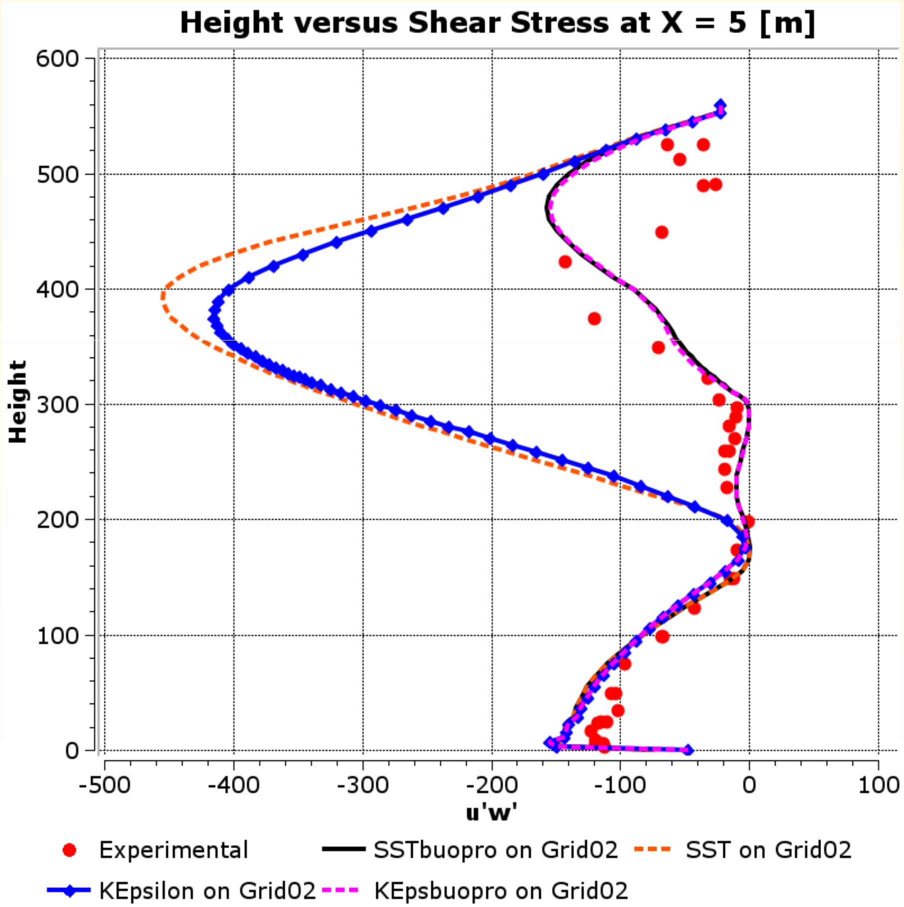
K Epsilon



K Epsilon with Buoyancy production for the k equation

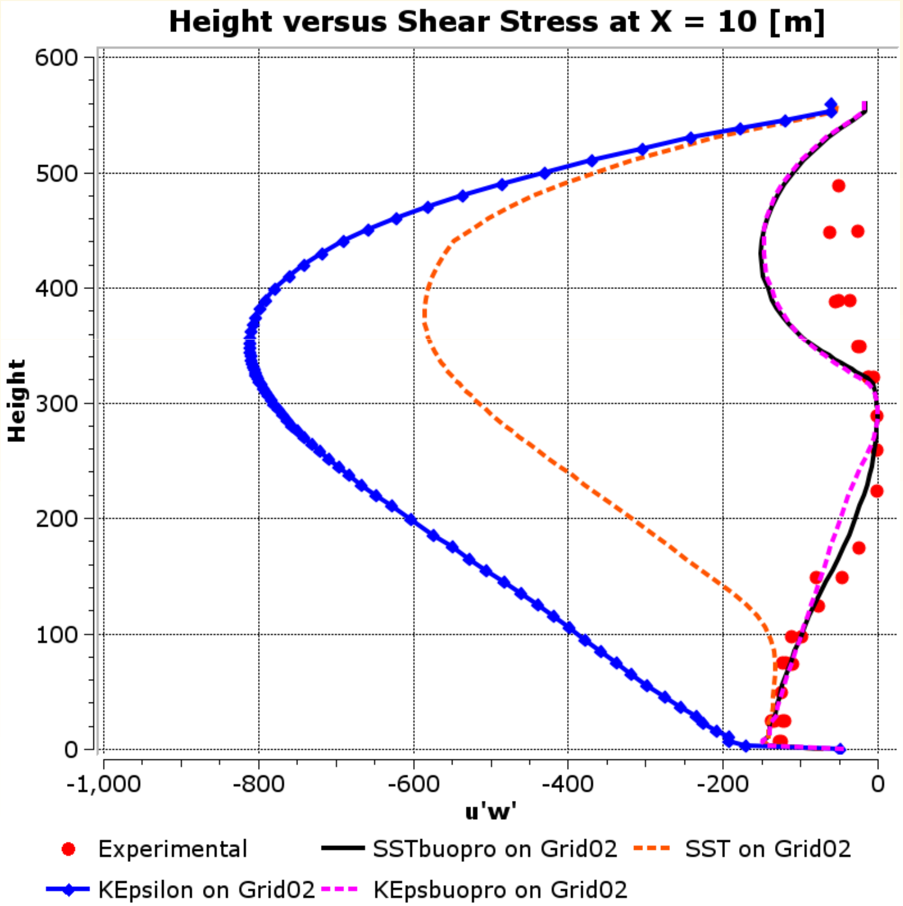


Model comparison



$$u'w' = -\left(\frac{\mu_t}{\rho}\right)\left(\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z}\right)$$

Model comparison



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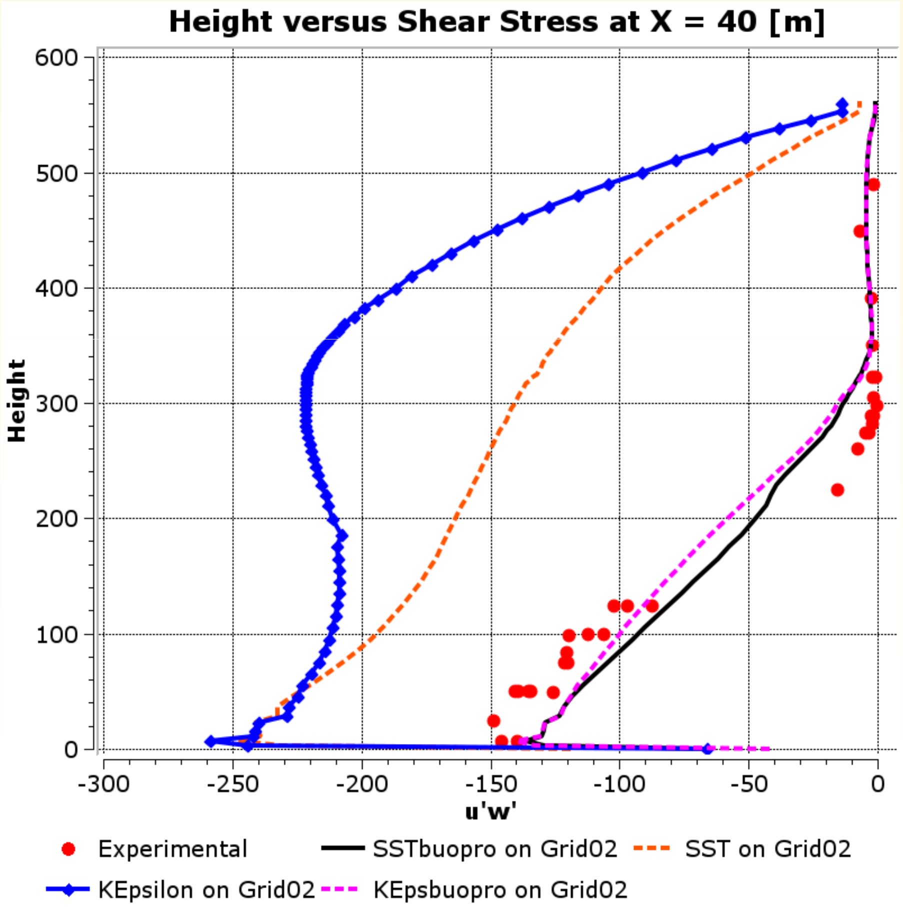
Model comparison



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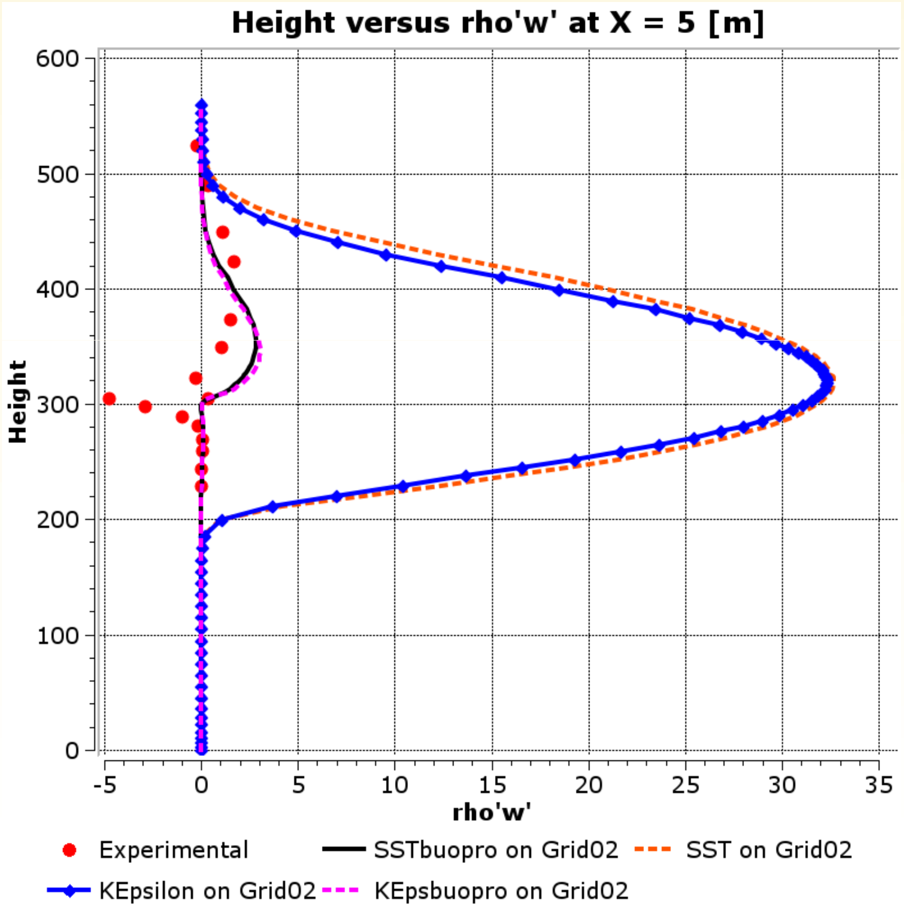
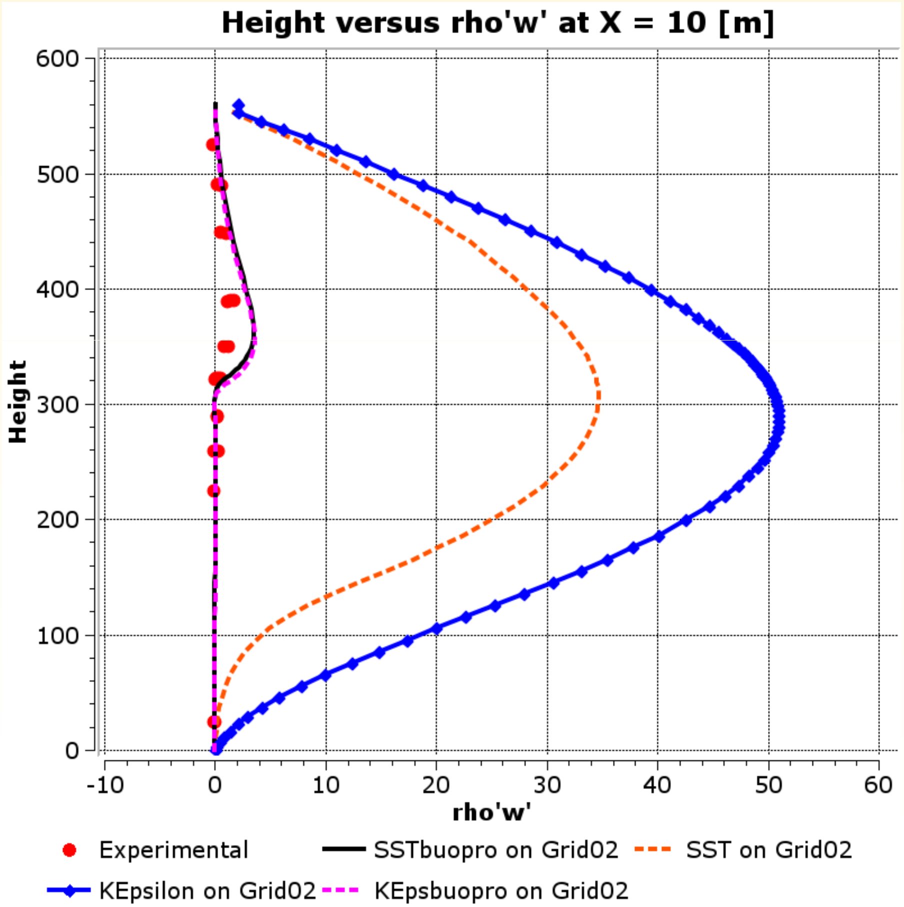
Model comparison



$$\rho' w' = -\left(\frac{\mu_t}{\rho . Sch}\right)\left(\frac{\partial \rho}{\partial z}\right)$$

Model comparison



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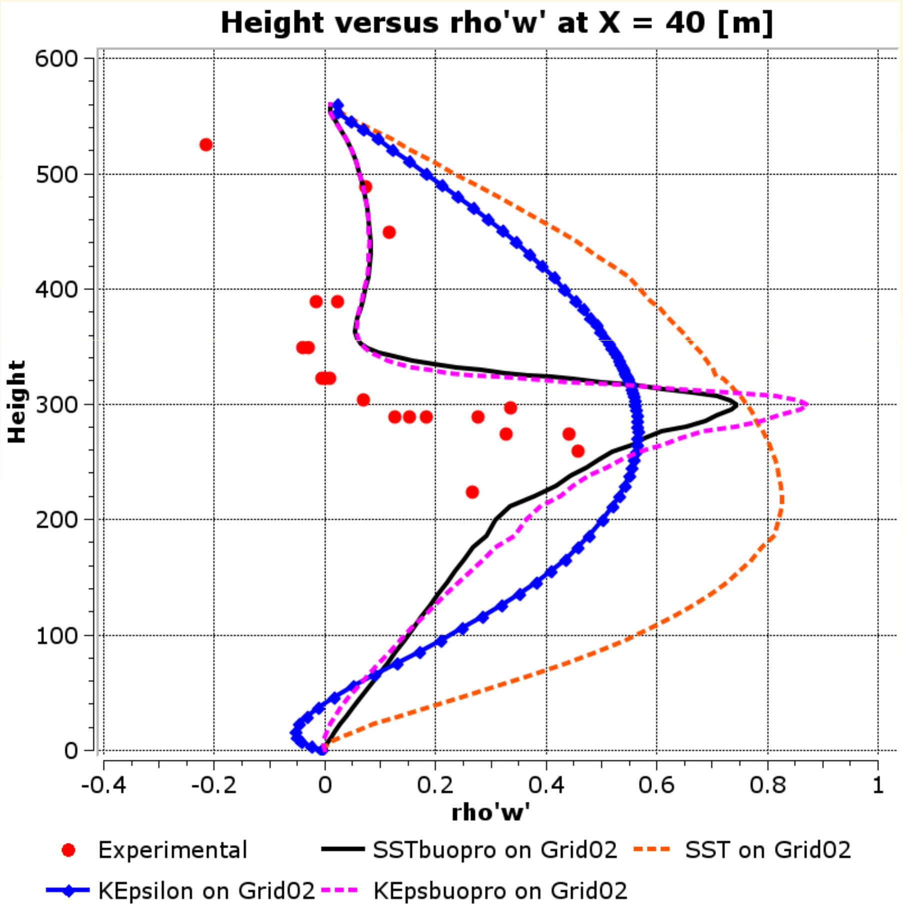
Model comparison



$$\rho' w' = -\left(\frac{\mu_t}{\rho . Sch}\right)\left(\frac{\partial \rho}{\partial z}\right)$$

Conclusions

- Mesh convergence was achieved (curves overlap)
- It is necessary to switch buoyancy turbulence on to match experimental results
- In the measurements made at 40 m from the inlet, the experimental values might be shifted because the experiment was conducted in an open channel leading to an inconstant free surface height

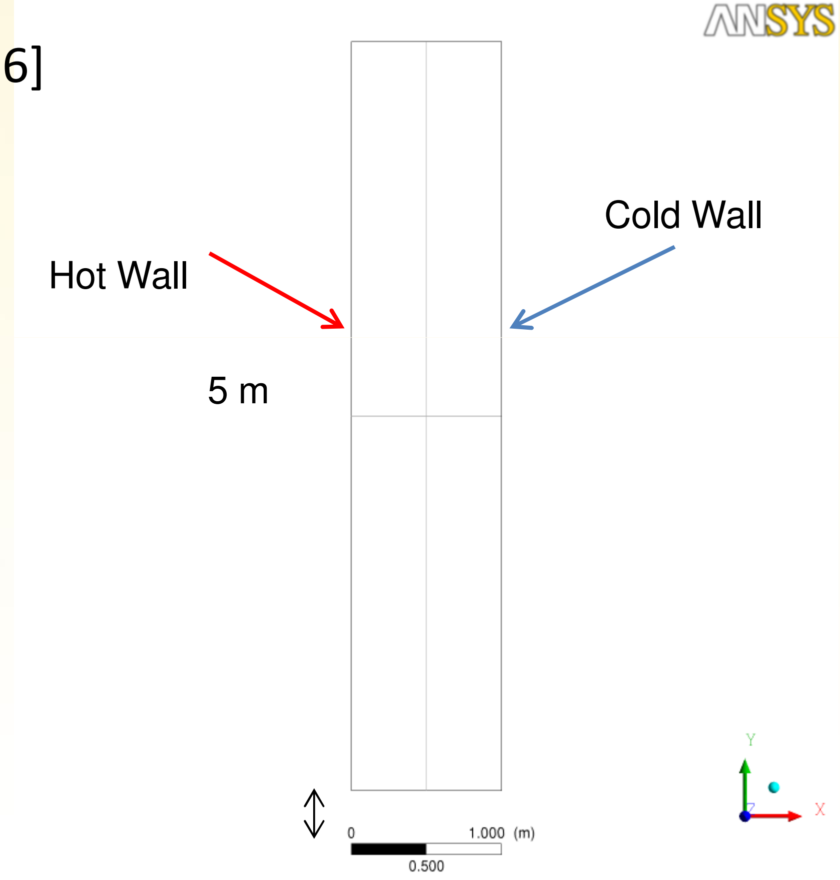
Description

- Experiment made by Cheesewright et al [1986]
- Cavity containing air
- Equation of state: $\rho = \dfrac{\rho_{ref} . T_{ref}}{T}$

- $T_{hot} = T_{Ref} + 0.5\ \Delta T = 74.4$ [℃]
- $T_{cold} = T_{Ref} - 0.5\ \Delta T = 28.6$ [℃]

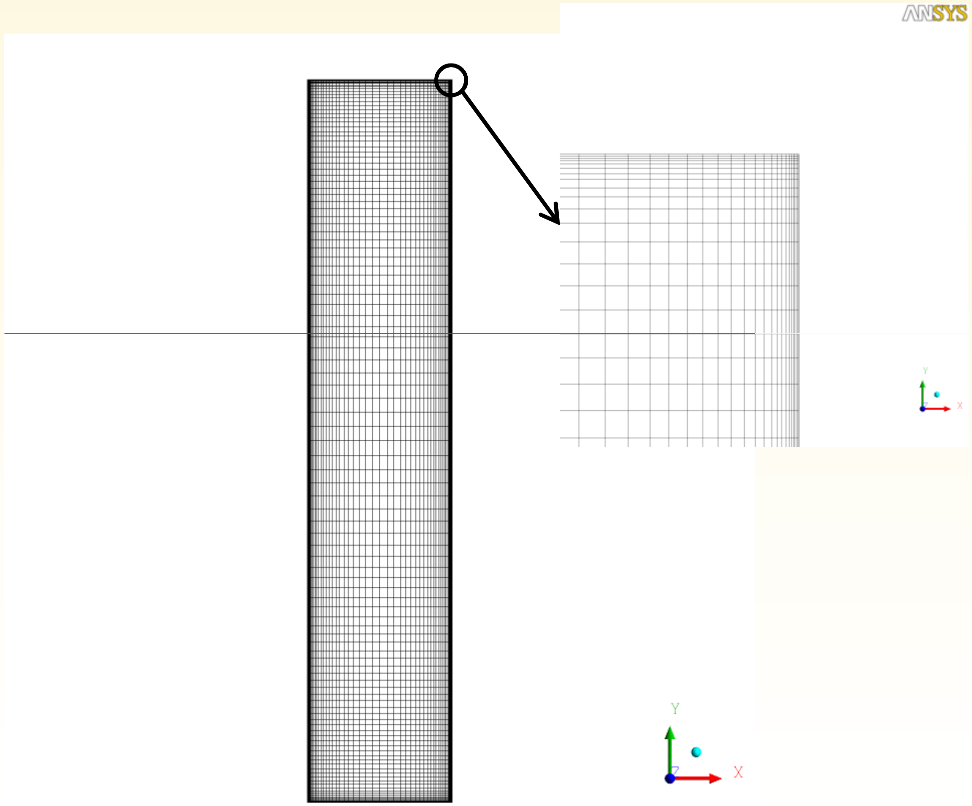
  Where:

  - $T_{ref} = 51.5$ [ºC]
  - $\Delta T = 45.8$ [ºC]
  - $P_{ref} = 1$ [atm]
  - $\rho_{ref} = \dfrac{P_{ref} . M}{T_{ref} . R}$



Mesh

- 2D Meshes
- Coarse Mesh:
  - 6272 hexahedrical elements
  - y^+=1.11 with BSL model*
- Refined Mesh:
  - 25088 hexahedrical elements
  - y^+=1.18 with BSL model*



*Average y^+ values

Coarse Mesh figures

Numerical Model

- CFX 12.0 version used for simulations
- Stationary Simulation
- High Resolution advection scheme
- First order turbulence Numeric's
- Full Buoyancy Model
- Convergence Criteria:
  - 1e-5 MAX residuals
  - 1e-5 conservation target for the energy equation
  - 0.01 conservation target for other equations

Numerical Model

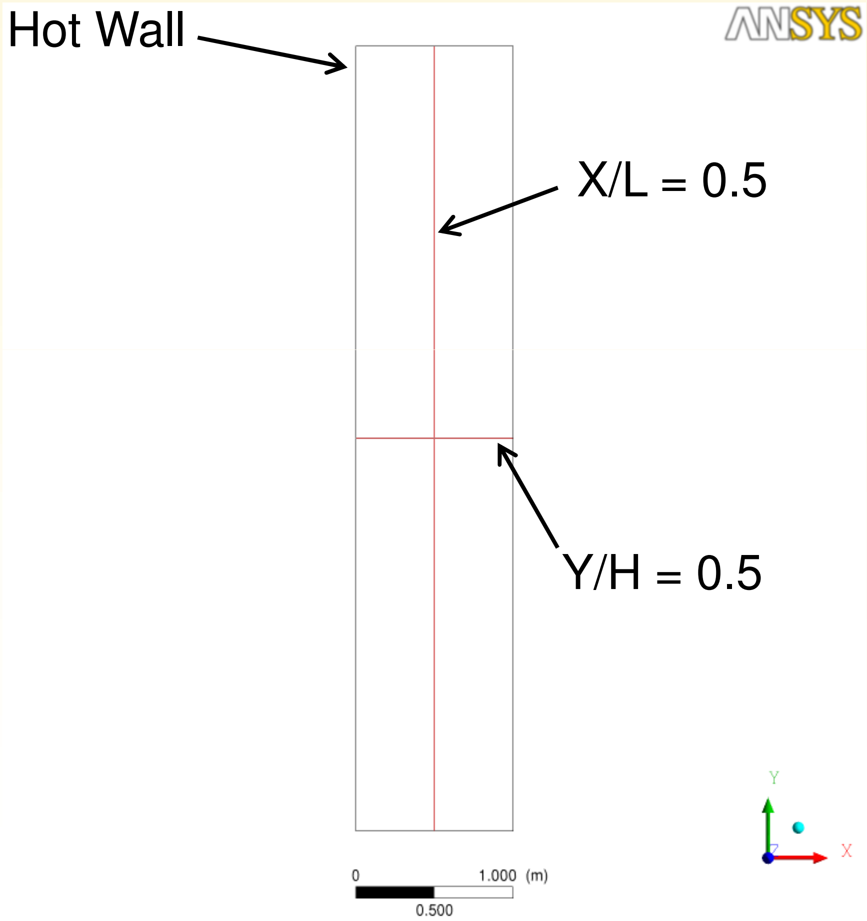
- Turbulence:
  - BSL
  - K – Omega
  - Reynolds Stress BSL
  - K – Epsilon
  - Reynolds Stress SSG

BSL, K – Omega, Reynolds Stress BSL: Automatic Wall function

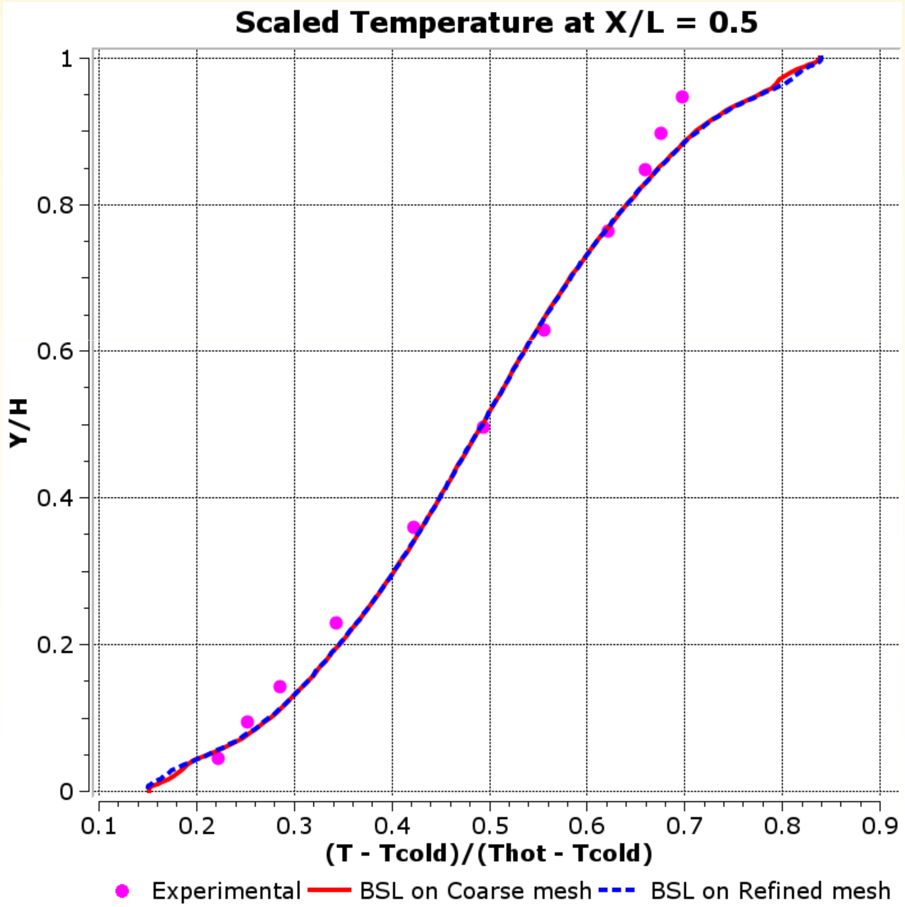
K – Epsilon, Reynolds Stress SSG: Scalable Wall function

- Stationary simulation
- Pseudo time step:
  - Automatic time step (0.7 seconds for both meshes)

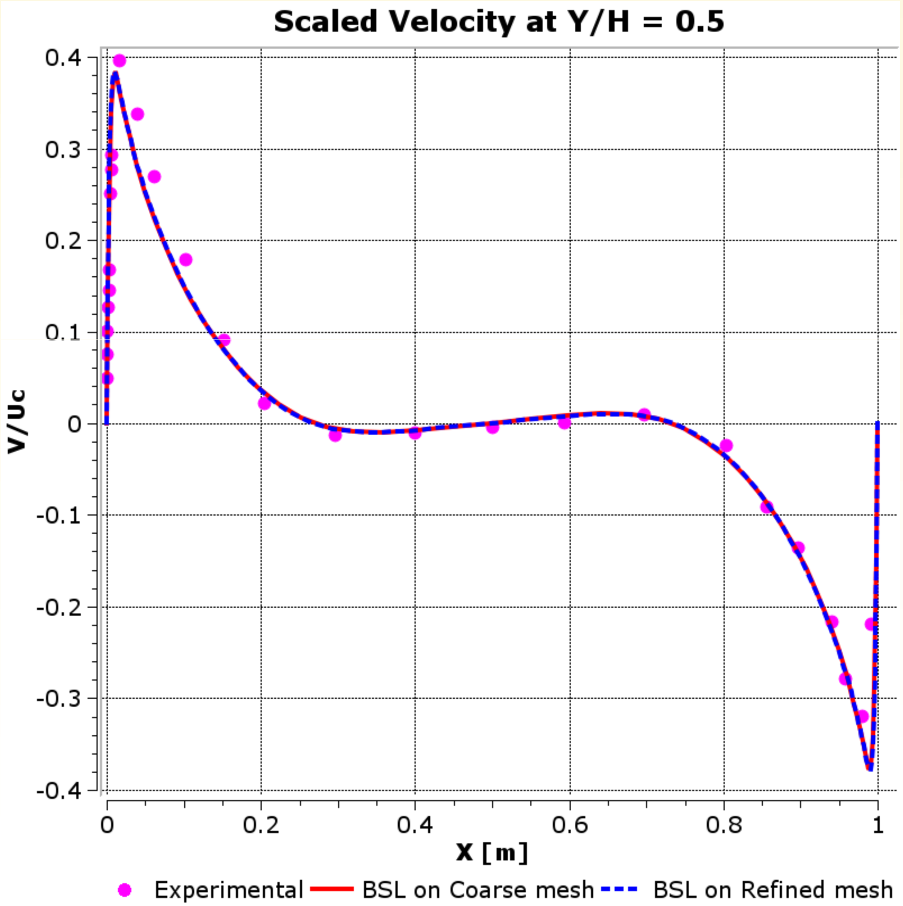
Profiles Locations



Mesh Comparison



Mesh Comparison

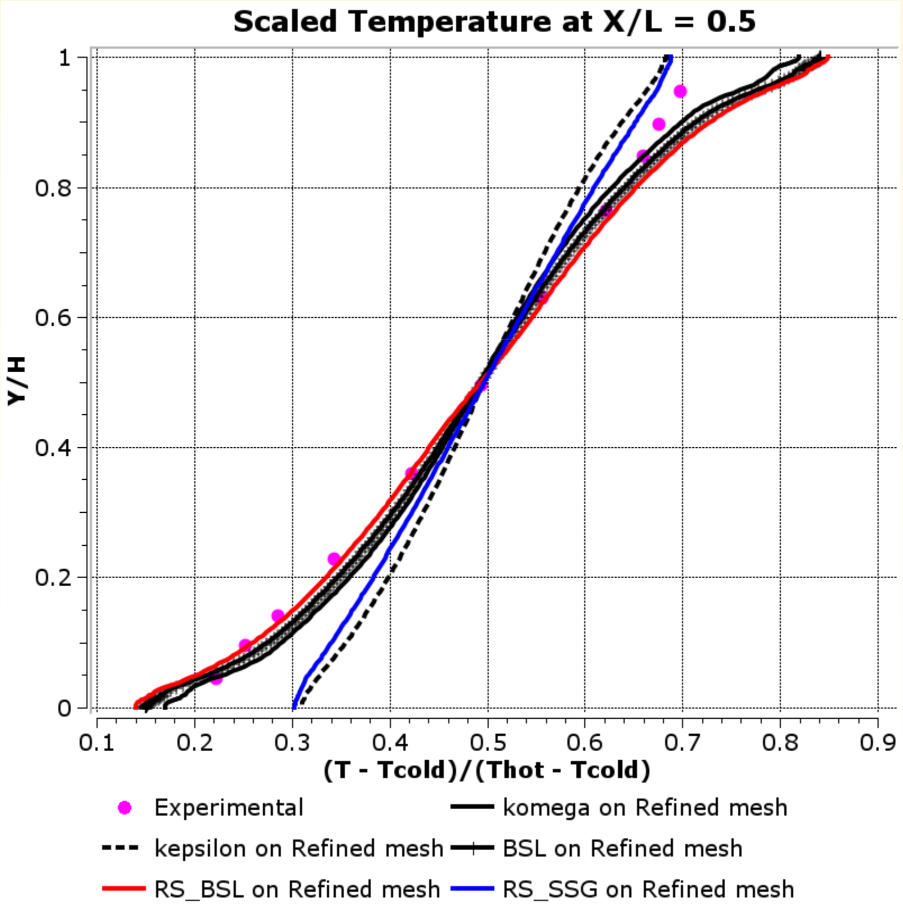


Where Uc is the convection velocity calculated as:

$$U_C = \sqrt{g.Width.\beta.\Delta T}$$

Where β is the thermal expansion coefficient

Model Comparison



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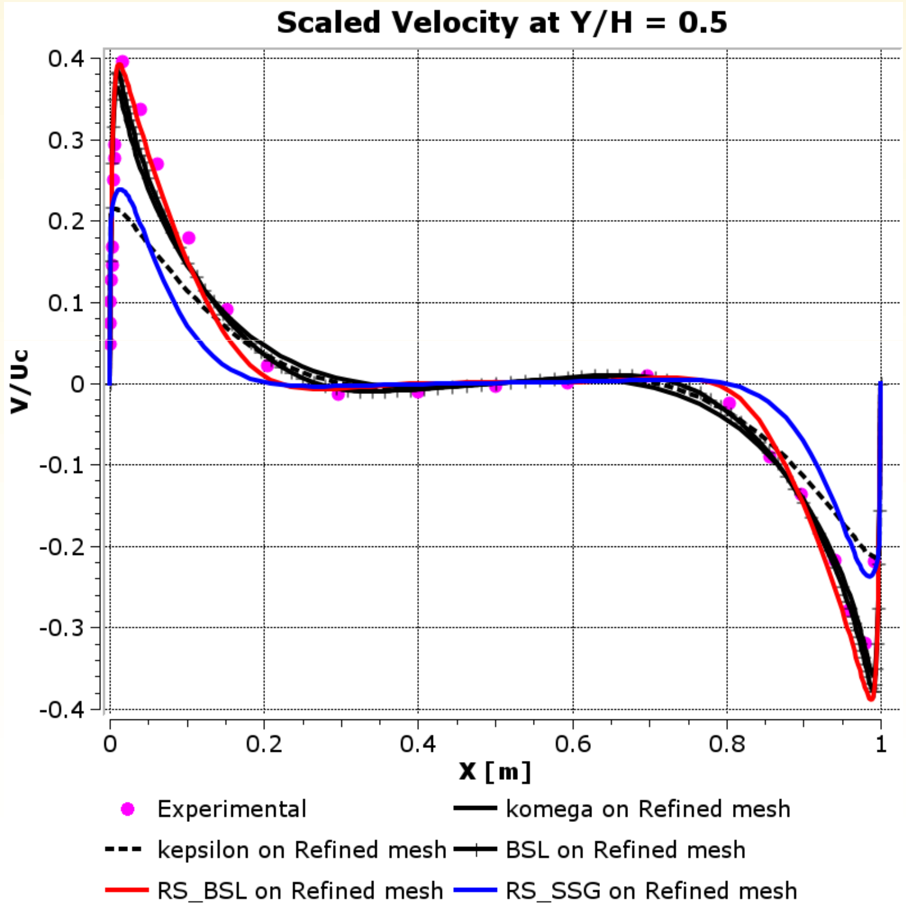

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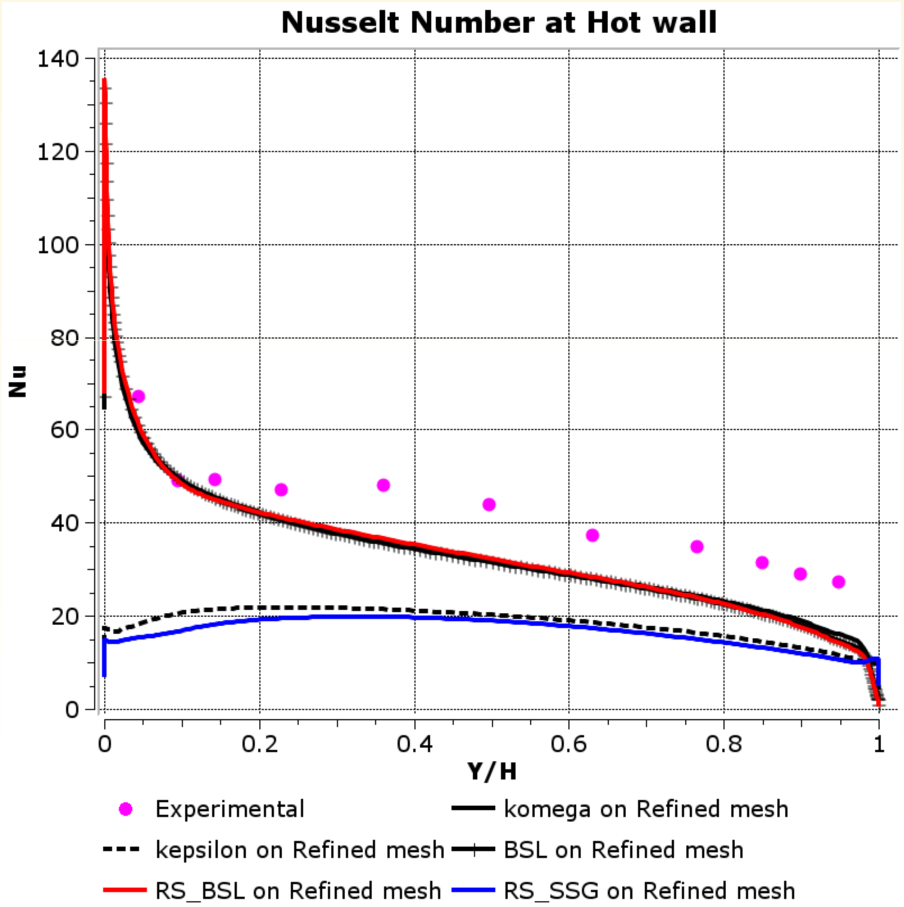
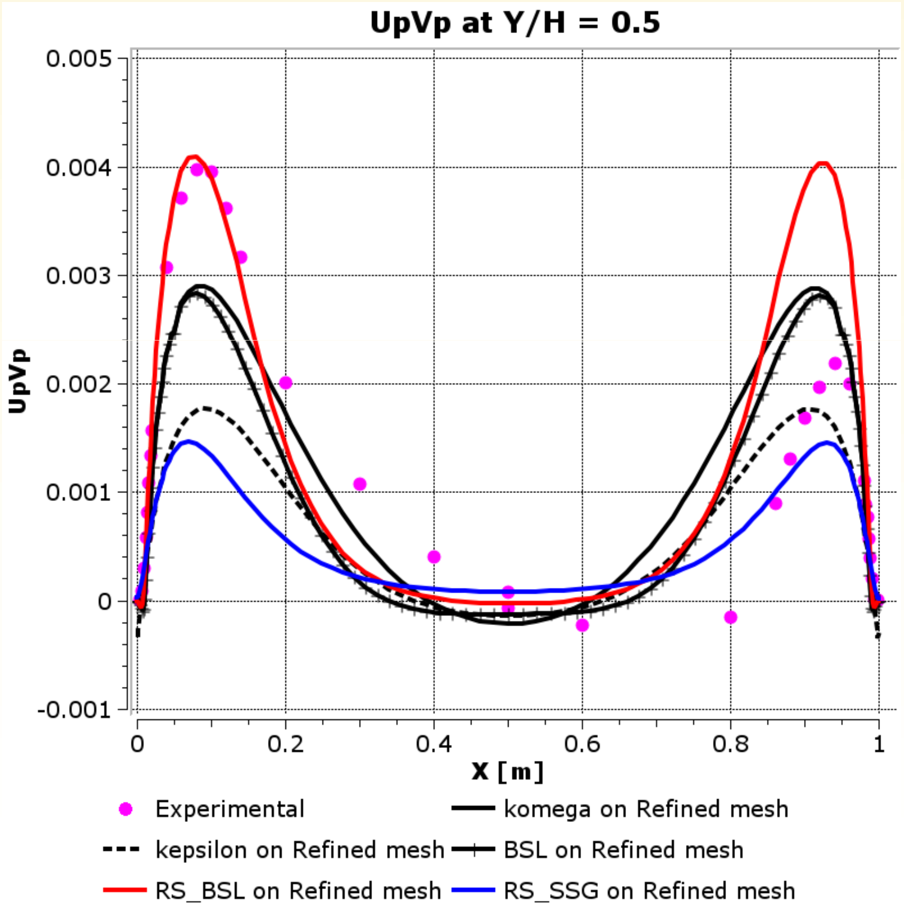


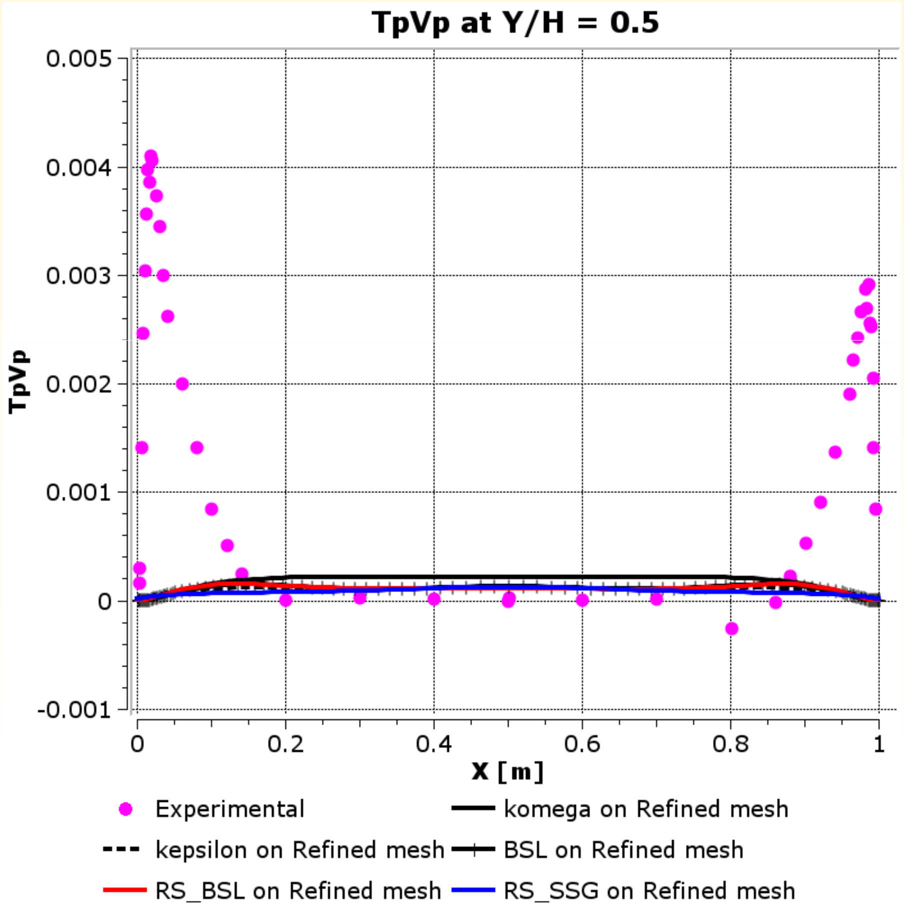
Model Comparison



For the two equation models:

$$u'v' = -\frac{\left(\frac{\mu_t}{\rho}\right)\left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)}{U_C^2}$$

Model Comparison



$$T'v' = -\frac{\left(\frac{\mu_t}{\rho}\right)\left(\frac{\partial h}{\partial y}\right)}{0{,}9.\Delta T.U_C.c_p^{ref}}$$

Where:

c_p^{ref}= 1.005 J Kg^-1 K^-1

h = Static Enthalpy

Conclusions

- Mesh convergence was achieved
- Omega based models in CFX resolve viscous sub-layer and therefore provide better prediction of the flow
- Omega based models correctly predict Nusselt numbers (turbulent heat flux normal to wall is correctly predicted)
- For all models the turbulent heat flux in the Y direction (TpVp) is greatly under predicted due to the turbulent Prandtl number approximation

References

- Uittenbogaard, R.E. [1989] Stably Stratified Mixing Layer. Data Report for the 14th meeting of the IAHR Working Group on Refined Flow Modelling
- Uittenbogaard, R.E. [1995] The Importance of Internal Waves for Mixing in a Stratified Estuarine Tidal Flow
- R.Cheesewright, K.J.King and S.Ziai [1986] Experimental data for the validation of the computer codes for the prediction of two-dimensional buoyant cavity flows, Proc. ASME Meeting, HTD, Vol. 60, pp. 75-81.
- S.K. Choi, E.K. Kim and S.O. Kim [2003] Evaluation of two different k-epsilon-vv-f turbulence models for natural convection in a rectangular cavity