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AALBORG UNIVERSITY
**Department of Civil Engineering**

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by

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# Contents

## 1. INTRODUCTION

The purpose of this investigation is to compare the different flow patterns obtained for the 2D isothermal test case defined in Annex 20 (1990) using different turbulence models. The different results are compared with the existing experimental data.
Similar study has already been performed by Rong et al. (2008) using Ansys CFX 11.0. In this report, the software Star-CCM+ has been used.

## 2. PRESENTATION OF THE ISOTHERMAL CASE

The simulations are performed with the two dimensional isothermal Annex 20 room benchmark test described by Nielsen (1990). The sizes of the annex 20 room are specified as:

L = 9m, H = 3m, $h_1$ =0.168m, $h_2$ =0.48m

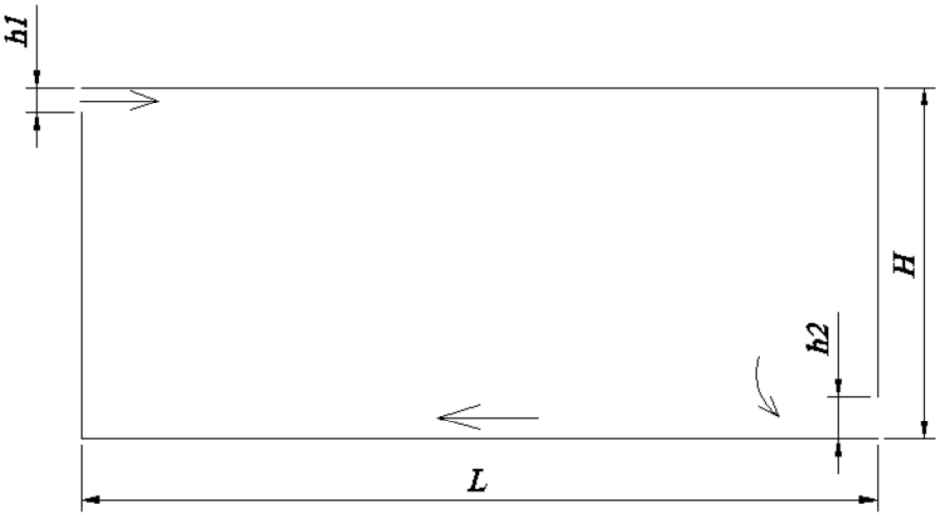



*Figure 1: Sketch of the benchmark test*

The air is supplied from left top with velocity in 0.455 m/s and exhausted from right bottom. The inlet conditions are listed in the following:

$$u_0 = 0.455\, m/s$$

$$k_0 = 1.5 * (0.04\, u_0)^2 = 4.97\,.10^{-4}\, J/kg$$

$$\varepsilon_0 = \frac{{k_0}^{1.5}}{l_0} = 6.59\,.10^{-4}\, J/kg.s \qquad \text{with} \quad l_0 = \frac{h_1}{10}$$

According to Nielsen (1990), the inlet conditions correspond to a turbulence intensity of 4%.

## 3. PRESENTATION OF THE SIMULATIONS

It has been shown by Olmedo et al. (2010) that the studied case can be considered as a steady two dimensional case (steady or unsteady) in the major part of the domain. Therefore the simulations have been performed with a two dimensional geometry, and assuming a steady state. The CFD models are solved using the segregated flow model and air is considered as an ideal gas.

In this report the results obtained with different meshes are presented, and different k-ε and k-ω models are tested.

Figure 2 shows four line locations where the simulations results can be compared with measurements.

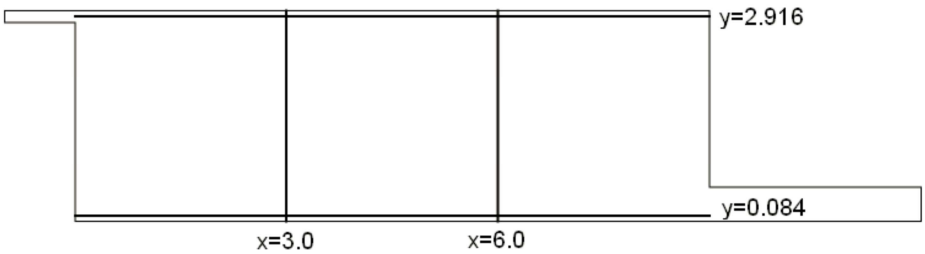


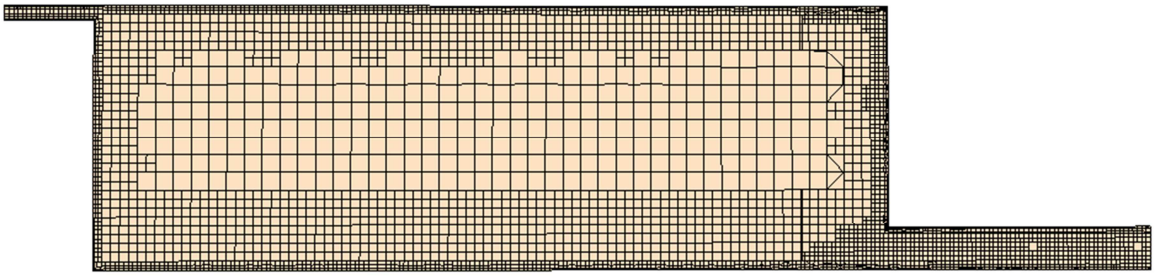

*Figure 2: Sketch of the vertical and horizontal lines where the velocity profiles have been measured*

## 4. DIFFERENT COMPUTATIONAL GRIDS

The number of cells in the computational grid has been chosen similar to Voigt (2000). Different grids are used in combination with the k-ε and k-ω models.

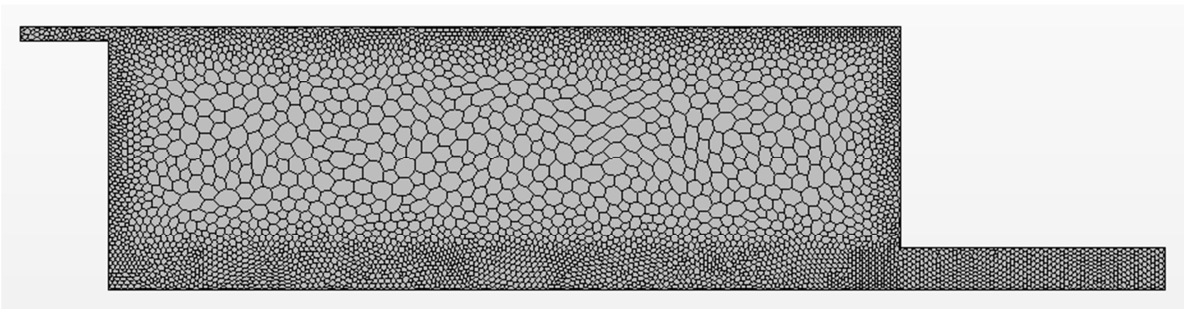
- Mesh 1: coarse & structured

| Characteristics | Surfaces mesh 3D | Volume mesh 3D | Surface mesh 2D |
|---|---|---|---|
| Structured<br><br>Base size: 0.2m<br>Custom size at the border: 30% (0.06m) | 38 930 faces<br><br>(surface remesher) | 185 125 faces<br><br>(trimmer with prism layer mesher) | 4 068 cells |



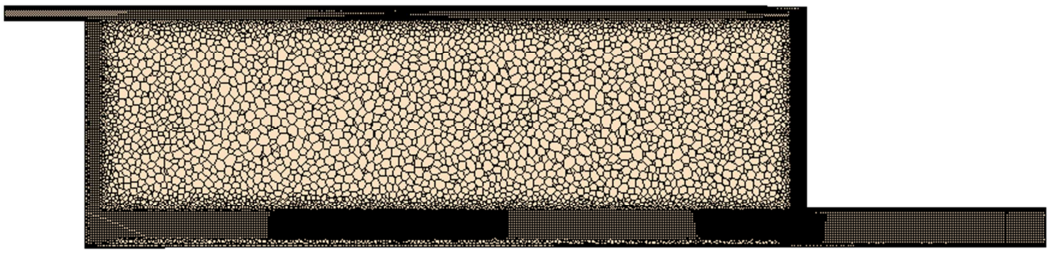
- Mesh 2: coarse & unstructured

| Characteristics | Surfaces mesh 3D | Volume mesh 3D | Surface mesh 2D |
|---|---|---|---|
| Unstructured<br><br>Base size: 0.2m<br>Custom size at the border: 30% (0.06m) | 38 930 faces<br><br>(surface remesher) | 117 567 faces<br><br>(polyhedral with prism layer mesher) | 4 793 cells |



- Mesh 3: fine & unstructured

| Characteristics | Surfaces mesh 3D | Volume mesh 3D | Surface mesh 2D |
|---|---|---|---|
| Unstructured<br><br>Base size: 0.1m<br>Custom size at the border: 30% (0.03m) | 140 762 faces<br><br>(surface remesher) | 4 840 630 faces<br><br>(polyhedral with prism layer mesher) | 16 658 cells |



## 4.1 LIST OF SIMULATIONS

| Nbr | Type of turb. model | Wall function | Others... | Mesh |
|---|---|---|---|---|
| 2 | k- ε | High y + Wall treatment | Steady state – 2D<br>Ideal gas<br>Segregated flow | 1- Structured Coarse (4,1 k-cells) |
| 1 | | | | 2- Unstructured Coarse (4,8 k-cells) |
| 3 | | | | 3- Unstructured Fine (16,7 k-cells) |

## 4.2 CONVERGENCE

The figures below show the convergence with different grids. Convergence is longer to reach with a finer mesh.

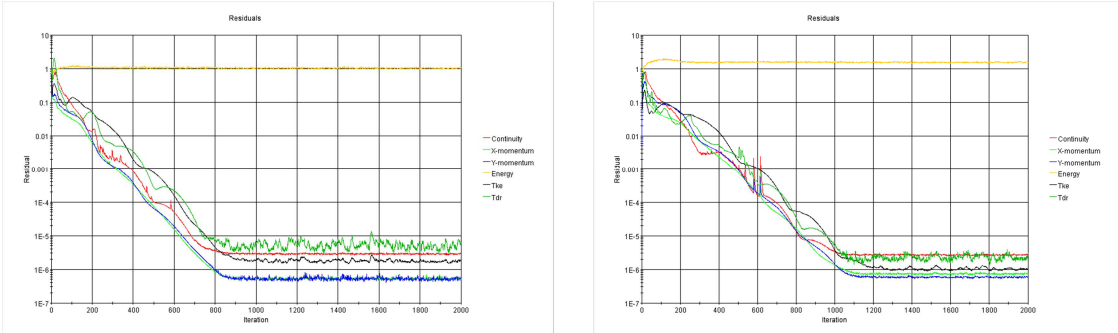



*Figure 3: Structured grid (left) vs. Unstructured grid (right) – Coarse mesh*

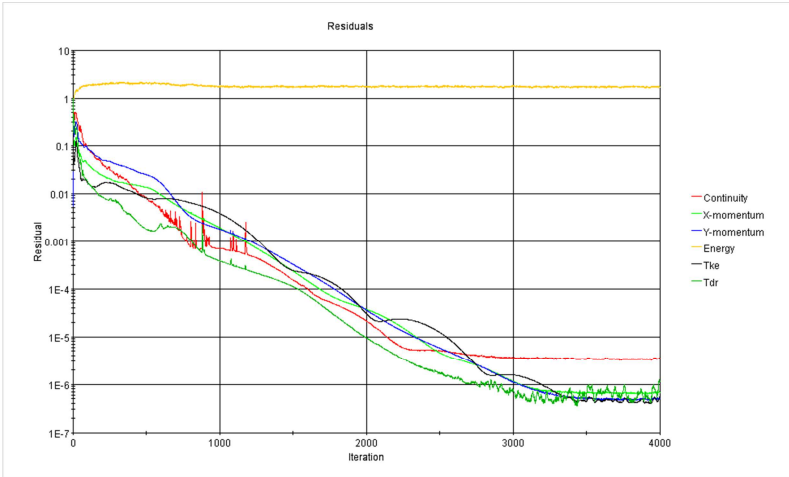
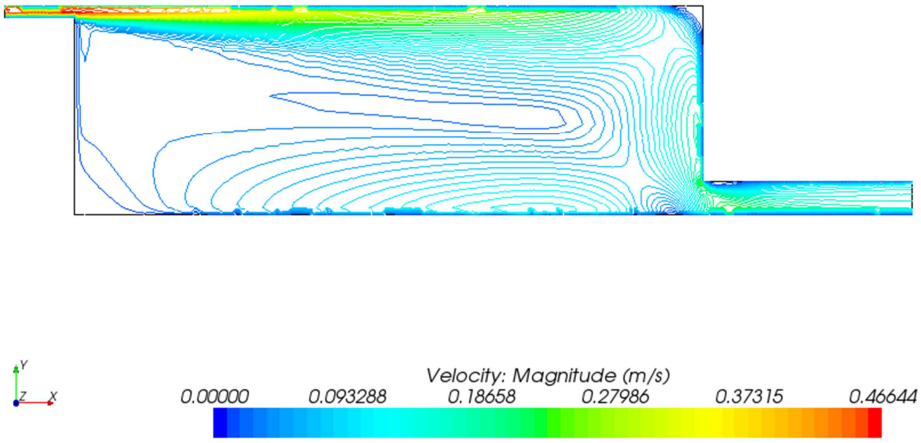


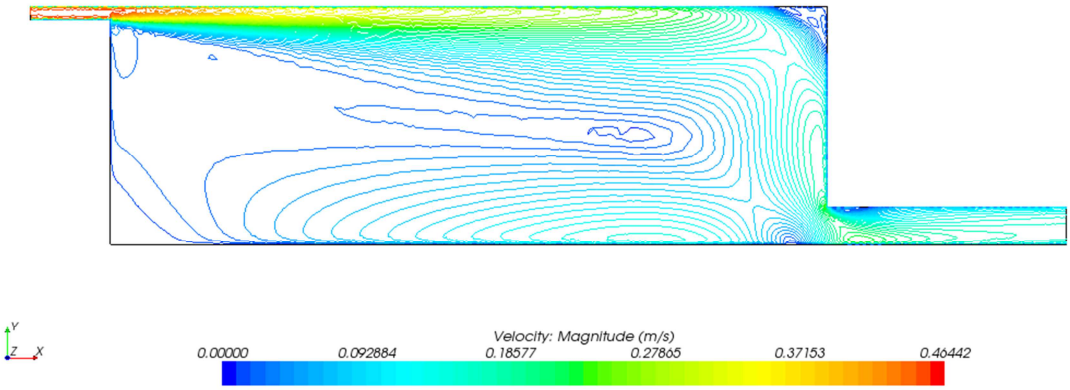

*Figure 4: Fine and unstructured mesh*

## 4.3 STREAMLINES

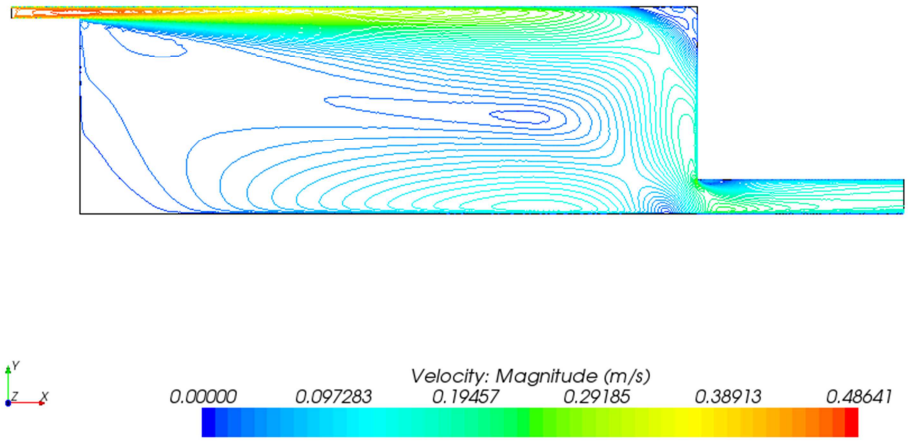
Simulation 2: Structured & coarse



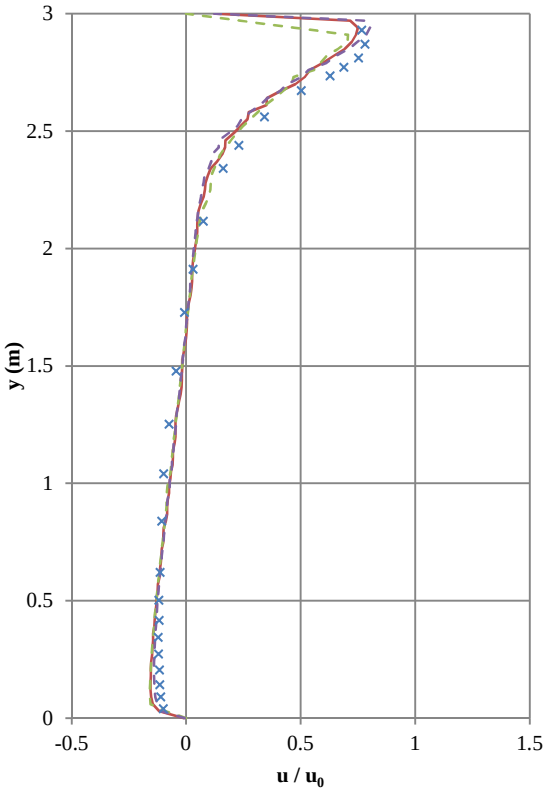

Simulation 1: Non-structured & coarse

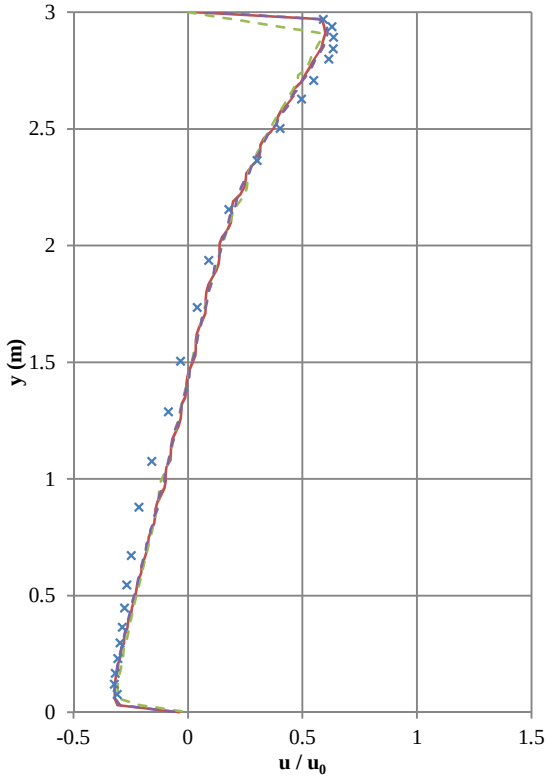


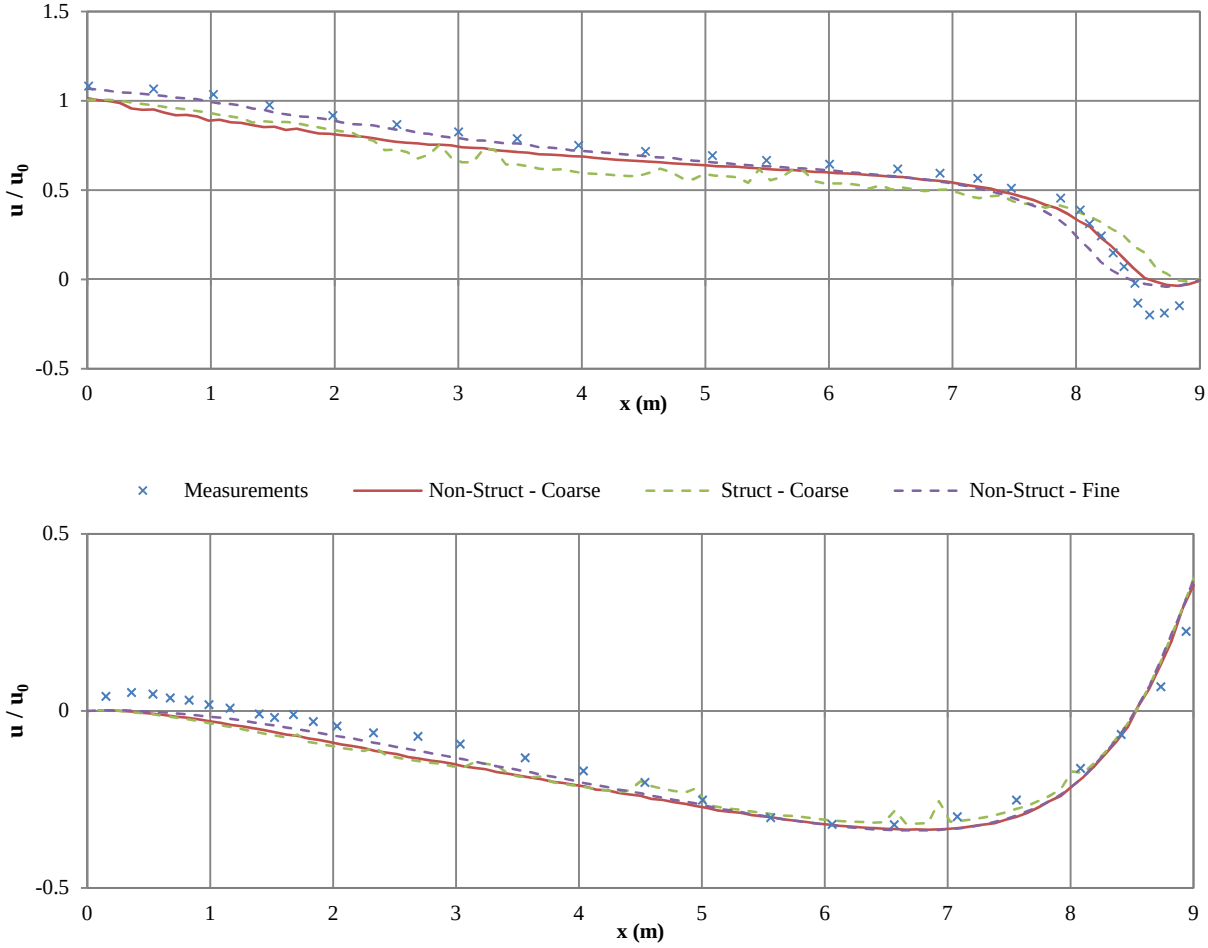

Simulation 3: Non-structured & fine



## 4.4 VELOCITY PROFILES



⇒ The structured mesh showed the less accurate results. This could be due to the slightly lower number of cells used, or due to the layout, which might be less efficient. A finer mesh is required. With an unstructured grid, a finer mesh gives better results compared to experiment, but still doesn't fit exactly with the results.
Nevertheless it has to be noticed that this analysis has been performed only with the standard k-ε model. Conclusions might change with another turbulence model.

# 5. DIFFERENT K-E MODELS

## 5.1 LIST OF SIMULATIONS

| Nbr | Type of turb. model | Wall function | Others... | Mesh |
|---|---|---|---|---|
| 3 | Standard k- ε | High y + Wall treatment | Steady state – 2D<br>Ideal gas<br>Segregated flow | 3- Unstructured Fine (16,7 k-cells) |
| 4 | Standard k-ε Low-Re | All y + Wall treatment | | |
| 5 | AKN k-ε Low-Re | All y + Wall treatment | | |
| 6 | Realizable k-ε | High y + Wall treatment | | |

The inlet conditions are defined with:

$$k_0 = 1.5 * (0.04\, u_0)^2 = 4.97\,.10^{-4}\, J/kg$$

$$\varepsilon_0 = \frac{{k_0}^{1.5}}{l_0} = 6.59\,.10^{-4}\, J/kg.s$$

When using the Standard k- ε model, the inlet turbulent viscosity is therefore equal to (CD Adapco - 2011):

$$\mu_t = \rho\ C_\mu\ k\ max\left(\frac{k}{\varepsilon}\ ;\ 0.6\sqrt{\frac{\bar{v}}{\varepsilon}}\right) \approx 1.225 \cdot 0.09 \cdot \frac{k^2}{\varepsilon} \approx 4.13\,.10^{-5}\, Pa.s$$

And the inlet turbulent viscosity ratio:

$$\frac{\mu_t}{\mu} \approx \frac{4.13\,.10^{-5}}{1.855\,.10^{-5}} \approx 2.22$$

## 5.2 CONVERGENCE

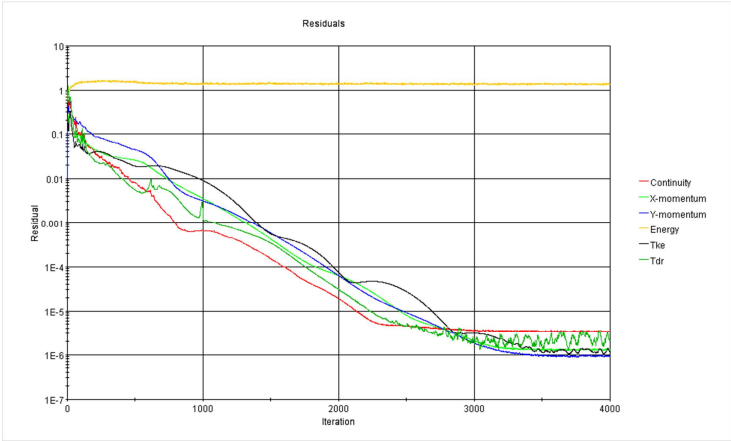



*Figure 5: Simulation 4*

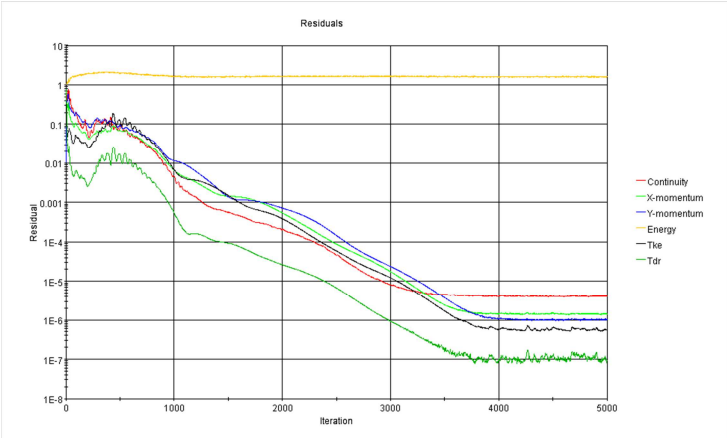



*Figure 6: Simulation 5*

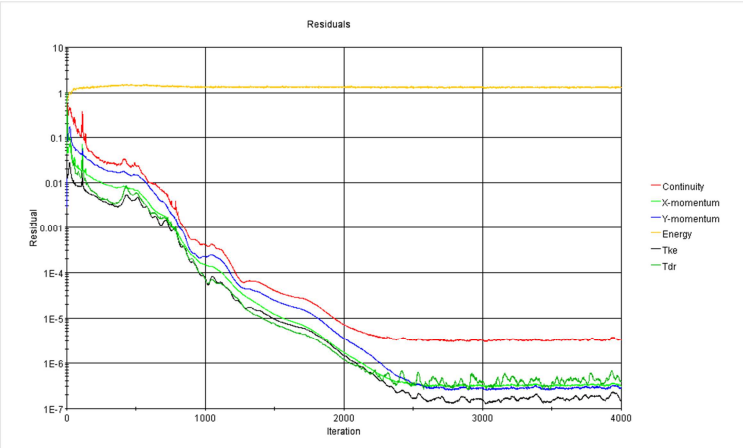
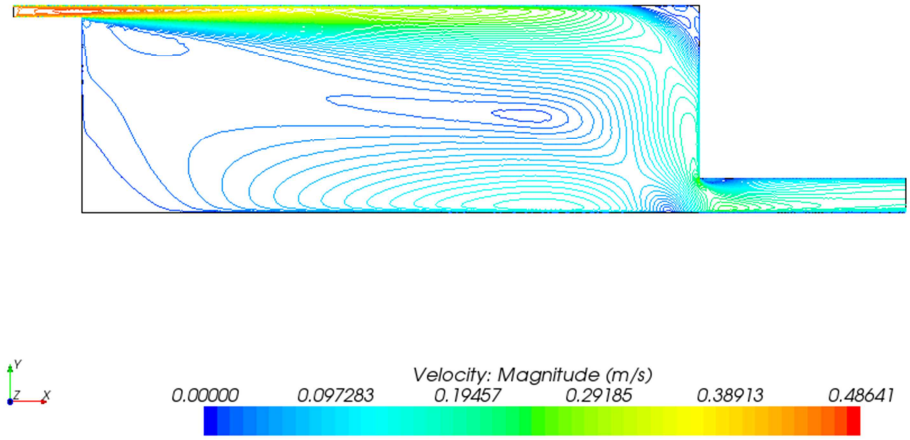


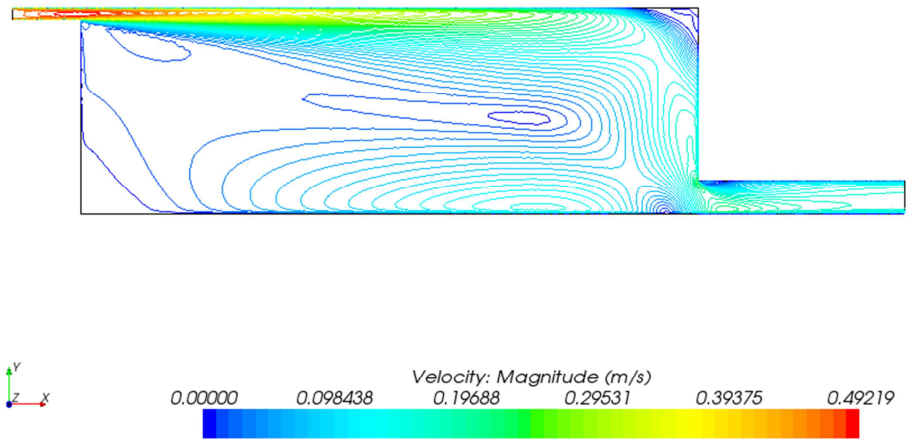

*Figure 7: Simulation 6*

## 5.3 STREAMLINES

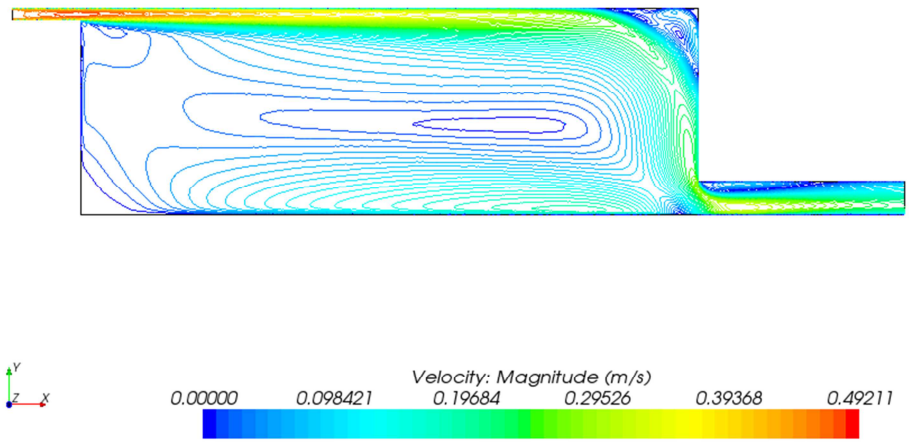
Simulation 3: Standard k- ε



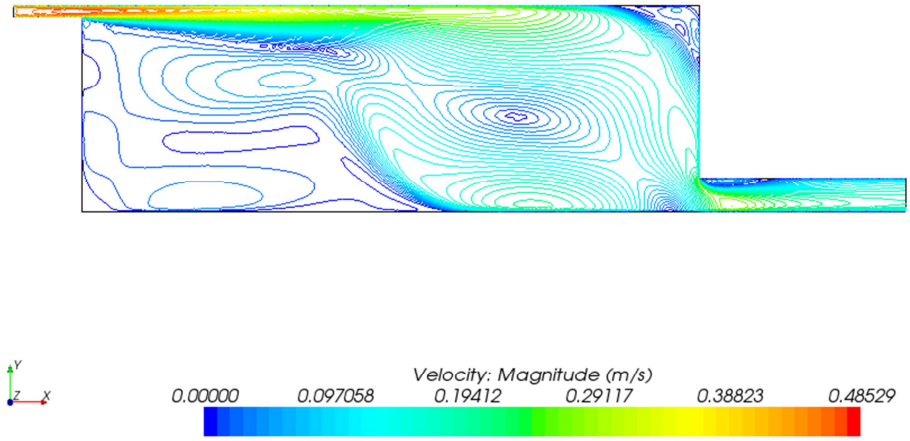

Simulation 4: Standard k- ε Low-Re



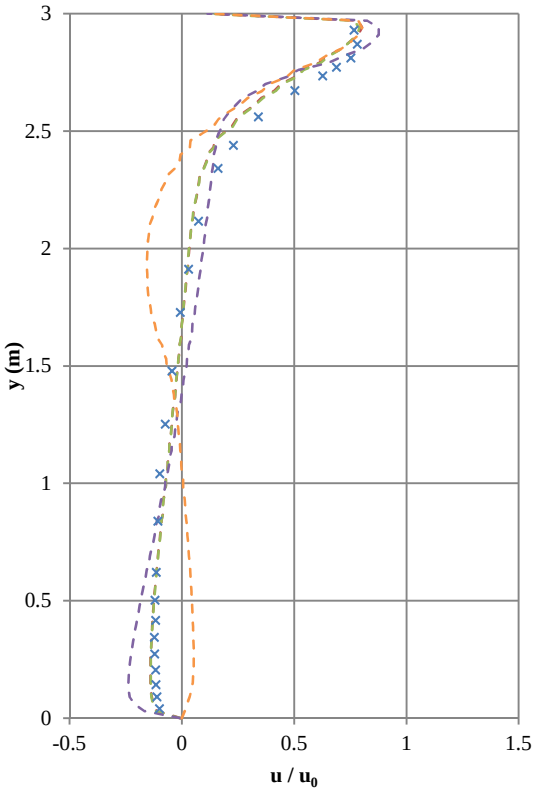

Simulation 5: AKN k- ε Low-Re

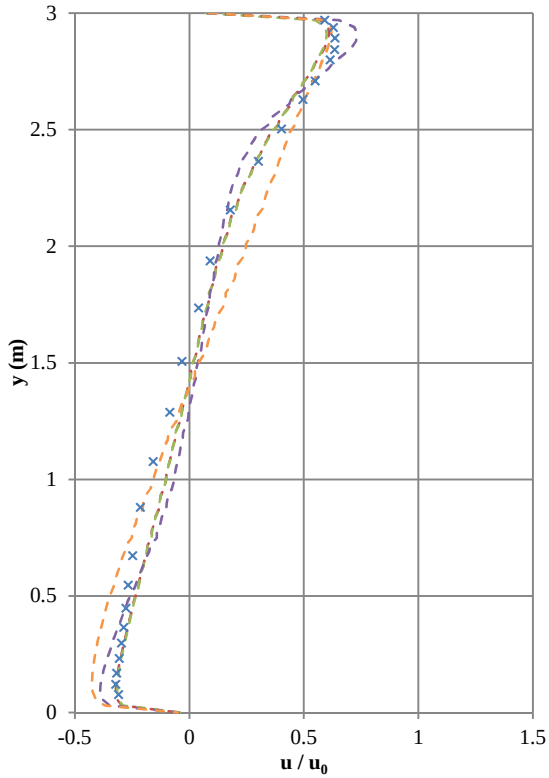


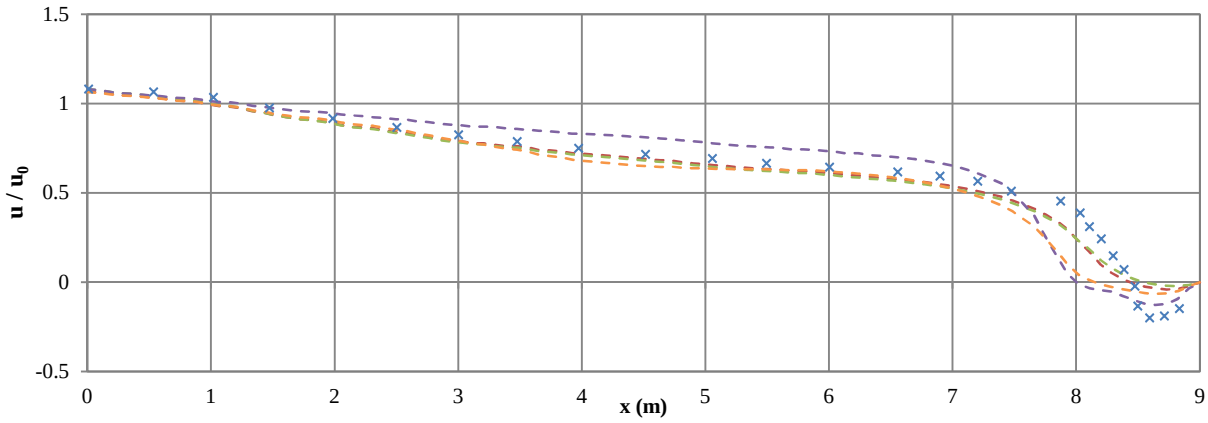
Simulation 6: Realizable k- ε

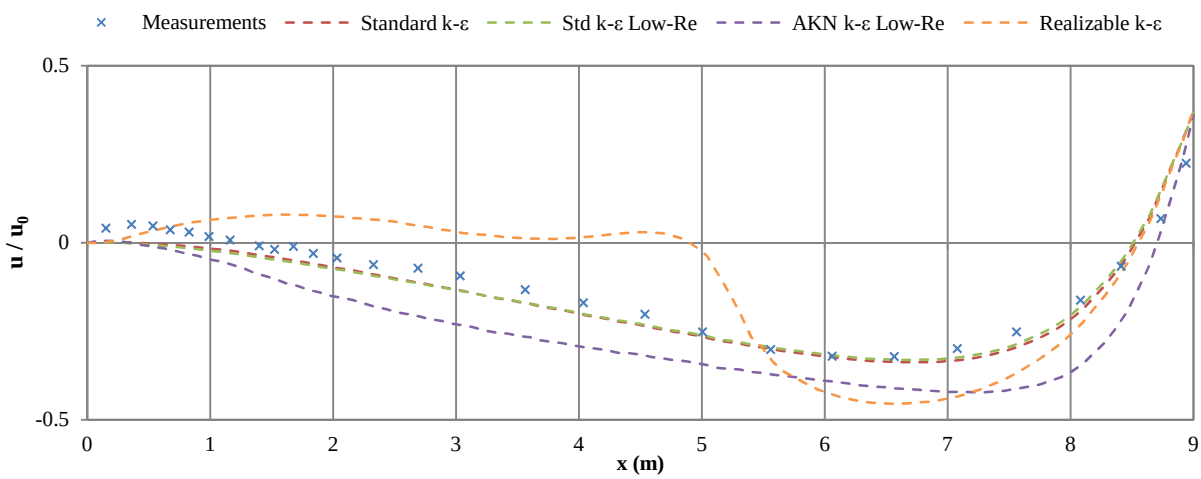


## 5.4 VELOCITY PROFILES



⇒ The performance of the standard k-ε and standard k-ε Low-Re are comparable and quite close to the measurements. Nevertheless the wall bounded flow is difficult to predict with all the models.
When applying the model AKN k-ε Low-Re, a recirculation zone appears in the right-upper corner. A less accurate correspondence with the results can be observed.
The results obtained with the turbulence model Realizable k-ε diverge the most with the experimental results. This is due to the presence of a complex zone of recirculation on the left part of the room.

## 5.5 About the Low-Reynolds number model

It has been seen that the results of the standard k-ε and standard k-ε Low-Re are almost the same. This might be due to the fact that the Low-Reynolds model is almost never activated during the simulation, and the standard k-ε model dominates. In fact, a standard k-ε model can be considered as a special version of a Low-Re number model, without any damping function at low local turbulence Reynolds number $R_t$ .
Nielsen (1995) suggested that the limit for $R_t$ was 400: above this value, a Low-Re model corresponds to a standard k-ε model. Even if the Low-Re model used in Star-CCM+ is slightly different (model from Lien, and not from Launder and Sharma), this limit has been kept, as the basis of the two models are the same.
This means that if the turbulent viscosity ratio is above around 40, the damping functions will disable the Low-Reynolds number model.

The turbulent viscosity ratio obtained from the simulation can be seen on the figure below. It can be seen that this ratio is in most of the domain above 40, therefore deactivating the Low-Re model. This explains why the results of the standard k-ε and standard k-ε Low-Re are similar.

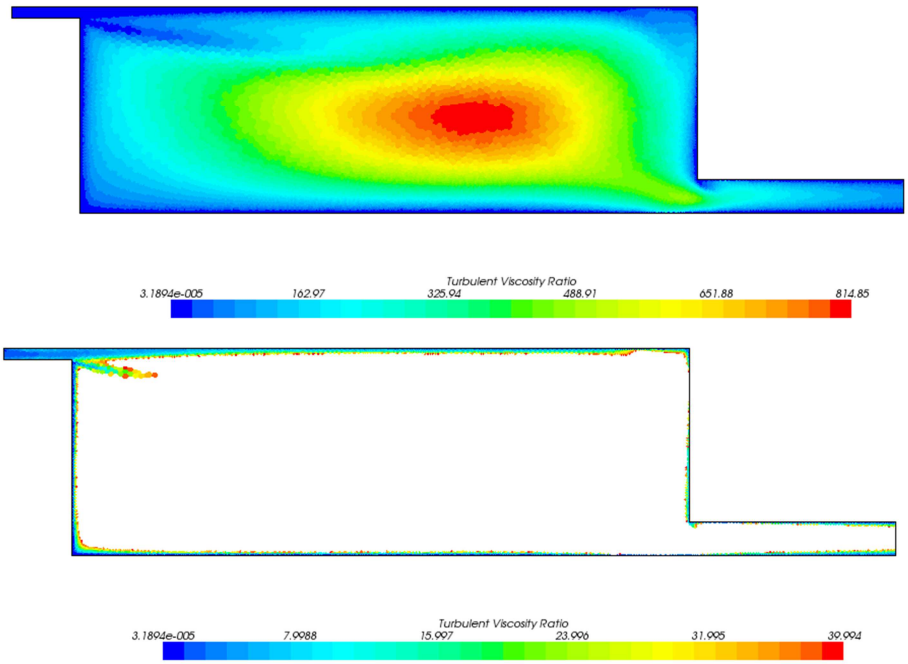



*Figure 8: Turbulent viscosity ratio - Standard Low-Re turbulence model*
*Below are only represented the cells where the turbulent viscosity ratio is below 40.*

When having a closer look to the inlet, it can be observed that the turbulence viscosity ratio is relatively small, close to 2. This can be explained by the values of $k_0$ and $\varepsilon_0$ that have been set at the inlet: it will lead to a turbulence viscosity ratio around 2.2 for the standard k-ε model (cf. page 10).

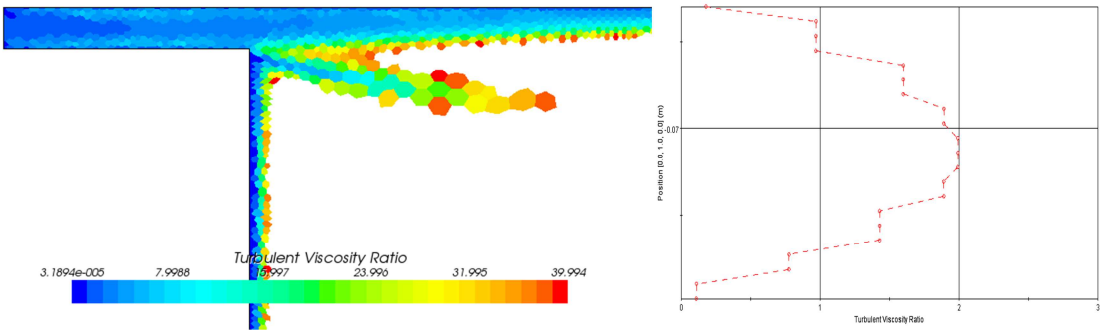



*Figure 9: Turbulence viscosity ratio at the inlet*

# 6. DIFFERENT K-Ω MODELS

## 6.1 LIST OF SIMULATIONS

| Nbr | Type of turb. model | Wall function | Others... | Mesh |
|---|---|---|---|---|
| 7 | Standard k-ω (Wilcox) | All y + Wall treatment | Steady state – 2D<br>Ideal gas<br>Segregated flow | 3- Unstructured Coarse (4,8 k-cells) |
| 8 | SST k-ω (Menter) | All y + Wall treatment | | |

The inlet conditions are defined with:

$$turbulence\ intensity = 0.04$$

$$l_0 = \frac{h_1}{10} = 0.0168\ m$$

## 6.2 CONVERGENCE

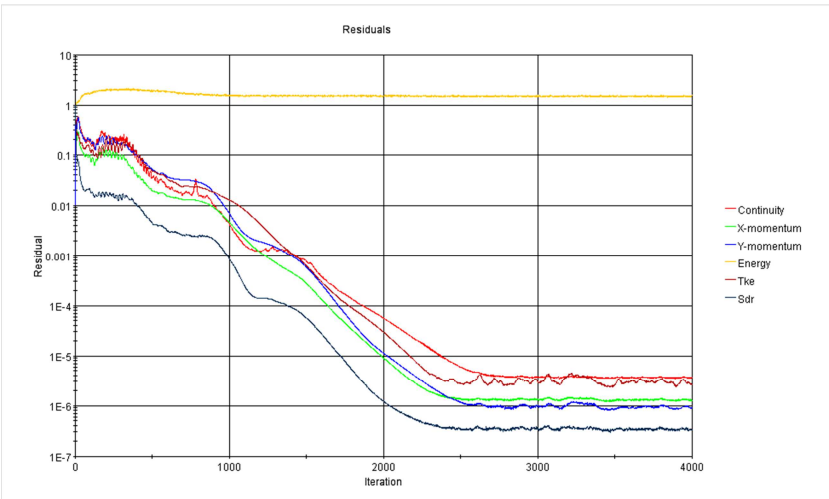



*Figure 10: Simulation 7*

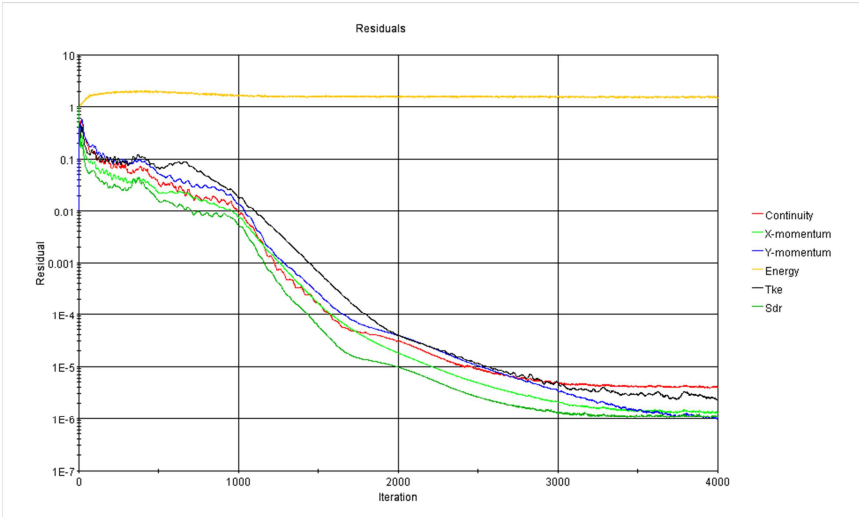
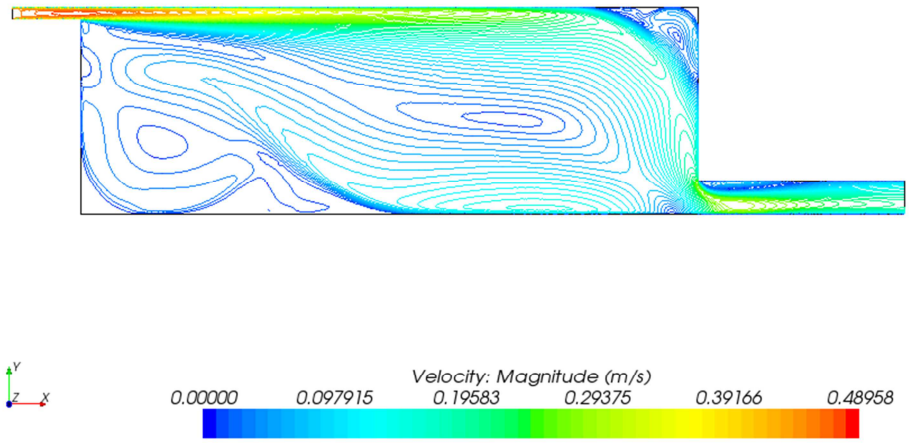


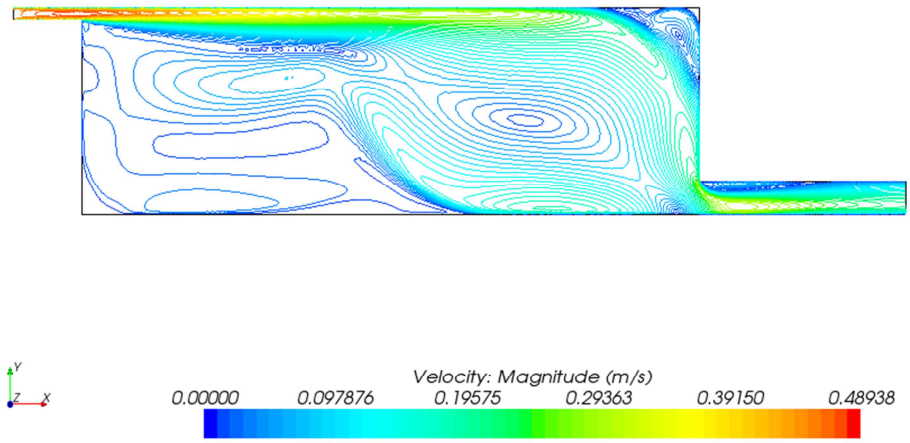

*Figure 11: Simulation 8*

## 6.3 STREAMLINES

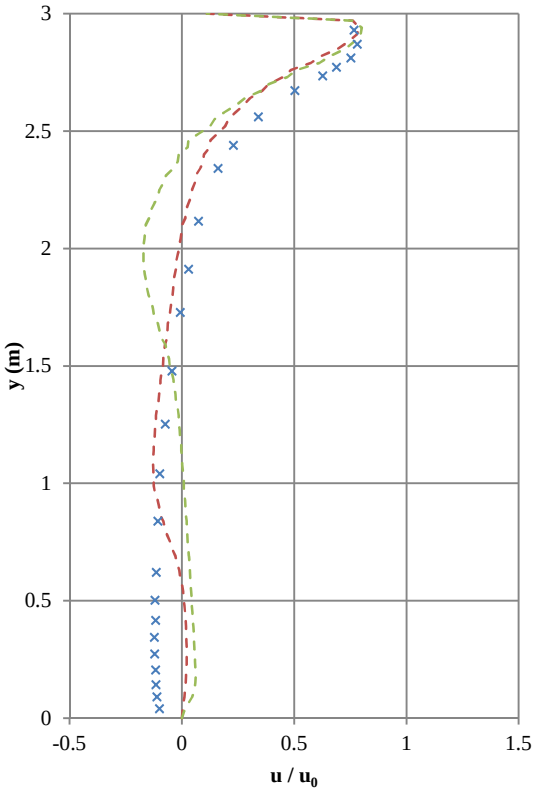
Simulation 7: Standard k-ω

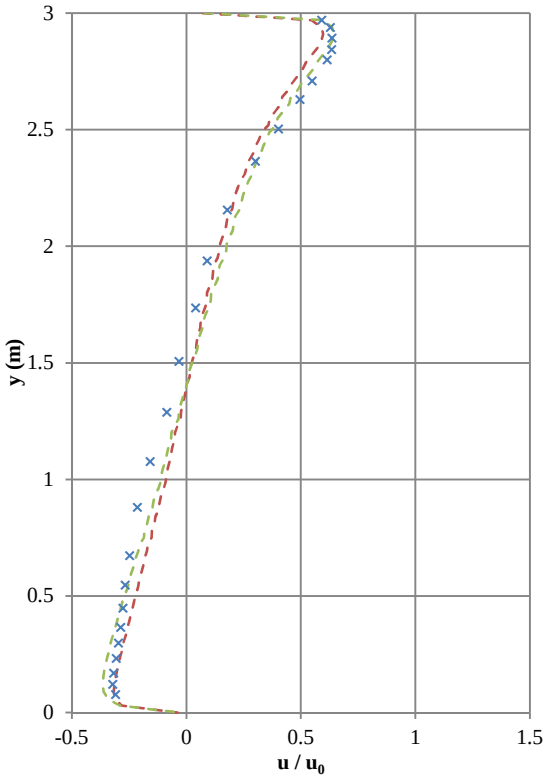


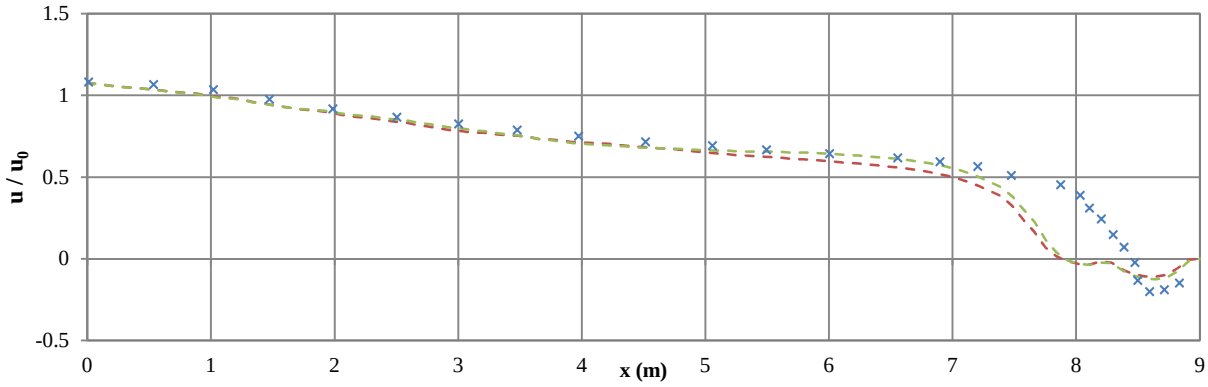

Simulation 8: SST k-ω



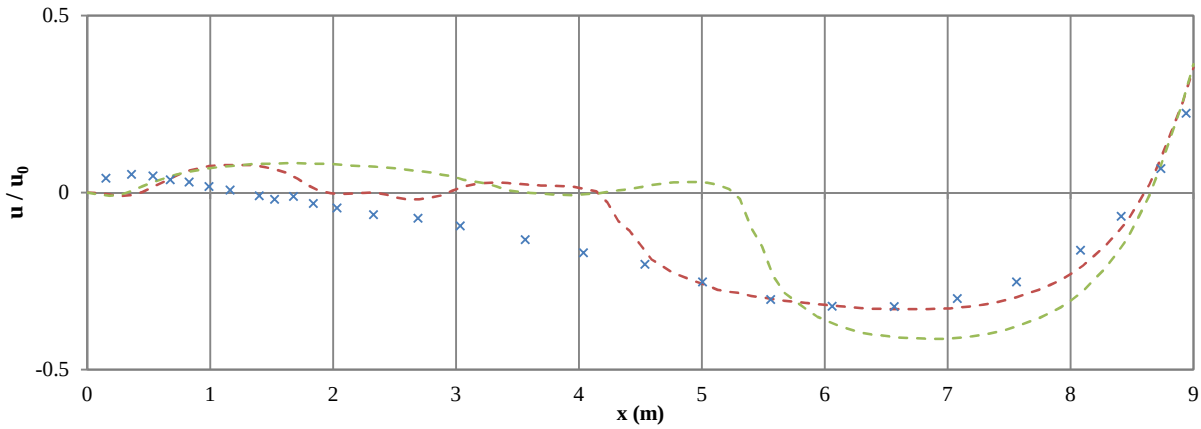
## 6.4 COMPARISON PROFILES




× Measurements — — Standard k-ω — — SST k-ω



⇒ The results obtained with a k-ω model are not in accordance with the experimental results, especially away from the main stream. In these two cases, a complex recirculation zone can be observed on the left part of the room.
But the eddy recirculation in the right upper corner is better predicted with these models than with the k-ε model.

## 7. CONCLUSION

In this report, simulations with the Annex 20 benchmark test have been performed using Star-CCM+. The goal was to study how different turbulence models predict the velocity distribution in a ventilated room.

In the main stream away from the wall (upper part and right part of the test room), all turbulence models give relatively accurate results. Differences can be observed in the recirculation zone on the upper right corner and on the left part. The standard k-ε or the standard k-ε low-Re models predict well the recirculation zone on the left part, but no eddy recirculation is predicted in the right upper corner.
The other models (k-ω, k-ε AKN and Realizable) predict this eddy recirculation, but underpredict its intensity. Nevertheless the velocity profile in the left part of the room is not well-predicted with these models.

These simulations pointed out the fact that numerical simulations should always be compared with measurements since different turbulence models will give different results in a specific case.

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