

STUDY OF THE INFLUENCE OF THE COMPUTATIONAL GRID ON THE RSM TURBULENCE MODEL IN THE LAYER MIXING PROBLEM

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Abstract: This paper investigates the effect of changing the computational grid on the results of the nonlinear turbulence model RSM (Reynolds Stress Model) in combination with the SST (Shear Stress Transport) ω -model. The RSM model is one of the most advanced models for calculating turbulent flows, which takes into account the anisotropy of turbulent stresses. To test the effectiveness of this model, a mixed flow problem was considered based on NASA experimental data. Calculations were performed using the ANSYS Fluent software package. During the study, the numerically obtained distributions of flow velocity and Reynolds stresses were compared with experimental data in several control sections. Also, an assessment was made of the effect of different types and resolutions of computational grids on the accuracy of modeling in order to determine which grid provides the best agreement with the experiment and improves the accuracy of model predictions.

KEYWORDS: Navier–Stokes equations, separated flow, mixing layer, RSM S-omega model, Ansys Fluent

1 Introduction

Turbulent flows are central to most processes involving the dynamics of fluids and gases. Their accurate modeling plays a key role in solving a wide range of problems, from aerodynamic calculations in aviation to forecasting flows in natural and industrial systems. However, despite significant advances in computational fluid dynamics (CFD), modeling turbulent flows remains a challenging task, especially in the presence of complex geometries, strong velocity gradients, and multilayer flows. Various turbulence models are actively used to solve these problems, each with its own advantages and limitations [1]. One of the most advanced turbulence models is the Reynolds Stress Model (RSM). Unlike simpler models such as k - ϵ or k - ω , which rely on the hypothesis of isotropic turbulence, the RSM model is able to take into account the anisotropic properties of turbulent stress, which makes it more accurate in modeling complex flows. However, for the correct use of the RSM model, it is necessary to adapt it to specific problems and conditions, which requires careful selection of the computational grid parameters and verification of the accuracy of the simulation [2–3].

One of the important aspects in solving turbulence problems using the RSM model is the quality of the computational grid. The fineness of the grid, its structure, distribution of nodes and the quality of the elements can have a significant impact on the accuracy of the results obtained. An insufficiently dense grid can lead to the loss of important information about local turbulent structures, while an overly dense grid significantly increases computational costs without a noticeable improvement in accuracy. In this regard, an urgent task is to determine the optimal grid for specific simulation conditions, which allows finding a balance between accuracy and computational costs [4–6].

This paper studies the effect of changing the computational grid on the results of the nonlinear RSM turbulence model in combination with the SST (Shear Stress Transport) ω -model when solving a mixed flow problem based on NASA experimental data. The aim of this study is to analyze how changing the structure and density of the computational grid affects the accuracy of flow velocity and Reynolds stress modeling, as well as the agreement between the numerical results and experimental data. The ANSYS Fluent software [7] was used as a modeling tool, which allows flexible adjustment of the computational grid and turbulence model parameters. The study will consider different types of grids and conduct a comparative analysis of their accuracy and computational efficiency [8–12]. This study contributes to the field of turbulent flow numerical modeling by providing recommendations for selecting a computational grid for problems involving multilayer flows and demonstrates the capabilities of the RSM model in complex conditions.

2 Physical statement of the problem.

In the experiment, a 3 mm thick separator plate was used in a 300 mm wide tunnel [13–14]. The end of the plate was positioned at $x = 0$, where two fluid flows with different velocities merged. The plate had a taper starting at $x = -50$ mm and ending with a 0.3 mm thick trailing edge at $x = 0$. During the experiment, the upper flow, characterized by a higher velocity, had a boundary layer thickness of about 9.6 mm and a momentum layer thickness of about 1 mm near the trailing edge of the plate (at $x = -10$ mm). The lower flow, characterized by a lower velocity, had a boundary layer thickness of about 6.3 mm and a momentum layer thickness of about 0.73 mm. The Reynolds number based on the length L (where $L = 1$ mm is the length of the grid cell) was 2900. The reference temperature was set to $T_{ref} = 293$ K (528 R), the speed of sound was $a_{ref} = 343$ m/s, and the static pressure was considered to be equal to the atmospheric value of 101325 Pa. The flow velocities were 41.54 m/s for the upper flow and 22.40 m/s for the lower flow. Figure 1 shows the schematic of the computational grid and the boundary conditions used in the experiment. Four different computational grids were used in the problem, the characteristics of which are presented in Table 1. Figure 1 also shows grid #3, which was used for the numerical simulation.

Table 1

№		red	black	blue	Total grid
1	Grid 1	47x47	12x21	16x21	2797
2	Grid 2	93x93	23x41	31x41	10863
3	Grid 3	185x185	45x81	61x81	42811
4	Grid 4	369x369	89x161	121x161	169971

3 Mathematical statement of the problem

The RANS (Reynolds-Averaged Navier-Stokes) equations are a modified time-averaged Navier-Stokes equation used to model turbulent flows. The basic idea is to separate each flow variable (e.g. velocity, pressure, etc.) into two components: a time-averaged component and a component describing turbulent fluctuations. This separation is known as Reynolds decomposition and is written mathematically for an incompressible fluid as follows: [15]:

$$\begin{aligned} \frac{\partial \bar{U}_i}{\partial x_i} &= 0, \\ \frac{\partial \bar{U}_i}{\partial t} + \frac{\partial (\bar{U}_i \bar{U}_j)}{\partial x_j} &= -\frac{\partial \bar{p}}{\rho \partial x_i} + \frac{\partial}{\partial x_j} \left(\nu \frac{\partial \bar{U}_i}{\partial x_j} + \frac{\partial \overline{u_i' u_j'}}{\partial x_j} \right) + g_i, \end{aligned} \quad (1)$$

here $\overline{u_i' u_j'}$ – components of the Reynolds stress tensor.

- U_i - velocity components, - t - time, - p - pressure, - ρ - density, - ν - kinematic viscosity.

A new term $u_i' u_j'$ appears in the RANS equations, which represents the correlation of velocity fluctuations and is known as the Reynolds stress tensor [16]. This term describes the additional turbulent dynamics arising from the interaction of fluctuating velocity components. The Reynolds stress tensor actually reflects the effect of turbulence on the averaged flow and adds additional unknowns to the system of equations.

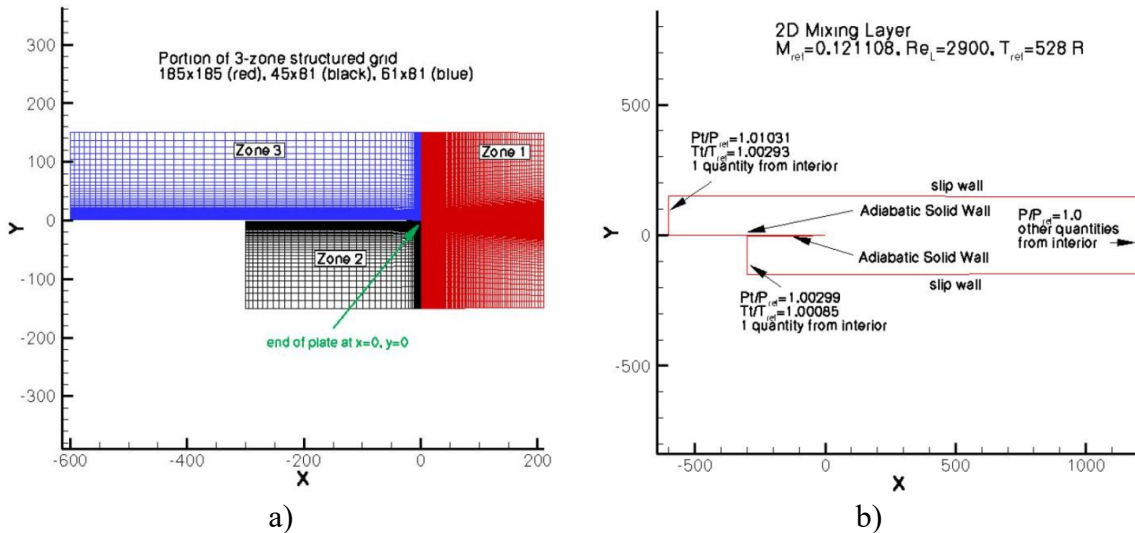


Fig. 1. 2D Mixing Layer. a) computational mesh and b) boundary conditions.

4 Turbulence models

The Reynolds Stress Model (RSM) [17–19] is one of the most accurate and detailed turbulence models used in computational fluid dynamics (CFD). Unlike models based on turbulent viscosity, such as $k-\varepsilon$ or SST, RSM solves the equations for each component of the Reynolds stress tensor directly. This allows for a more accurate description of complex and anisotropic turbulent flows. However, such accuracy requires significantly more computational resources, making the model more time-consuming to calculate. The Reynolds stress equations are as follows:

$$\frac{\partial R_{ij}}{\partial t} + \frac{\partial U_k R_{ij}}{\partial x_k} = P_{ij} + \Pi_{ij} - \varepsilon_{ij} + D_{ij}, \quad (2)$$

here $\rho R_{ij} = -\tau_{ij} = \rho u_i' u_j'$; P_{ij} – Reynolds stress generation; D_{ij} – diffusion, ε_{ij} – dissipation, Π_{ij} – member of the pressure redistribution. The remaining values are presented in the works [17–19].

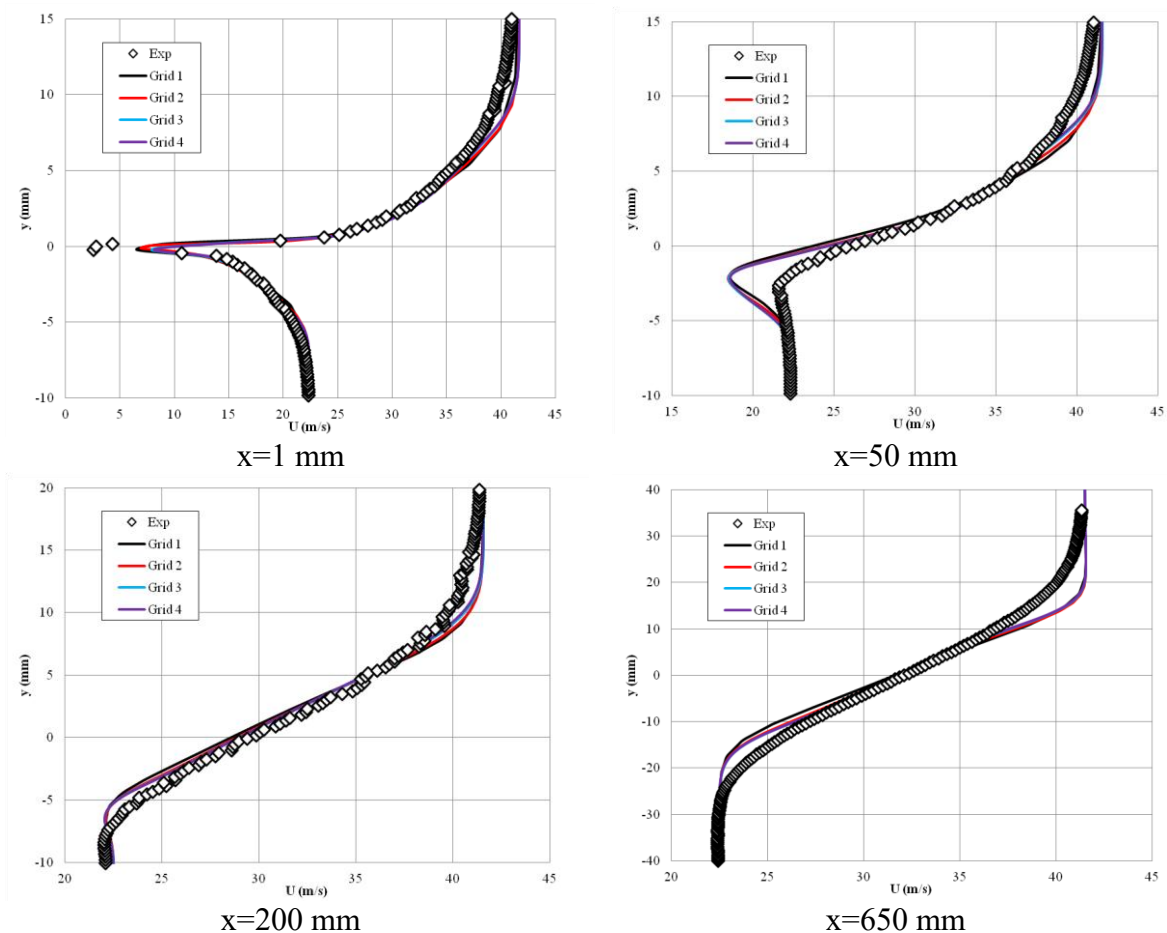
The Reynolds stress model (RSM) is particularly effective for strongly rotating flows, since such flows do not satisfy the isotropic assumption underlying the Boussinesq approximation [16]. Although this model may seem computationally excessive for many problems, its use is justified in cases where it is important to account for turbulence effects that are not described by standard turbulent viscosity-based models. Using the RSM allows one to study the effects of turbulent closure stresses without using the Boussinesq approximation, which is of particular interest for more complex and unsteady flows.

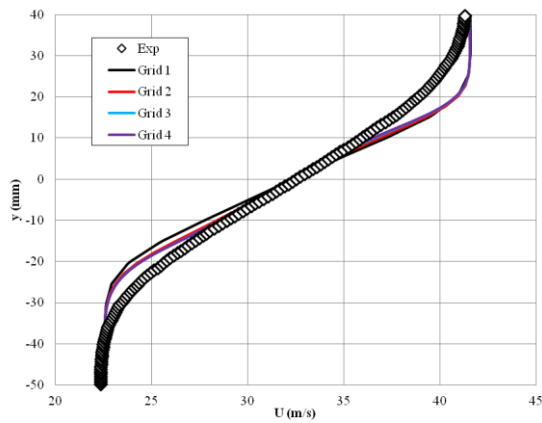
5 Method of solution

ANSYS Fluent offers a wide range of tools for numerical modeling of fluid dynamics processes, including turbulent flows, heat transfer, and chemical reactions. For turbulence problems, such as the Reynolds stress model (RSM S- ω), the fully coupled SIMPLE algorithm was used, known for its high accuracy and stability in solving systems of equations. This method is especially effective for jointly solving the velocity and pressure equations, which is critical for adequately modeling turbulent flows and obtaining reliable results. One of the important features of the applied approach is the use of a second-order accuracy scheme for all equations. This significantly improves the accuracy of the numerical solution due to a more accurate approximation of derivatives, which helps minimize numerical errors such as artificial dispersion and diffusion. This accuracy is especially important when modeling turbulent flows and complex thermal processes, where even small approximation errors can cause significant discrepancies with real physical processes. The use of the second-order "upstream" scheme improves the quality of interpolation and the stability of the solution under conditions of sharp gradients and rapid changes in flow parameters. This approach provides more accurate modeling of the dynamics of turbulent flows and heat transfer, which is an important aspect when performing complex engineering calculations and creating reliable mathematical models.

6 Calculation results and their discussion

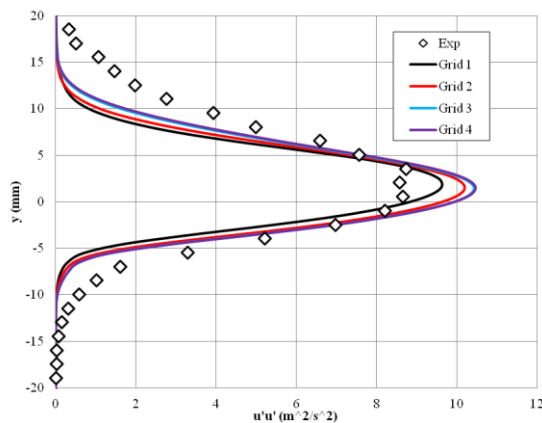
Fig. 2 shows the longitudinal flow velocity in different sections..



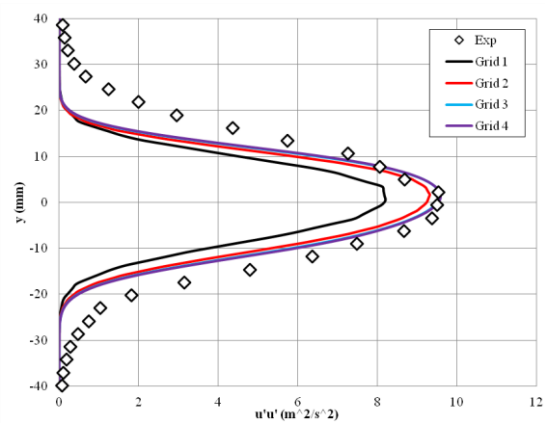


x=950 mm

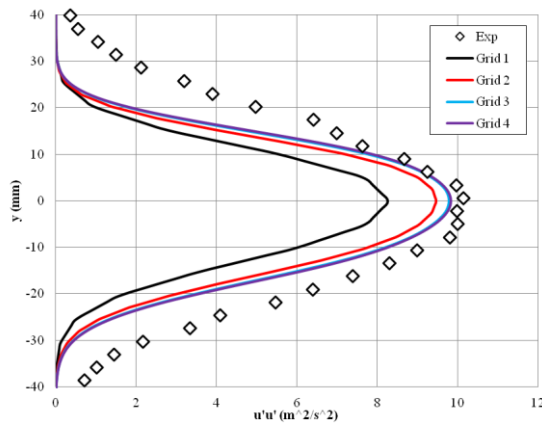
Fig. 2 Longitudinal flow velocity in different sections



x=200 mm



x=650 mm



x=950 mm

Fig. 3 Components of the Reynolds stress tensor $u'u'$

As can be seen from Figure 2, the results obtained for all the computational grids used are very similar to each other. However, it is worth noting that only the results obtained using the RSM model show significant deviations from the experimental data in the area of the merger of two flows with different velocities. This deviation may be due to the fact that the Reynolds stress model (RSM) takes into account the anisotropy of turbulent stresses, which makes it sensitive to complex flow interactions, especially in places of sharp changes in velocity and turbulence. In particular, in the junction zone of two flows with different velocities, complex turbulent structures may arise, which are described with less accuracy by standard turbulence

models based on the isotropy hypothesis. Figures 3–5 present the components of the Reynolds stress tensor calculated in different sections. These images illustrate the distribution of turbulent stresses in different areas of the study, which allows us to visualize their variations and assess the effect of turbulence on the flow in different parts of the model.

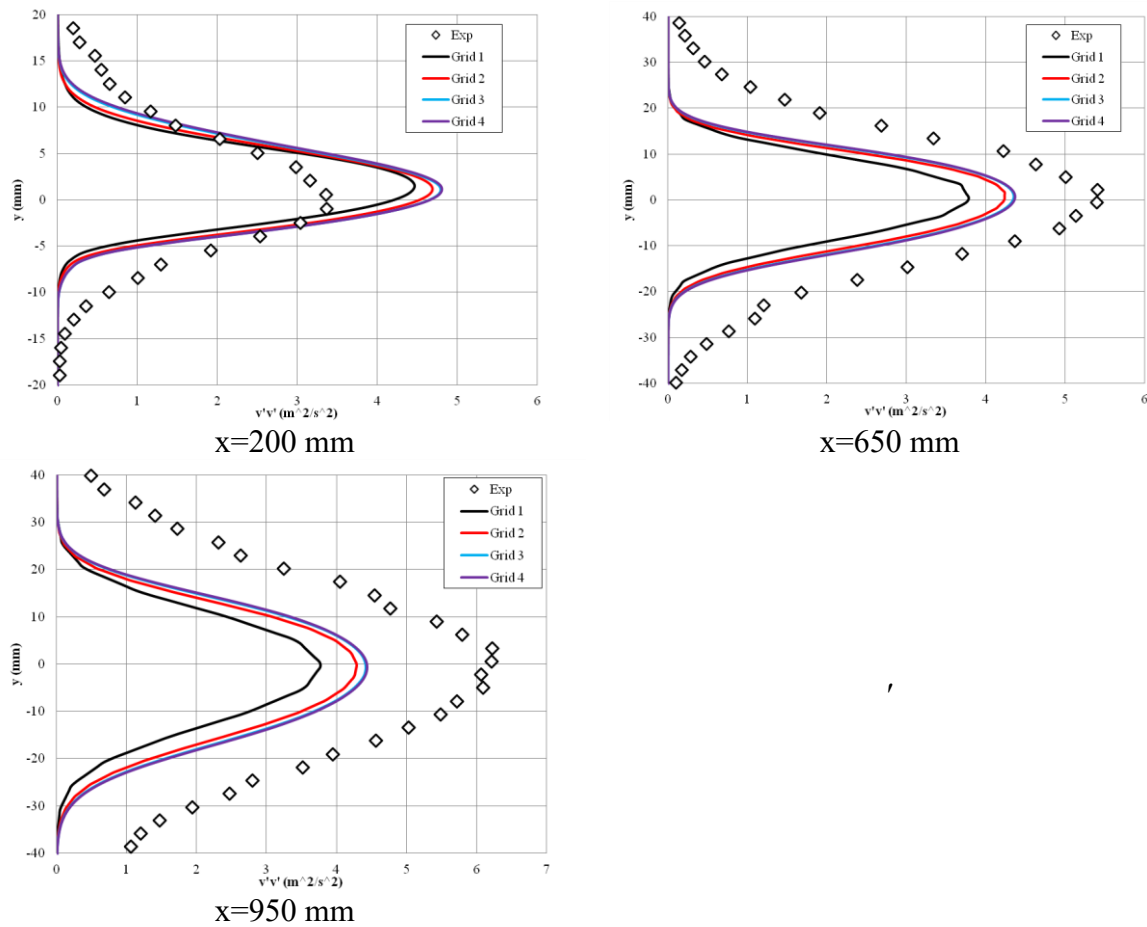


Fig. 4. Components of the Reynolds stress tensor $\overline{v'v'}$

As can be seen from Figures 3–5, the results obtained for the 3rd and 4th computational grids are very close to each other. These grids demonstrate a high level of consistency, which indicates the stability and accuracy of their calculations. At the same time, the results obtained for the 1st and 2nd computational grids show lower Reynolds stress values, which indicates insufficient detailing of turbulent effects in these grids. It follows from the analysis of Figures 3–5 that an increase in the resolution of the computational grid helps to improve the accuracy of the results, especially in the area where a more detailed representation of turbulent stresses is necessary. An increase in the number of grid elements allows for a more accurate modeling of complex turbulent structures and interactions. However, it should be taken into account that denser computational grids lead to an increase in computational time, which can be a significant factor when performing complex calculations. Thus, the choice of the optimal resolution of the computational grid is a compromise between the accuracy of the results and the computational costs. Increasing the mesh increases the accuracy of modeling, but at the same time requires more calculation time, which must be taken into account when planning and conducting numerical experiments.

Conclusion

The study examined the effect of changing the computational grid on the results of turbulent flow simulations using the Reynolds stress model (RSM) in the ANSYS Fluent software. The

main focus was on analyzing the accuracy of numerical simulation and the effect of different grid types on the calculation results. The results showed that increasing the resolution of the computational grid leads to an improvement in the accuracy of turbulent flow simulation, which is especially noticeable in the region of merging of two flows with different velocities. Models with a higher resolution (3rd and 4th computational grids) demonstrated a high degree of consistency, which indicates their reliability and accuracy. At the same time, using coarser grids (1st and 2nd computational grids) led to an underestimation of the Reynolds stress values, which indicated insufficient detailing of turbulent effects. The analysis showed that increasing the computational grid allows for a more accurate description of complex turbulent structures, but this is also accompanied by an increase in computational time. Therefore, the choice of the optimal computational grid resolution requires taking into account the trade-off between the required accuracy and the available computational resources. The results of the study highlight the importance of careful selection of the computational grid to achieve the accuracy of turbulent process modeling and computational efficiency. Future work can focus on developing grid optimization methods and improving turbulence models to further improve the accuracy and efficiency of numerical calculations.

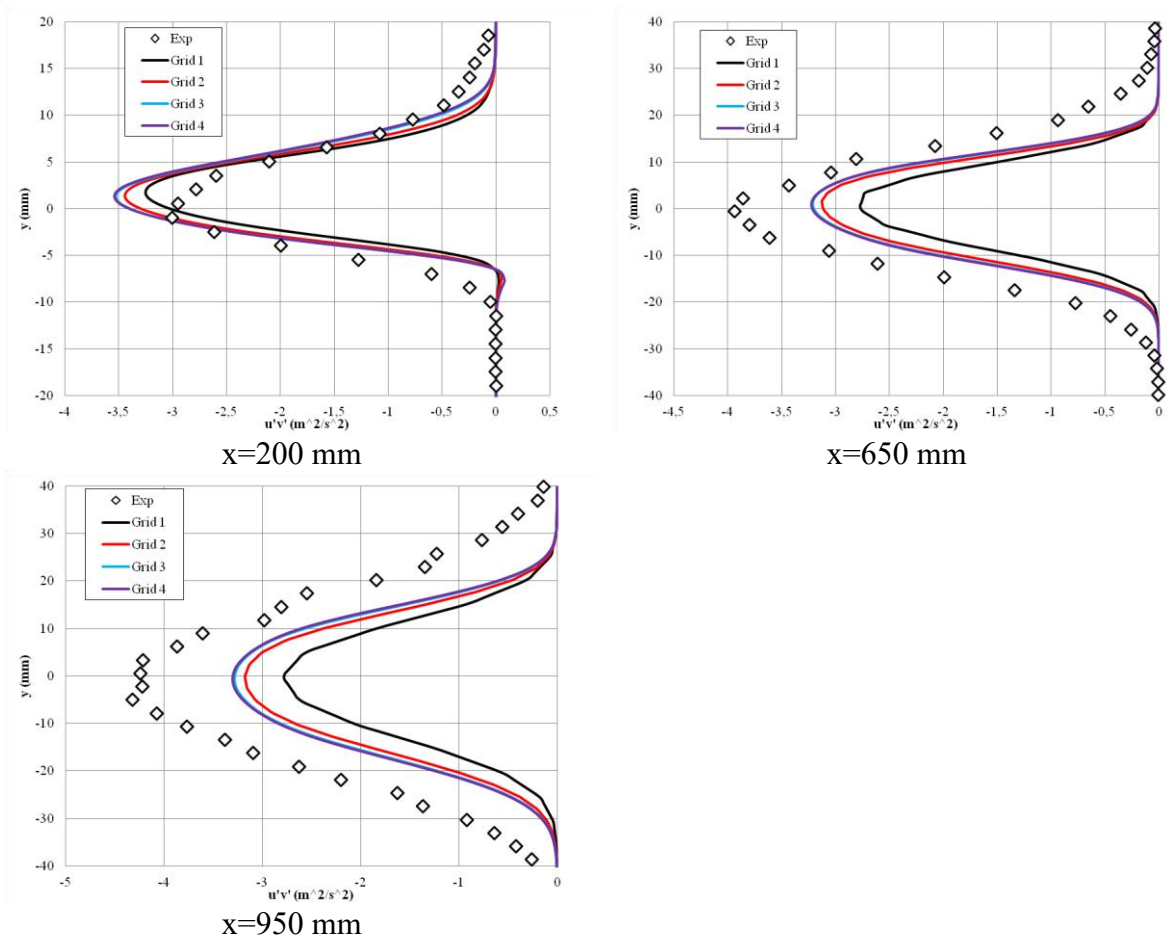


Fig. 5. Components of the Reynolds stress tensor $u'v'$

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