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Influence of the turbulence model in the CFD simulation of hydrogen tank Filling by an impinging oblique jet

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ABSTRACT :

During a hydrogen tank filling, high temperatures can be generated inside the vessel with a vertical or/and horizontal thermal stratification that can potentially further increase the temperature of the gas and the tank wall. CFD tools can help predict this thermal stratification within the tank by providing complete and detailed 3D information on the flow characteristics and temperature distribution. The eddy viscosity turbulence model (Boussinesq hypothesis) approach is most often used since it gives the best compromise between the number of grid cells and equation solving time. This hypothesis is reasonable for turbulent shear flows without big curvature and swirl. These models show their limitations when the anisotropy of the turbulence significantly affects the mean flow. This paper compares several turbulence models (Eddy viscosity and RSM model) for the case of hydrogen tank filling with a turbulent tilted impinging jet. The CFD (Computational Fluid Dynamics) simulations will also be compared to experimental results.

Keywords: Hydrogen storage, tank filling, turbulence model, impinging jet, stratification

INTRODUCTION

In a context of global awareness of environmental issues, a revolution in production methods is challenging the current operation of the conventional energy system. Hydrogen is widely seen as an energy carrier that could help to overcome issues such as greenhouse gas emission, air pollution and safe energy supply. Compressed hydrogen is the technology of choice for on-board storage in hydrogen vehicles in the automotive industry. Due to the low density of hydrogen at atmospheric conditions, high pressures are required inside the fuel tanks to achieve a range comparable to conventional vehicles. The large pressure increases during refuelling, the gas temperatures inside the tank increase inside the vessel with possible stratification phenomena that can locally increase the high temperature areas. The maximum allowed temperature of 85°C inside the composite tank walls is specified by the international standards.

MATERIALS AND METHODS

In the frame of the FCH JU funded project (PRHYDE), aiming at defining a hydrogen tank filling protocol, a series of experimental tests was performed on several type IV tanks with various filling conditions. The tanks were instrumented with thermocouples trees monitoring the temperature evolution of the gas inside the tank. Some experimental cases presented new physical results, which are difficult to explain, such as horizontal stratification. These cases have been used for the 3D numerical simulation modeling. The 3D computational domain consists of two subdomains: one for the fluid part (hydrogen) and another for the thermal transfer with the solid (tank material). This type of 3D simulation solves Navier-Stokes equations. Real gas model (NIST tables) is essential for the pressure range considered in the experiments.

The solved equations are of the form:

$$\underbrace{\frac{\partial}{\partial t}\int_V \rho\Phi dV}_{\text{instationnaire}} + \underbrace{\int_A \rho\Phi V dA}_{\text{Convection}} = \underbrace{\int_A \Gamma_\Phi \nabla\Phi . dA}_{\text{Diffusion}} + \underbrace{\int_V S_\Phi dV}_{\text{Generation}}$$

After decomposing the velocity into mean and instantaneous parts, the transient Navier-Stokes equations can be rewritten as the Reynolds-Averaged Navier-Stokes (RANS) equations with the Reynolds stress tensor as additional unknowns:

$$\left(\rho\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_k\frac{\partial \bar{u}_i}{\partial x_k}\right) = -\frac{\partial \bar{P}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu\frac{\partial \bar{u}_i}{\partial x_j}\right) + \frac{\partial R_{ij}}{\partial x_j}$$

Reynolds stress tensor

Previous work ([4],[5],[6],[7]) used k-epsilon or k-omega SST and SAS turbulence models (Boussinesq hypothesis). Several publications ([1],[2],[3]) have demonstrated the limitations of models that use Boussinesq hypothesis when anisotropy of turbulence significantly affects the mean flow. This type of limitation can be reached in the case of an impacting jet on concave surfaces, which is the case when the injector is not aligned with the tank.

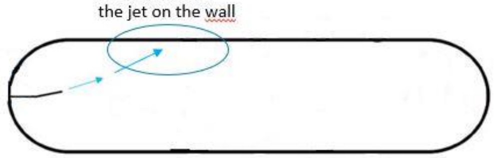

Fig. 1 Illustration of an impinging oblique jet on the tank wall during the filling stage.

To overcome this issue the RSM (Reynolds Stress Model) turbulence model could be used. A crucial step for the application of numerical modelling is the validation of the model against the corresponding experimental measurements. Several numerical simulations were performed to get a qualitative and quantitative comparison of several turbulence models available in ANSYS Fluent and more specifically to compare RSM and Boussinesq turbulence models (like k-epsilon) and SAS.

RESULTS AND DISCUSSION

Experimental results in the selected cases show horizontal stratification, probably due to a recirculation of the cold jet at the front of the tank and a local overheating at the back due to a limited propagation of the cold jet at the rear of the tank (fig 2).

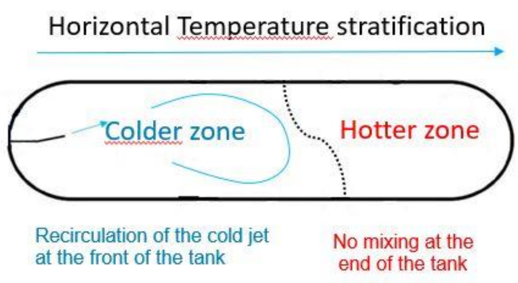

Fig. 2 Diagram of the fluid behaviour observed experimentally

With k-epsilon model, the flow does not behave as in the experiment: no horizontal temperature stratification is numerically observed. As shown on the figure below (fig. 3), the model only predicts vertical temperature stratification.

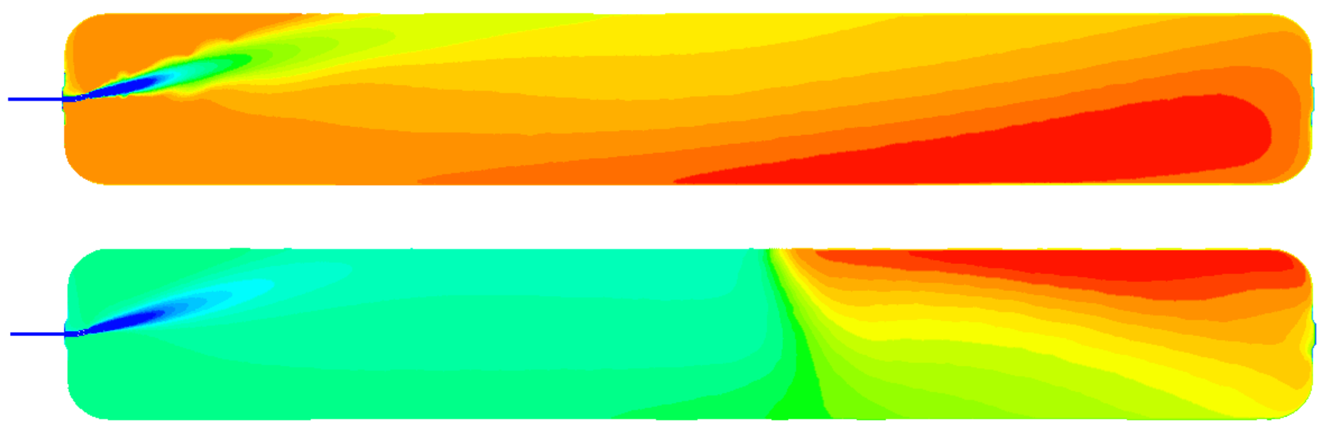

Fig. 3 Temperature field found using k-epsilon model (top frame) and RSM model (bottom frame) for the same time

The results of the two turbulence models show completely different temperature fields. The RSM model clearly demonstrates a horizontal stratification. In order to verify the jet recirculation hypothesis , we have analyzed the velocity fields of both simulations. Comparisons with experimental measurements have also been performed. They show that the RSM model is better adapted for the impacting jets.

CONCLUSIONS

The impact of the jet on the tank wall is a complicated phenomenon to solve numerically. It shows the limit of Eddy viscosity turbulence models. In order to keep horizontal stratification, RSM turbulence model has been tested and allows highlighting this horizontal thermal stratification.

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