Simulation of plane and round impinging jet heat transfer with k-ω based hybrid RANS/LES models for electrochemical applications

Erik Dick[a], Slawomir Kubacki[b],
[a]Department of Flow, Heat and Combustion Mechanics, Ghent University,
St.–Pietersnieuwstraat 41, B-9000 Gent, Belgium
Erik.Dick@UGent.be
[b]Institute of Aeronautics and Applied Mechanics, Warsaw University of Technology,
Nowowiejska 24, 00-665 Warsaw, Poland

1. Summary

Plane impinging jets with nozzle-plate distances H/B = 10 for Re = 13500 and H/B = 9.2 for Re = 20000 are simulated with k-ω based hybrid RANS/LES models and with a RANS k-ω model. The results are compared to experimental and LES data. We consider hybrid models where the subgrid eddy viscosity in LES mode is obtained from a modification of the RANS eddy viscosity. Three different ways of substitution of the turbulent length scale by the local grid size in the LES mode of the hybrid RANS/LES models are tested. The results show that the hybrid models give much better prediction of the wall shear stress and the heat transfer rate along the impingement plate than the pure k-ω RANS model. The good performance of the hybrid models is due to their ability to resolve the evolution and break-up of the vortices in the shear layer of the jet, which strongly affects the turbulent flow and convective heat transfer in the stagnation region and the developing wall-jet region. We do not see much difference in the performance of the three hybrid models. On theoretical grounds, we have preference for one of them. This is the model with substitution of the turbulent length scale by the grid size in the destruction term of the k-equation and in the formula for the subgrid eddy viscosity.

We further test the chosen model, which we call a RANS type eddy viscosity hybrid model, on a round impinging jet with nozzle-plate distance H/D = 13.5 for Re = 5000. We introduce a fourth model where the k-equation is the same as in the chosen model, but where the subgrid eddy viscosity in LES mode is a classic Smagorinsky eddy viscosity. For high nozzle-plate distance and low Reynolds number, only the Smagorinsky type subgrid eddy viscosity performs well.

2. Motivation

RANS models present shortcomings for simulation of impinging jet flows such as overestimation of the length of the core region (underestimation of the jet expansion) or overprediction of the turbulent kinetic energy production to dissipation ratio in the stagnation flow region. On the other hand, LES methods are able to reproduce the large scale structures initiated at the jet exit, their evolution and degradation into smaller eddies. However, since LES aims at resolving the scales of motion responsible for turbulence production, it comes into difficulties in near-wall regions, where the size of the eddies is comparable to the Kolmogorov scales, requiring extremely fine grid resolution, approaching that of DNS. In order to alleviate this grid resolution problem in near-wall regions, a hybrid RANS/LES can be applied, where the method acts in RANS mode near walls and in LES mode away from walls.

The newest version of the k-ω model of Wilcox (2008) is applied as a “state-of-the-art” turbulence model. Since the RANS model provides poor description of the flow physics for free jet flows, a hybrid RANS/LES model is constructed in order to resolve the evolution of large scale instabilities in flow regions where the grid density is fine enough, replacing the turbulent length scale by the local grid size. In near wall regions, the model switches to RANS mode which is known to be adequate for modelling fine scale structures. First, three different ways of substitution of the turbulent length scale by the local grid scale are tested. Then we consider also blending with a classic LES subgrid model.

3. The newest k-ω model

The newest k-ω model of Wilcox (2008) reads

$$\frac{Dk}{Dt} = P_k - \beta^* k\omega + \frac{\partial}{\partial x_j}\left[\left(\nu + \sigma^* \frac{k}{\omega}\right)\frac{\partial k}{\partial x_j}\right], \quad (1)$$

$$\frac{D\omega}{Dt} = \alpha\frac{\omega}{k}P_k - \beta\omega^2 + \frac{\partial}{\partial x_j}\left[\left(\nu + \sigma\frac{k}{\omega}\right)\frac{\partial \omega}{\partial x_j}\right] + \frac{\sigma_d}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j}, \quad (2)$$

where ν is the kinematic molecular viscosity, k is the turbulent kinetic energy, ω is the specific dissipation rate and $P_k = \tau_{ij}\partial U_i/\partial x_j$ the turbulence production rate. The components of the modelled stress tensor are given by $\tau_{ij} = 2\nu_t \overline{S}_{ij} - 2/3k\delta_{ij}$. The turbulent viscosity ν_t is defined by

$$\nu_t = \frac{k}{\tilde{\omega}}, \quad \tilde{\omega} = \max\left(\omega, C_{lim}\sqrt{\frac{2\overline{S}_{ij}\overline{S}_{ij}}{\beta^*}}\right), \quad (3)$$

with C_{lim} = 7/8 and $\overline{S}_{ij} = S_{ij} - 1/3(\partial U_k/\partial x_k)\delta_{ij}$ the components of the shear rate tensor. The components of the strain rate tensor are $S_{ij} = 1/2(\partial U_i/\partial x_j + \partial U_j/\partial x_i)$.