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HYBRID RANS/LES OF PLANE JETS IMPINGING ON A FLAT PLATE AT SMALL NOZZLE-PLATE DISTANCES

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A k-ω based hybrid RANS/LES model is employed for simulation of plane impinging jets at small nozzle-plate distances H/B=2 and 4 (where B is the slot width) and two Reynolds numbers Re=10,000 and 20,000 (based on the slot width and the velocity in the symmetry plane). The hybrid model belongs to the class of unified DES-type approaches. In LES mode, the hybrid RANS/LES model uses two definitions of the local grid size, one based on the maximum distance between the cell faces in the destruction term of the turbulent kinetic energy equation and one based on the cube root of the cell volume in the eddy-viscosity formula. This allows accounting for flow non-homogeneity on anisotropic grids. Under the assumption of local equilibrium, the eddy viscosity of the hybrid model reduces to a Smagorinsky subgrid viscosity with the usual constant $C_s=0.1$. In RANS mode, the hybrid model turns into the newest version of the k-ω model by Wilcox (2008).

The transport equations for the turbulent kinetic energy, k, and the inverse of the turbulent time scale (frequency),ω, read:

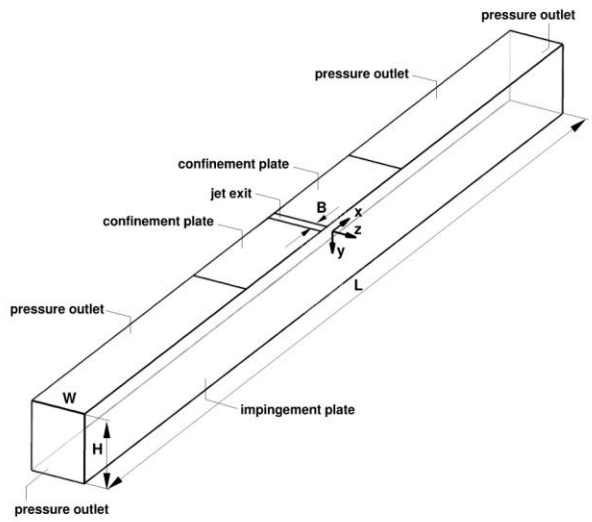
$$\frac{Dk}{Dt}=\tau_{ij}\frac{\partial U_i}{\partial x_j}-\max\left(\beta^* k\omega,\frac{k^{3/2}}{C_{DES}\Delta}\right)+\frac{\partial}{\partial x_j}\left[\left(\nu+\sigma^*\frac{k}{\omega}\right)\frac{\partial k}{\partial x_j}\right], \tag{1}$$

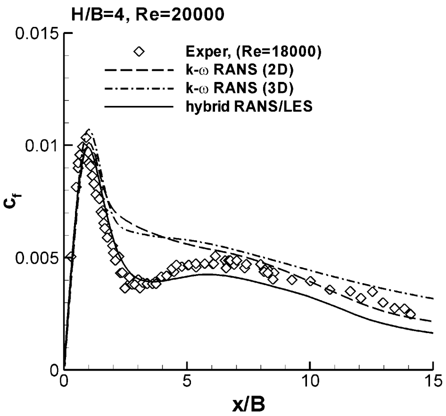
$$\frac{D\omega}{Dt}=\alpha\frac{\omega}{k}\tau_{ij}\frac{\partial U_i}{\partial x_j}-\beta\omega^2+\frac{\sigma_d}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j}+\frac{\partial}{\partial x_j}\left[\left(\nu+\sigma\frac{k}{\omega}\right)\frac{\partial \omega}{\partial x_j}\right],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

where ν is the kinematic molecular viscosity. The modelled stress tensor and the shear rate tensor are $\tau_{ij}=2\nu_t S_{ij}-2/3k\delta_{ij}$, $S_{ij}=1/2(\partial U_i/\partial x_j+\partial U_j/\partial x_i)-1/3(\partial U_k/\partial x_k)\delta_{ij}$. The local grid size Δ is defined by $\Delta=\max(\Delta_x, \Delta_y, \Delta_z)$ where Δ_x, Δ_y, Δ_z denote the distances between the cell faces in x, y and z directions. The grid size is multiplied with a tuning constant C_{DES}. The motivation for the modification of the destruction term in (1) is that the dissipation in the k-ω RANS model is $\varepsilon=\beta^* k\omega=k^{3/2}/L_t$, where the turbulent length scale is $L_t=k^{1/2}/(\beta^*\omega)$. So, it means that in the dissipation term, the turbulent length scale is replaced by the grid size when the model turns into LES mode. The eddy viscosity is $\nu_t=\min(k/\omega,\beta^* C_{DES}\Delta_{LES}k^{1/2})$ where $\Delta_{LES}=(\Delta_x\Delta_y\Delta_z)^{1/3}$. The motivation for this modification is that the RANS eddy viscosity is $\nu_t=\beta^* L_t k^{1/2}$. So, it means that also in the eddy viscosity expression, the turbulent length scale is replaced by the grid size. The chosen grid size is here the cube root measure, so the typical LES grid size. The grid size is again multiplied with the tuning constant C_{DES}.

Under local equilibrium (production of k equal to dissipation of k), the eddy viscosity in LES mode is a Smagorinsky subgrid viscosity $\nu_t=((\beta^*)^{3/4}C_{DES}\Delta_{LES}(\Delta/\Delta_{LES})^{1/4})^2 S$. The role of the term $(\Delta/\Delta_{LES})^{1/4}$ is to increase the eddy viscosity on high aspect ratio cells, with respect to the value obtained by the cube root grid size in all turbulence length scale substitutions. This improves the predictive qualities of LES on anisotropic grids (Scotti et al., 1993). The Smagorinsky constant $C_s=(\beta^*)^{3/4}C_{DES}$ is set to the usual value 0.1, which gives C_{DES}=0.6086.

The model with the two different length scales was developed in the most recent work of the authors (Kubacki and Dick, 2011, Kubacki et al., 2011b), where it was tested, proving good qualities, on round impinging jets with small and large nozzle-plate distances. Other hybrid models were proposed in work on plane impinging jets (Kubacki et al., 2010, 2011a) and tested for large nozzle-plate distances. For large nozzle-plate distance, the plate is in the mixed-out zone of the jet and the challenge is to predict the mixing accurately. The mixing is not well predicted by RANS, leading to big errors in the skin friction and heat transfer in the impact zone of the plate. This deficiency is cured with a hybrid formulation. For small nozzle-plate distance, the plate is in the core region of the jet. The impact is then essentially laminar. RANS models cope with such a situation through a stress limiter reducing the typical overproduction of turbulent kinetic energy in normal straining. Such a stress limiter is used in the RANS model by Wilcox (2008). We do not use this limiter in the hybrid version of the model, as this limiter specifically is meant for a RANS model. A second feature is that there is laminar-turbulent transition from the quasi-laminar impact zone to the zone of the developing boundary layer on the plate. This transition cannot be detected by a RANS model. The figure shows the computational domain used and the plot of the skin friction for one of the cases studied. It is obvious that RANS is in error in the transition zone, both 2D RANS and 3D RANS. With the hybrid model, the deficiency is cured. Further illustrations will be given in the paper. Also a discussion will be included explaining why the hybrid model functions well.





Skin friction coefficient for H/B=4, Re=20000.

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