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# 9th International ERCOFTAC Symposium on Engineering Turbulence Modeling and Measurements

## DAY 1 // JUNE 6, 2012

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HYBRID RANS/LES, PANS AND PRNS COMPUTATIONS OF PLANE IMPINGING JETS

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Abstract

The qualities of a hybrid RANS/LES, a PANS and a PRNS model, all based on the k-ω RANS model of Wilcox (2008), are analysed for simulation of plane impinging jets at various nozzle-plate distances (H/B=10, 9.2 and 4, B is slot width) and two Reynolds numbers (Re=13,500 and 20,000). The hybrid RANS/LES model is formulated in two variants, employing either one or two grid size measures in LES mode. In the first approach, the single grid size measure is the cube root of the cell volume. In coarse grid resolution control parameter by Liu and Shih (2006), but with the interpretation using the local grid size in the resolution control parameter by Song and Park (2009). The model changes between RANS and DNS/LES, based on the cube root of the cell volume. The derivation of the PRNS model is done according to Liu and Shih (2006), with the interpretation of Hsieh et al. (2010), with the switch to DNS/LES mode based on the local grid size, being the cube root of the cell volume. In coarse grid regions and near-wall regions, all models switch to the same k-ω RANS model.

1 Introduction

Plane impinging jets were studied experimentally by Tu and Wood (1996), Ashforth-Frost et al. (1997), Zhe and Modi (2001), Maurel and Sollic (2001) and numerically using LES with the dynamic Smagorinsky model by Beaubert and Viazzo (2003), among others, in order to provide a database for assessment of turbulence models and to understand the relationship between heat transfer and shear along the plate. The predictive qualities of various RANS models were verified by Jaramillo et al. (2008), among others. RANS models suffer from difficulties in reproducing the turbulence mixing in the developing shear layers of the jet (large nozzle-plate distance) as well as in capturing the stagnation point heat transfer.

In the present work, two k-ω based hybrid RANS/LES models (denoted with single and double length scale variants), a PANS and a PRNS model are tested by comparing the numerical results with experimental data and LES data of the researchers mentioned above.

2 Turbulence modelling

The transport equations of all the models have a common structure, derived from the basic k-ω RANS model:

\[
\frac{Dk}{Dt} = \tau_k = \beta_k \frac{\partial U_j}{\partial x_j} - F_k \beta_k \frac{\partial k}{\partial x_j} \left( \sigma_k + \frac{k}{\omega} \frac{\partial k}{\partial x_j} \right),
\]

\[
\frac{D\omega}{Dt} = \alpha_\omega \frac{\partial \omega}{\partial x_j} \left( \frac{\beta_\omega}{\omega} \frac{\partial \omega}{\partial x_j} \right),
\]

with \( k \) the turbulent kinetic energy and \( \omega \) the specific dissipation rate. \( \tau_k = 2\nu \delta_k = 2/3k \delta_k \) are the components of the modelled stress tensor and \( \delta_k = 1/2(\partial U_j / \partial x_j + \partial U_j / \partial x_i) - 1/3(\partial U_i / \partial x_i) \delta_{ij} \) the components of the shear rate tensor. \( \nu \) is the modelled viscosity:

\[
\nu = \beta_k \frac{k}{\omega}.
\]

The equations contain 3 control parameters, \( F_k \), \( F_{\omega} \), \( F_{\nu} \). With these parameters equal to unity, the basic RANS model is recovered.

In a hybrid RANS/LES model of DES type, the length scale of the turbulence in the destruction term of the k-equation and the length scale in the eddy viscosity definition are replaced by the grid size in order to turn the model into LES mode. Thereto, these terms are written as

\[
e = \beta_k \omega = \frac{k^{3/2}}{L_t}, \quad \nu = \beta_k k^{1/2} L_t,
\]

where \( L_t = k^{1/2} / (\beta_k \omega) \) is the turbulent length scale. The switching functions \( F_k \) and \( F_{\omega} \) are

\[
F_k = \max(L_t, (C_{\text{DES}} \Delta_x)), \quad F_{\omega} = \min(C_{\text{DES}} \Delta_x / L_t).
\]

The choice of the grid size measure is crucial in any LES-like formulation (Scotti et al., 1993). The litera-
ture shows that there is a preference for the maximum size in a DES formulation (Strelets, 2001), while there is a preference for the cube root measure in a LES formulation (Scotti et al., 1993). We study the influence of the grid size in LES mode of the hybrid model. In the first approach, we take the cube root of the cell volume for both length scales, \( \Delta x = \Delta y = \Delta z = \alpha (\Delta x, \Delta y, \Delta z) \), where \( \Delta x, \Delta y, \Delta z \) denote the distances between the cell faces in \( x, y \) and \( z \) directions. This approach is called the single length scale method (SLS). In the second approach, we take the maximum size \( \Delta x = \Delta_{\text{max}} = \max (\Delta x, \Delta y, \Delta z) \) in the \( k \)-equation, in the style as first proposed by Strelets (2001). This approach is called the double length scale method (DLS). The grid size is always multiplied with the tuning constant \( C_{\text{DES}} \).

Under local equilibrium (production of \( k \) equal to dissipation of \( k \)), the eddy viscosity reduces in LES mode to a Smagorinsky subgrid viscosity (\( S \) is the magnitude of the shear rate tensor). In the single length scale model the Smagorinsky eddy-viscosity is

\[
\nu_t = \left( C_{\text{DES}} \Delta_{\text{LES}} \right)^2 S, \tag{5}
\]

where \( C_{\text{DES}} = 0.6086 \), which gives \( C_{\text{DES}} = 0.6086 \). In the double length scale model the Smagorinsky eddy-viscosity is

\[
\nu_t = \left( C_{\text{DES}} \Delta_{\text{LES}} \left( \Delta_{\text{max}} / \Delta_{\text{LES}} \right)^{-1/4} \right)^2 S. \tag{6}
\]

The role of the term \( (\Delta_{\text{max}} / \Delta_{\text{LES}})^{-1/4} \) is to increase the eddy viscosity on high aspect ratio cells, as in the LES model by Scotti et al. (1993), which improves the predictive qualities of LES on anisotropic grids.

In a PANS approach (Partially-Averaged Navier-Stokes), the turbulence equations (1) and (2) describe sub-filter scale quantities. Girimaji (2006) showed that this can be obtained by modifying the destruction term in the scale determining equation (here, the \( \omega \)-equation) and the diffusion coefficients. The coefficient of the destruction term in the \( \omega \)-equation becomes

\[
\nu_t = \beta \frac{\nu_t}{\Delta_{\text{LES}}} \left( 1 - \beta \right) \beta^{3/4}. \tag{7}
\]

where \( \beta \) denotes the ratio of the sub-filter turbulent kinetic energy to the total turbulent kinetic energy. In principle, the factor \( \beta \) may be chosen arbitrarily, but the grid has to be fine enough to capture the intended resolved part of the turbulence. Based on Kolmogorov scaling, this factor can be estimated by

\[
\beta = \min \left( \frac{C_{\text{DES}} \Delta_{\text{LES}}}{L_0} \right)^{1/2}, \tag{8}
\]

where \( L_0 = (\bar{u}^2/\nu) \). In principle, such a technique is inconsistent and it leads to a systematic underestimation of the turbulence length scale of the total turbulence. This overestimation can be compensated by the tuning factor \( C_{\text{DES}} \). According to Song and Park (2009), and other researchers in the field, the physical value of \( C_{\text{DES}} \) in \( \beta \) is \( (\beta^{3/4})^{-3/4} \approx 6 \) and they actually use this physical factor. Here, we propose to tune the factor so that the same small scale Smagorinsky limit for the sub-filter viscosity is obtained as with the hybrid model. If we accept, that for fine enough grid, equilibrium is obtained in the \( k \)-equation and that the length scale \( C_{\text{DES}} \Delta_{\text{LES}} \) is imposed to the sub-filter turbulence, PANS leads to a Smagorinsky eddy viscosity (5). So, we can use the same value for \( C_{\text{DES}} \) as with the hybrid model. Herewith, we follow the reasoning by Fadai-Ghotbi et al. (2010).

Following the derivation by Girimaji (2006), the Prandtl numbers \( \sigma_t \) and \( \sigma_s \) can be left unchanged with the so-called maximum transport option, but the constant \( \sigma_d \) in Eq. (2) should be multiplied by \( \frac{\nu_t}{v} \). Tests showed that this has only a very small effect on the results, as \( \sigma_d \) is set to zero close to walls (see below). We keep, therefore, the cross-diffusion term with the RANS-value. So, in the implementation here, the PANS model means introducing the \( F_k \) factor in the destruction term of the \( \omega \)-equation, which determines \( F_\omega \) by Eq. (7), while all other terms remain as in RANS and also the definition of the eddy viscosity is as in RANS. Thus \( F_k \) and \( F_\omega \) are unity in PANS.

The transport equations for the PRNS (Partially Resolved Numerical Simulation) model are the RANS equations (1) and (2), while in the eddy viscosity a reduction factor is introduced of form \( F_\omega = \min \left( \frac{C_{\text{DES}} \Delta_{\text{LES}}}{L_0} \right)^{3/4}, 1 \). The reduction factor follows, again, from Kolmogorov scaling and \( C_{\text{DES}} \), in principle, is unity, or above it. Since in PRNS, the turbulence equations (1) and (2) describe large scale behaviour, close to RANS, the determination of the turbulent length scale is determined consistently from the turbulence quantities. In the original formulation by Liu and Shih (2006), a uniform value of the reduction factor was used, but we follow here the interpretation by Hsieh et al. (2010), with the reduction factor determined locally from the grid measure. The technique becomes then very similar to a latency technique or a Limited Numerical Scales (LNS) in the style of Batten et al. (2004) and as already studied by the present authors (model M3 in Kubacki and Dick, 2010). The factor \( C_{\text{DES}} \) can, again, be tuned for small scale behaviour, as for the other models. Under equilibrium conditions in the \( k \)-equation, rescaled to the small scales, the PRNS eddy viscosity is a Smagorinsky eddy-viscosity (5). So, we can use the same value for \( C_{\text{DES}} \) as with the other models. The PRNS model means, therefore, unchanged \( k \)- and \( \omega \)-equations (\( F_k = F_\omega = 1 \)) and multiplication of the eddy viscosity formula with \( F_\omega = \min \left( \frac{C_{\text{DES}} \Delta_{\text{LES}}}{L_0} \right)^{3/4}, 1 \).

For the RANS simulations (Wilcox, 2008), a stress limiter is applied. This means that the turbulent viscosity \( \nu_t \) is defined by

\[
\frac{\nu_t}{\nu} = \max \left( \nu_t \left( \frac{C_{\text{lim}}}{2S_{\text{lim}}} \right)^{1/2} \right), \tag{8}
\]

with \( C_{\text{lim}} = 7/8 \). The limiter is not used with the other models.

The closure coefficients and some additional relations are:
\[ \beta^* = 0.09, \quad \alpha = 0.52, \quad \beta = \beta_0 \beta_0, \quad \beta_0 = 0.0708, \]
\[ \sigma = 0.5, \quad \sigma^* = 0.6, \quad \sigma_0 = 0.125 \]
\[ f_\beta = \frac{1 + 85 \chi_0}{1 + 100 \chi_0}, \quad \chi_0 = \frac{|\Omega_{\omega} - \omega_k| S_k}{(\beta^* \omega)^2} \]
\[ \sigma_d = 0 \text{ for } \frac{\partial k}{\partial x_j} \frac{\partial \omega_s}{\partial x_j} \leq 0, \text{ else } \sigma_d = \sigma_{d0}, \]
and \( \Omega_{\omega} = 1/2(\partial U_i/\partial x_j - \partial U_j/\partial x_i) \) is the vorticity tensor.

At the walls, \( k \) and \( \omega \) are set to
\[ k = 0, \quad \omega = \left( \frac{u^2}{\nu} \right) S_R, \] (9)
where \( S_R = \min[(200/k^*)^2, 6/(\beta_0 \Delta y^*)^2] \), \( \Delta y^* = \Delta y/u_\tau \), \( u_\tau = (\tau_w/\rho)^{1/2} \), \( \tau_w = \mu S \) and \( k^* \) is a dimensionless roughness height. The walls are assumed to be hydraulically smooth, so the dimensionless roughness height was set here to 4 (Wilcox, 2008).

3 Computational framework

The computational domain consists of a rectangular box as shown in Fig. 1. The grids have been refined close to walls and in the shear layer of the jet. \( y^+ \) was less than 1 along the impingement plate and less than 3 at the confinement plate.

![Figure 1: Sketch of the computational domain, coordinate system and boundary conditions for plane impinging jet simulation at H/B=4. Periodic conditions are imposed in the z direction.](image)

For the hybrid RANS/LES, PANS and PRNS models, the bounded central differencing scheme was applied to the convective terms in the momentum equations. The second order upwind scheme was used for the convective terms in the \( k \) - \( \omega \)-equations. For RANS, the second order upwind scheme was used for discretisation of the convective terms in all equations. For temporal discretisation, a second-order implicit scheme was applied for all the models. An implicit time stepping technique was chosen to guarantee stability for large CFL number. The time step was, however, chosen small enough so that the CFL-number was at maximum 2, so that the dissipation due to the time stepping remained small. In all simulations the time step was set to \( \Delta t V_0/B = 2 \cdot 10^{-3} \) (\( V_0 \) denotes the mean y-velocity component in the symmetry plane at the jet exit). At each time step, inner iteration steps were applied to drive the residuals of the momentum and the transport equations below \( 10^{-5} \). The governing equations were solved sequentially with the pressure-correction SIMPLE method and momentum interpolation was used for the pressure-velocity coupling.

The heat transfer is described with the energy equation with the gradient diffusion hypothesis for the modelled heat flux
\[ \frac{DT}{Dt} = \frac{\partial}{\partial x_j} \left( \frac{\nu}{Pr} + \frac{\nu_t}{Pr_t} \right) \frac{\partial T}{\partial x_j}, \] (10)
where \( T \) is the mean temperature, \( Pr \) and \( Pr_t \) are the molecular and turbulent Prandtl numbers, respectively \( Pr = 0.744 \), \( Pr_t = 0.850 \). A constant value of the heat flux was imposed on the impingement plate, set to \( h_w = 350 \text{W/m}^2 \). The inlet temperature was set to \( T_{\text{inlet}} = 300 \text{K} \) in the jet and in the ambient incoming flow. The Nusselt number is defined by
\[ \text{Nu} = -\frac{(\partial T/\partial y)_w B}{(T_w - T_{\text{inlet}})}, \] (11)
where the subscript \( w \) refers to the wall value.

We introduce a buffer layer by imposing full RANS representation from a streamwise distance of about 7 times the slot width on. We do this because the grid becomes coarse in x-direction towards the outlet and by using the cube root as length scale we have the risk that LES-like behaviour would be introduced quite near to the wall, where the grid is not fine enough in x-direction to justify this. This means that we compare the term \( C_{\text{DES}} L_e / L_s \) with a reference hyperbolic tangent function, switching from zero to unity at \( |x/B|=7 \).

4. Results

Fig. 2 shows contour plots of an instantaneous mean velocity magnitude in the x-y plane for H/B=10 and Re=13,500. The velocity field obtained with the PANS model is much smoother than the one obtained with the hybrid RANS/LES and PRNS models. This is due to a much higher level of the turbulent viscosity reproduced with PANS in the LES/DNS-like region with respect to the other models. This is illustrated in Fig. 3 (a) and (b) showing the ratio of the subgrid model to the turbulent length scales, \( \min(C_{\text{DES}} L_e / L_s) \), and the ratio of modelled to molecular viscosity, \( \nu/\nu_\tau \) at distance \( y/H=0.5 \) from the jet exit. PANS generates a much higher level of \( \nu/\nu_\tau \) (about 50-100 for \( |x/B|>0.5 \) ) with respect to the values obtained by the other models (about 1), even though low values of the \( C_{\text{DES}} L_e / L_s \) are set with PANS at \( |x/B|>0.5 \) (Fig 3, a). The low values of \( \nu/\nu_\tau \) at \( y/H=0.5 \) mean that the hybrid RANS/LES and PRNS techniques function properly in LES mode. It should be noted, that the damping factor \( C_{\text{DES}} L_e / L_s \) is higher with the hybrid RANS/LES models than with the PANS and PRNS techniques since in the hybrid models the length scale substitution is realized.
Figure 2: Contour plots of instantaneous velocity magnitude in the xy-plane with a) the hybrid RANS/LES model (single length scale), b) the hybrid RANS/LES model (double length scale), c) PANS, and d) PRNS models for H/B=10, Re=13,500.

in both the destruction term of the k-equation and in the eddy-viscosity formula. PANS and PRNS techniques introduce the grid size measure only in the destruction term of the $\omega$-equation and in the eddy-viscosity formula, respectively, so this requires a stronger damping term. The SLS variant of the hybrid model gives higher values of $C_{DES}\Delta LES/L_t$ with respect to those obtained with the DLS version, since in the former a smaller grid size measure is used in the destruction term of the k-equation.

Fig. 4 shows the Reynolds stress profile at distance $y/H=0.5$ from the jet exit for H/B=10 and Re=13,500. RANS (2D) seriously underpredicts the turbulence mixing in the developing shear layer of the jet. The hybrid RANS/LES (DLS) and PANS models overpredict the peak values of the Reynolds stress at $|x/B|=0.5$. The peak values reproduced with the hybrid RANS/LES (SLS) and PRNS model are in good agreement with the data. The width of the shear layer is somewhat too big with the hybrid RANS/LES (DLS) model and somewhat too small with the PANS model. It means that the PANS model transitions more gradually from RANS behaviour in the jet core region to LES-like behaviour in developing shear layers than the hybrid RANS/LES and PRNS models.

The mean and fluctuating $y$-velocity components are displayed in Fig. 5 along the symmetry plane. The decay of the mean velocity profile is quite well reproduced by all models. However, the hybrid RANS/LES (DLS) model shows the worst correspondence between computations and measurements. The too strong decay of the mean velocity with the hybrid RANS/LES (DLS) model is due to its tendency to produce too large vortex structures in the shear layer of the jet (Fig. 4), which delays the vortex break-up process. As a result, the fluctuating velocity level is too large with the hybrid RANS/LES (DLS) model at $y/B>4$ (Fig 5). The hybrid (SLS) model produces much faster break-up of the vortex structures in the shear layer of the jet due to a smaller grid size measure in the destruction term of the k-equation. With the hybrid (SLS) model, the rise of the fluctuating velocity component is much too early ($y/B=1$), but predictions become very good near to the plate. PANS produces a too large level of the total fluctuation intensity at $y/B>5$, with a high ratio of modelled energy to total fluctuation energy (25%). The other techniques give a much lower ratio of about 10% (results not shown here). The results obtained by the PRNS model are in very good agreement with experiments and LES. Note that only resolved fluctuations are shown in LES by Beaubert and Viazzo, (2003).
The quality of the models can be further verified in Fig. 6, showing the profile of normalized wall shear stress along the impingement plate. RANS overpredicts the peak values at $|x/B|=1$. This is due to a too small turbulence mixing in the shear layers of the jet, which leads to a too high momentum in the stagnation flow region. PANS, similarly to RANS, produces a too high peak of the wall shear stress, owing to somewhat too weak turbulence mixing in the jet region. The overprediction by PRNS is probably due to enhanced activity of the small-scale structures near the wall. The wall shear stress by the hybrid RANS/LES models (both SLS and DLS) is in good agreement with experiments and LES.

Fig. 7 (a) shows the profile of the mean streamwise velocity component along a line perpendicular to the impingement plate at distance $x/B=5$ from the symmetry plane for $H/B=9.2$ and $Re=20,000$. RANS gives a too steep velocity gradient close to the wall which is, similarly as before, due to underprediction of the turbulence mixing in the shear layers of the jet. The mean velocity profiles produced by the hybrid RANS/LES, PANS and PRNS models are very close to each other and are in good agreement with the experiments.

Fig. 7 (b) shows the Nusselt number profile along the impingement plate. RANS produces an unphysical non-monotonic distribution along the wall. The Nusselt number profiles by the SLS version of the hybrid RANS/LES, PANS and PRNS models are in good agreement with the experimental data. The somewhat too high stagnation point Nusselt number by the hybrid RANS/LES (DLS) model is likely due to overprediction of the fluctuating velocity level in the jet region. The monotonic behaviour with increasing distance from the symmetry plane is well reproduced with all hybrid, PANS and PRNS models.

Fig. 8 (a) shows the skin friction profile along the impingement plate for $H/B=4$ and $Re=20,000$. In principle, all modelling techniques produce a too high peak value of $c_f$ at $x/B=1$, but we have to doubt seriously the experimental values of the skin friction coefficient in the stagnation flow region (obtained from near wall velocity measurements using the hot-wire technique). RANS gives a too high wall shear stress at larger distances from the symmetry plane.
(x/B>3). Here (low nozzle-plate distance), the over-prediction of the wall shear stress is likely due to overprediction of the turbulence kinetic energy in the stagnation flow region. A somewhat smaller over-prediction is obtained by PANS in the transition region (3<x/B<7). The hybrid and PRNS models results agree much better with experiments. Some over-prediction remains, which again might be due to inaccuracy of the measuring technique very near to the wall. The RANS model does not reproduce the dip in the Nusselt number profile (Fig. 8 b), but shows a good agreement with experimental data at larger distance from the symmetry line (x/B>7). All the hybrid RANS/LES, PANS and PRNS models underpredict the secondary peak at x/B=7. This is likely due to inability to reproduce the final phase of the vortex break-up process by the rather coarse grid (the grid coarsens with increasing distance from the symmetry plane).

![Figure 8: (a) Skin friction coefficient and (b) the Nusselt number profile for H/B=4, Re=20000.](image)

5. Conclusion

Overall, the PNRS and the single length scale hybrid RANS/LES model perform the best. So, there seems not to be an advantage in using two different length scales in the hybrid model. The mean flow predictions by the PANS model stay somewhat too close to those of the RANS model. This is most likely caused by the inconsistent implementation used here, leading to a systematic underprediction of the global turbulent length scale. The inconsistent formulation cannot be avoided when no information on the turbulent length scale is available from other sources. The hybrid RANS/LES and PNRS are clearly fully consistent techniques.

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