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Hybrid RANS/LES computations of plane impinging jets with DES and PANS models

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ABSTRACT

The qualities of a DES (Detached Eddy Simulation) and a PANS (Partially-Averaged Navier–Stokes) hybrid RANS/LES model, both based on the k–ω RANS turbulence model of Wilcox (2008, "Formulation of the k–ω turbulence model revisited" AIAA J., 46: 2823–2838), are analysed for simulation of plane impinging jets at a high nozzle-plate distance (H/B = 10, Re = 13,500; H is nozzle-plate distance, B is slot width; Reynolds number based on slot width and maximum velocity at nozzle exit) and a low nozzle-plate distance (H/B = 4, Re = 20,000). The mean velocity field, fluctuating velocity components, Reynolds stresses and skin friction at the impingement plate are compared with experimental data and LES (Large Eddy Simulation) results. The k–ω DES model is a double substitution type, following Davidson and Peng (2003, "Hybrid LES–RANS modelling: a one-equation SGS model combined with a k–ω model for predicting recirculating flows" Int. J. Numer. Meth. Fluids, 43: 1003–1018). This means that the turbulent length scale is replaced by the grid size in the destruction term of the k-equation and in the eddy viscosity formula. The k–ω PANS model is derived following Girimaji (2006, "Partially-Averaged Navier–Stokes model for turbulence: a Reynolds-Averaged Navier–Stokes to Direct Numerical Simulation bridging method" J. Appl. Mech., 73: 413–421). The turbulent length scale in the PANS model is constructed from the total turbulent kinetic energy and the sub-filter dissipation rate. Both hybrid models change between RANS (Reynolds-Averaged Navier–Stokes) and LES based on the cube root of the cell volume. The hybrid techniques, in contrast to RANS, are able to reproduce the turbulent flow dynamics in the shear layers of the impacting jet. The change from RANS to LES is much slower however for the PANS model than for the DES model on fine enough grids. This delays the break-up process of the vortices generated in the shear layers with as a consequence that the DES model produces better results than the PANS model.

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1. Introduction

Accurate prediction of flow impingement is of particular importance in many engineering applications. An example is internal impingement cooling of gas turbine blades. The design of efficient cooling systems is important from the point of view of minimisation of the coolant flow rate. Therefore, highly accurate modelling techniques are needed to properly address the complexity of the flow dynamics. Impinging jet heat transfer is also relevant in other processes as cooling of electronic devices, tempering of glass, printing, de-icing of an aircraft.

Plane impinging jets can also serve as a good test case for validation of RANS (Reynolds-Averaged Navier–Stokes), LES (Large Eddy Simulation) and hybrid RANS/LES models, owing to the complexity of the flow characteristics. The analysis of models with such test cases is attractive due to presence of free shear layers and stagnation flow regions with strong effects of streamline curvature and pressure gradient.

Plane impinging jets were studied experimentally by Ashforth-Frost et al. (1997), Tu and Wood (1996), Zhe and Modi (2001), Maurel and Solliec (2001), Guo and Wood (2002), Dogruoz (2005) and numerically using LES with the dynamic Smagorinsky model by Beaubert and Viazzo (2003), LES and DNS by Tsubokura et al. (2003) and DNS (combined with RANS) by Jaramillo et al. (2012), among others, in order to provide a database for assessment of turbulence models and to understand the relationship between heat transfer and skin friction along the plate.

The measurements by Ashforth-Frost et al. (1997), Tu and Wood (1996), Zhe and Modi (2001), Guo and Wood (2002) and Dogruoz (2005) were performed to study the near-wall fluid flow and/or heat transfer characteristics of plane impinging jets at various nozzle-plate distances and at different Reynolds numbers. The near-wall mean and fluctuating velocity characteristics have been studied by Ashforth-Frost et al. (1997) and Zhe and Modi (2001) for H/B = 4 and 9.2, Re = 20,000 and H/B = 2–9.2, Re = 10,000–30,000,

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respectively. The stagnation flow measurements by Guo and Wood (2002) were conducted with a low level of the turbulence intensity at the nozzle exit (0.35%) at three nozzle-plate distances (H/B = 2, 4 and 5) and two Reynolds numbers (Re = 87,000–89,000). They found that the decay of the mean velocity along the stagnation line (plane) corresponds well with the theoretical solution by Hiemenz for laminar flow in a stagnation flow region (Schlichting, 1979). Somewhat higher discrepancy between the Hiemenz's solution and measured wall shear stress was earlier reported by Tu and Wood (1996). The difference between theory and measurements at low nozzle-plate distance was explained by Tu and Wood (1996) by influence of the inlet turbulence intensity (Tu = 4%). Dogruoz (2005) discussed the accuracy of two measuring techniques of the wall shear stress along the impingement plate for H/B = 2 and 4 and Re = 10,000–18,000. He demonstrated the advantage of the oil film technique over the Stanton gauge (0.1 mm) in reproducing the peak value of the skin friction coefficient along the impingement plate at the streamwise distance x/B = 1 from the symmetry plane. The work by Maurel and Solliec (2001) was related to the analysis of the Reynolds shear stress in the shear layers of the jet and to determination of the size of the counter-rotating vortices in the stagnation flow region at large distance between the nozzle exit and the impingement plate. They observed that the size of the Görtler vortices depends on the nozzle-plate distance.

The LES computations by Beaubert and Viazzo (2003) were performed to analyse the Reynolds shear stresses in the shear layers of the jet at large nozzle-plate distance H/B = 10 and Re = 13,500. The objective of the DNS and LES by Tsubokura et al. (2003) was to study the dynamics of the vortices in the shear layers of the jet and to determine the influence of the streamwise-oriented vortices coming from the shear layers of the jet on development of the Görtler vortices along the impingement plate. The jets were exited at the inlet. The DNS by Jaramillo et al. (2012) were performed to study the flow and heat transfer characteristics in the wall-jet region of a plane impinging jet at nozzle-plate distance H/B = 4 and Re = 20,000. The DNS data were also used for validation of turbulence models. The inlet turbulence intensity was set to zero in order to avoid ambiguity in specification of the boundary conditions for the turbulence quantities at the nozzle exit.

The predictive qualities of various RANS models were verified by Fernandez et al. (2007) and Jaramillo et al. (2008), among others. For large nozzle-plate distance, the jet is in turbulent state at impact. RANS models suffer from difficulties in reproducing the turbulent mixing in the developing shear layers of the jet, as well as in capturing the correct level of the shear stress in the impact zone. This poses a difficulty with application of RANS-based techniques in analysis of complex flow systems in which free jet development and its subsequent impingement determine the level of the wall shear stress along the impingement wall. For small nozzle-plate distance, the flow in the near-wall region of the impact zone is essentially laminar. The prediction of the shear stress level in the stagnation region is basically correct with RANS models due to use of stress limiters which damp most of the turbulence in the impact zone. The transition from laminar to turbulent state in the developing boundary layer on the plate is completely ignored by RANS models, however.

In the present work, the k–ω based DES and PANS models are tested by comparing the numerical results with experimental data and LES data of the researchers mentioned above. The hybrid techniques generally give superior results with respect to RANS. The change from RANS mode to LES mode is much slower however with the PANS model than with the DES model in regions with small grid size. This has as a consequence that PANS gives a too high peak value of the wall shear stress along the plate for large nozzle-plate distance and somewhat too low values of the wall shear stress in the developing wall jet region for low nozzle-plate distance. The best results are obtained with the DES model.

The present paper complements the analysis of the so-called double substitution DES model, reported in our previous work (Kubacki and Dick, 2010). In the present work, an improvement of this DES model (M2 model in our previous paper) is achieved in LES mode in the impact zone of the jet by employing as grid size measure the cube root of the cell volume. Moreover, improved inlet boundary conditions for the modelled scalars are used. In our previous work, the inlet turbulence was specified in an ad hoc fashion by assigning 10% of the inlet turbulence to the modelled turbulence and 90% to the resolved one. The inlet conditions are now imposed in a rigorous way (see Section 3.1). Further, the DES model results are compared with the results obtained by the PANS model, employing a grid size dependent filter control parameter. The primary objective of the present paper is the comparison of the qualities of a DES model and a PANS model when these are formulated with as much identical ingredients as possible.

2. Turbulence modelling

The transport equations of both models have a common structure, derived from the basic k–ω RANS model (Wilcox, 2008):

$$\frac{Dk}{Dt} = \tau_{ij}\frac{\partial U_i}{\partial x_j} - F_k\beta^* k\omega + \frac{\partial}{\partial x_j}\left[\left(\nu + \sigma^*\frac{k}{\omega}\right)\frac{\partial k}{\partial x_j}\right], \tag{1}$$

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

with k the turbulent kinetic energy and ω the specific dissipation rate. $\tau_{ij} = 2\nu_t S_{ij} - 2/3\, k\delta_{ij}$ are the components of the modelled stress tensor and $S_{ij} = 1/2(\partial U_i/\partial x_j + \partial U_j/\partial x_i) - 1/3(\partial U_k/\partial x_k)\delta_{ij}$ the components of the shear rate tensor. ν_t is the modelled eddy viscosity:

$$\nu_t = F_\nu(k/\omega). \tag{3}$$

The equations contain three control parameters, F_k, F_ω, F_ν. With these parameters equal to unity, the basic RANS model is recovered.

2.1. DES model

In a hybrid RANS/LES model of DES (Detached Eddy Simulation) type, with double substitution (Davidson and Peng, 2003), 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. Therefore, these terms are written as

$$\varepsilon = \beta^* k\omega = k^{3/2}/l_t, \quad \nu_t = k/\omega = \beta^* k^{1/2} l_t, \tag{4}$$

where $l_t = k^{1/2}/(\beta^*\omega)$ is the instantaneous turbulent length scale obtained from the modelled quantities. The switching functions F_k and F_ν are

$$F_k = \max[l_t/(C_{DES}\Delta), 1] \quad F_\nu = \min[(C_{DES}\Delta)/l_t, 1]. \tag{5}$$

By the control parameters F_k and F_ν, the turbulence model Eqs. (1) and (3) are modified into equations for sub-filter scale quantities in LES mode. The control parameter F_ω in (2) stays at unity, as the ω-equation has no role in LES mode. In LES mode, the length scale is defined in the present study as the cube root of the cell volume $\Delta = (\Delta_x\Delta_y\Delta_z)^{1/3}$, where Δ_x, Δ_y, Δ_z denote the distances between the cell faces in x, y and z directions (Scotti et al., 1993).

Under local equilibrium (production of k equal to dissipation of k), the eddy viscosity reduces in LES mode to a Smagorinsky viscosity:

$$\nu_t = (C_s\Delta)^2 S, \tag{6}$$

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