Simulation of plane and round impinging jet heat and mass transfer with a RANS k-ω model for electrochemical applications

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1. Summary

We study the qualities of the newest version of the k-ω turbulence model of Wilcox (2006, 2008) for heat and mass transfer prediction in turbulent jets impinging onto a flat plate for electrochemical applications. We compare with experimental data and with DNS results.

We first analyse the kinematic qualities of the model. We observe that for plane impinging jets, the prediction of the velocity field is quite accurate for small distance between the jet nozzle exit and the impingement plate. For round jets, the model overpredicts the turbulent kinetic energy in the impingement zone for small distance between the jet nozzle exit and the impingement plate. This is a common deficiency of eddy viscosity RANS models.

For the heat transfer, the Prandtl number is in the order of unity. We observe that for plane impinging jets, the predictions of the heat transfer are very accurate. For round impinging jets, there is overprediction of the heat transfer in the impingement zone due to the overprediction of the kinetic energy. We suggest a correction factor for impingement in the eddy viscosity formula. The correction factor contains the stagnation flow parameter of Goldberg (2006) and the vortex stretching parameter of Wilcox (2006, 2008). The third invariant of the strain rate tensor in the form of Shih et al. (1995) and the blending function of Menter (1994) are applied in order to make negligible the influence of the impingement modification in the benchmark flows for turbulence models. Significant improvements are obtained with respect to the original k-ω model.

For the mass transfer, the Schmidt number is very high. A simple method is proposed for simulation of impinging jet mass transfer at high Schmidt numbers. Two variants of algebraic models, based on the limiting behaviour of the turbulent diffusivity D_t for $y^+ \rightarrow 0$, are employed in order to provide D_t in the near-wall region. Away from walls, a formula based on the ratio of turbulent to molecular viscosity (ν_t/ν) is applied for determination of the turbulent Schmidt number. Blending between the algebraic expressions and the formula for ν_t/ν is performed in the buffer region of the boundary layer, making the model independent of y^+ at larger distances from the walls. With the proposed models, very good results have been obtained for the mass transfer at high Schmidt number in impinging jet flows. The model also functions well al low Schmidt number.

2. Motivation

RANS models have great interest because of their low computational cost in resolving turbulent flows in many engineering applications, where a LES method is too expensive. Among the RANS models, the eddy-viscosity models based on a linear relationship between the turbulent shear stress and the strain rate tensors are still very attractive due to their simplicity and robustness. On the other hand, RANS models based on the Boussinesq approximation have limitations, such as difficulties in prediction of boundary layer separation, secondary motion and turbulent production to dissipation rate in flow regions characterized by large level of strain. In the last few years some remedies have been proposed, leading to more reliable turbulent flow and convective heat transfer predictions and giving an impetus for their further validation in challenging test cases.

Among the eddy-viscosity models, the k-ω model (Wilcox, 1998) has received great interest because of its usefulness in resolving turbulent flows near walls without requirement of wall damping functions. The reason for this favourable behaviour of the k-ω model is that extra dissipation is produced near walls compared to a k-ε model as a result of a so called cross-diffusion term (Durbin, 1991). The cross-diffusion term appears when writing the k-ω model in the k-ε model formulation. Although this inherent property of the k-ω model poses advantages in resolving attached boundary layer flows and mildly separated flows, the accuracy of the earlier versions of the k-ω model were flawed by their sensitivity to the boundary conditions for the ω variable at the far-field boundaries, leading to ambiguous results in prediction of free shear flows. This drawback has been successfully removed in the newest version of the k-ω model by careful addition of a cross-diffusion term in flow regions away from walls where the cross-diffusion term takes positive values (Wilcox, 2006, 2008).

Another important modification in the newest version of the k-ω model is the addition of a stress limiter. This limiter is applied in order to bound overprediction of the turbulent shear stress in flow regions characterized by large rates of strain, e.g. in stagnation flow regions. It should be mentioned that an analogous stress limiter has been applied in the SST model (Menter, 1994).

It was demonstrated by Merci et al. (2004, 2005) that the influence of quadratic and cubic terms in the relation between Reynolds stresses and the velocity gradient has only negligible effect on the predicted heat transfer rate in an impingement region. Therefore, finally the constitutive relation was reduced to a first-order expression in their nonlinear turbulence viscosity model. The results obtained by Merci et al. (2004, 2005) show the potential of adding sensors based on scalar invariants to the first order Boussinesq relation between the Reynolds stress tensor and the strain rate tensor. Jaramillo et al. (2007, 2008) showed that k-ω models perform much better than k-ε models in prediction of the heat transfer rates of jet flows impinging onto a flat plate. They also showed that inclusion of higher order terms in the constitutive law does not considerably improve the heat transfer predictions in stagnation flow regions. Successful implementation of a k-l eddy-viscosity model for prediction of impinging jet heat transfer has been obtained by Goldberg (2006), by modifying the eddy-viscosity formula with a sensor based on the difference between the magnitude of the shear rate and the magnitude of the rotation. So, the cited works suggest that also a k-ω model can be improved for prediction of the heat transfer in impinging jet flows by modifying the Boussinesq relation between the Reynolds stress tensor and the strain rate tensor by taking into account sensors that detect impinging flow features.