NUMERICAL PREDICTION OF MOMENTUM AND SCALAR FIELDS IN A JET IN CROSS FLOW: COMPARISON OF LES AND SECOND ORDER TURBULENCE CLOSURE CALCULATIONS

Christian Mengler, Christoph Heinrich, Amsini Sadiki and Johannes Janicka
Department of Mechanical Engineering, Darmstadt University of Technology
D-64287 Darmstadt, Germany
cmengler@hrzpub.tu-darmstadt.de

ABSTRACT

The aim of the present work is to investigate the capability of LES using the eddy viscositiy approach along with the dynamic procedure to predict flow (mean velocity, Reynolds stress tensor) and a specified scalar eddy diffusivity approach to capture mixing fields (mean and variance of mixture fraction) in a jet discharging into a crossflow. This is achieved by comparing the LES results with linear and nonlinear second order turbulence closure models on the one hand and with experimental data of Andreopoulos (1983), Andreopoulos and Rodi (1984) on the other hand. For the RANS simulations, results by Heinrich (2000) are used. The results show the advantage of the LES compared to RANS simulations. Furthermore some aspects of the influence of the inlet conditions on the LES computation time has been pointed out.

INTRODUCTION

The jet in crossflow is a very interesting complex turbulent flow encountered in many engineering and environmental applications. Several works have been devoted to its experimental and numerical investigations in the past (for recent review, see Yuan et al. (1999), Schönfeld et al. (1999)).

From the numerical point of view, almost all contributions deal with the prediction of turbulence flow fields either by using RANS-methods or LES approach (Jones and Wille, 1996; Yuan et al., 1999). To predict the concentration fields, Alvarez et al. (1993), among other, used statistical turbulence closure models; they reported mean temperature profiles and velocity-temperature correlations in which the results with the second moment closure (Launder, Reece, Rodi (1975)) were somewhat more realistic than with $k-\epsilon$ turbulence models.

With regard to pollutant dispersion in environmental problems or modern aircraft gas turbine design purposes, an accurate prediction of the velocity fields and mixing is, however, of major relevance. The importance of large-scale structures in scalar mixing as well as in chemical reaction is now well accepted. Therefore, it is recommendable to use a method which incorporates both large-scale and (molecular) diffusion effects into scalar mixing modelling. LES alows all scales of motion larger than the grid resolution to be explicitly computed while the unresolved small scales must be modelled (e.g. Smagorinsky, 1963). Its extension to compressible flows and scalar transport problems has been carried out by Moin et al. (1991). Following Germano et al. (1991) and Lilly (1992) for flow field Cabot and Moin (1993) presented a dynamic SGS-model for LES of scalar transport in which the coefficient does not require ad hoc wall function (damping) to ensure its proper behaviour near solid boundaries. New approach to simulate passive scalar in large-eddy simulations of turbulence was recently presented by Flohr and Vassilicos (2000). With regard to complex flows of practical interest, a recent review paper is provided by Métais and Ferziger (1997). Especially in Schlüter et al. (1999) recent results for LES of jets in crossflow and its application to gas turbine burners are reported; a standard and a filtered Smagorinsky models with fixed Smagorinsky coefficients were used.

In this paper, we use the dynamic SGS model for the Reynolds residual stresses and a Smagorinsky extension (eddy diffusivity model) for the scalar flux field in order to investigate the flow and mixing fields in a jet in crossflow. To evaluate the capability of

LES in describing a such process, a comparison with linear and non-linear RANS-models as well as with experimental data of Andreopoulos (1983), Andreopoulos and Rodi (1984) will be performed. Although these data have used disputable measurement techniques, they constitute an interesting database for validation of numerical simulations of flow and mixing quantities in complex flows of such engineering importance.

CALCULATION METHODS

The filtered Navier-Stokes equations along with filtered continuity equation (eq: 1,eq: 2) describe the behaviour of any Newtonian fluid here considered with constant density. An additional filtered scalar equation (eq: 3) is used to describe the evolution of the passive scalar (here the mixture fraction).

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \quad (1)$$

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \bar{u}_i \bar{u}_j}{\partial x_i} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \frac{\mu}{\rho}\frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} - \frac{\partial \tau_{ij}^{sgs}}{\partial x_j} \quad (2)$$

$$\frac{\partial \bar{f}}{\partial t} + \frac{\partial \bar{f}\bar{u}_j}{\partial x_i} = \frac{\partial}{\partial x_j}\left(D\frac{\bar{f}}{\partial x_j}\right) - \frac{\partial}{\partial x_j} J_j^{sgs} \quad (3)$$

For the momentum equation the residual stresses τ_{ij}^{sgs} are determined by using the dynamic Germano procedure (eq:4) while for the scalar mixing fraction a constant eddy viscosity approach (eq:5) is used in which the scalar diffusion coefficient is expressed with turbulent viscosity divided by a Schmidt-number ($\sigma = 0.5$).

$$\tau_{ij}^{sgs} - \frac{1}{3}\tau_{kk}^{sgs} \approx -2\nu_t \bar{S}_{ij} = (C\Delta)^2 |\bar{S}_{ij}| \bar{S}_{ij} \quad (4)$$

$$J_j^{sgs} \approx -\frac{\nu_t}{\sigma}\frac{\partial \bar{f}}{\partial x_j} \quad (5)$$

As reference, a standard Smagorinsky model with constant coefficient ($C = 0.1$) is also used.

As basis for the simulations the 3-dimensional CFD-Code FASTEST [1] is used which is extended for the large-eddy simulation in complex geometries. The spatially filtered equations are discretized by finite-volume-method. Second order central differences are used for the spatial interpolation.

[1]by INVENT Computing GmbH, Erlangen, Germany

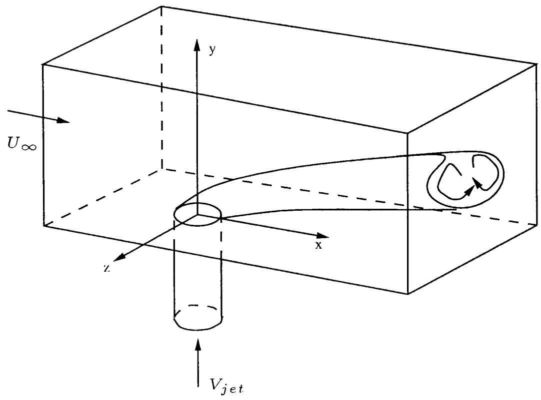

Figure 1: Jet in crossflow configuration

The variables are located at the cell centers (collocated grid). The velocity-pressure coupling is done by a SIMPLE algorithm which is extended by the pressure smoothing technique of Rhie and Chow (1982). As time integration scheme the Crank-Nicholson method is used. The whole system is solved by a SIP-solver. The calculation region is mapped on nonorthogonal block structured grids.

COMPUTATIONAL CONFIGURATION AND BOUNDARY CONDITIONS

The simulations are compared to the data measured by Andreopoulos and Rodi (1983, 1984) , who measured the velocity and mixing fields with hot wire anenometry. In a wind tunnel a round jet of air issues perpendicularly in the crossflow (Fig. 1). The jet is heated 4^oC about the crossflow to measure the mixing field. The velocity ratio $R = V_j/U_\infty$ of jet velocity to free crossflow velocity ($U_\infty = 13.9m/s$) is 0.5. The Reynolds-number of the jet ($Re_D = V_j D/\nu$) is 20500. The jet pipe diameter D is $0.05m$. For further details, see Andreopoulos (1983), Andreopoulos and Rodi (1984). The computational domain is $-2 < x/D < 7$ in streamwise (x-) direction, $0 < y/D < 4$ in jet exit (y-) direction and $-2 < z/D < 2$ in spanwise (z-) direction. The resolution is about 275000 CV's for the whole domain. As mentioned by Jones and Wille (1996) this domain is big enough. While it is clear that the jet exit is influenced by the crossflow, this fact has to be considered when choosing the inflow conditions of the jet. With regard to this influence, a length of two diameters of the jet pipe are modelled. As can be shown in the results the asymmetry of the jet exit is qualitatively reproduced.

For the wall boundary of the pipe and the bottom of the crossflow channel, no-slip conditions were used. The upper and the spanwise faces of the domain were treated as free-slip. The outflow condition is a simply zero-gradient condition like in Yuan et al. (1999). The inflow conditions are described by mean velocity profiles as measured by Andreopoulos and Rodi (1983, 1984) for the crossflow inlet. For the pipe inlet experimental data from Durst et al. (1995) is used. The mean profiles of mean velocities and fluctuations are in one case perturbed with white noise and in the other case calculated without pertubations.

RESULTS AND DISCUSSION

To obtain the results presented here, the problem was simulated for 10 flow-through-times ($\Delta\tau = 11D/U_\infty$). After $3\Delta\tau$ the flow was statistically stationary and samples were taken for $7\Delta\tau$ and averaged in time.

As first part of the results, the influence of inlet pertubation will be discussed. The different inlet conditions had dramatical influence on calculation time. The simulations were performed on an Alpha 21264. Due to the aritificial non-realistic velocity field produced with white noise, the implicit solver needs about a factor of 4.4 the time than simulations without pertubation as shown in Table 1. Both inlet conditions produced the same results for mean values and variances. As example in Figure 2 the $\sqrt{\overline{u'^2}}/U_\infty$ distribution is shown from $x/D = -2$ to 7 in a height of $y/D = 0.153$. It is shown that both simulations get nearly the same results. The simulation with white noise has a value at the inlet of 0.07. The simulation without pertubation starts at 0. At the first cell inside the domain both simulations reach the same value and predict almost the same distribution along the mainstream direction (see also Weinberger et al. (1997)).

After these considerations, the results of the large-eddy simulation using the dynamic

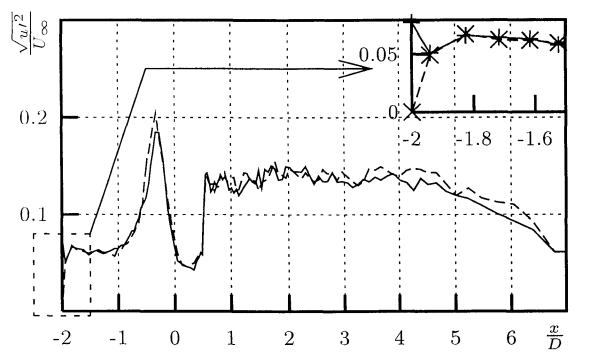

Figure 2: Comparison of normalized $\sqrt{\overline{u'^2}}$ at $y/D = 0.153$ (——) with and without (····) pertubation

Table 1: Comparison of calculation time

calculation time per timestep	
white noise	no pertubation
520.7 sec	119.9 sec

procedure, labelled GERM, and Smagorinskys model, labelled SMAG, are compared to the experimental data measured by Andreopoulos and Rodi (1983, 1984) and to RANS simulations by Heinrich (2000) using the models of Jones and Musonge (1988), labelled JM, and Speziale et al. (1991), labelled SSG. All data is shown in the symmetry plane $z/D = 0$ at several positions ($x/D = -0.25, 0, 0.25, 0.5, 1, 2, 4$). Taking in mind the experience with inlet conditions, the results presented in the following are calculated without pertubations.

Flow field

Figures 3 and 5 show the mean velocity profiles for U and V in the x- and y-directions, respectively. The data is non-dimensionalized with the free crossflow velocity U_∞ and the pipe diameter D. In Figures 4 the Reynolds stresses $\overline{u'v'}/U_\infty^2$ are displayed.

The U-velocity (Fig. 3) is predicted good with both, LES and RANS, at most positions. There are some discrepancies at the position x/D=1.0. All simulations (LES and RANS) show a recirculating zone, which cannot be prooved by the experiments. The last three positions are in a high turbulent region, where the measurement errors increase and sudden changes of flow direction are not treatable with hot wires. In this region the nonlinear SSG model differs from the linear JM model and the

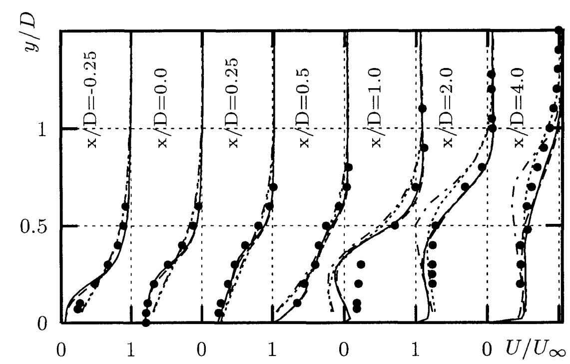

Figure 3: Profiles of mean Velocity U/U_∞ (Exp.:•; SMAG:– – –; GERM:——; JM:····; SSG:–·–·)

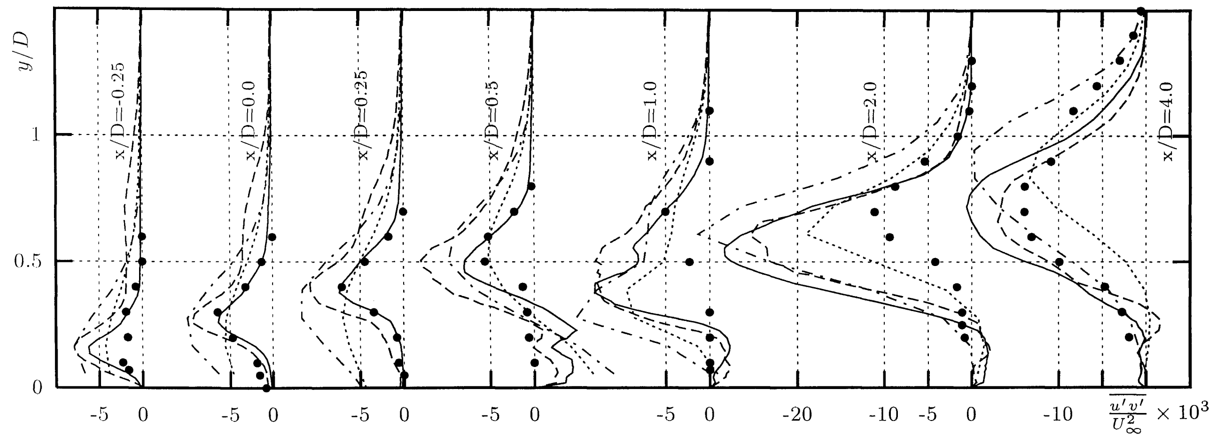

Figure 4: Profiles of $\overline{u'v'}/U_\infty^2 \times 10^3$ (Exp.:•; SMAG:– – –; GERM:——; JM:· · · ·; SSG:– · – ·)

experimental data. Overall the RANS models are not able to reproduce the sharp gradients of the experimental data while the LES does.

The V-velocity (Fig. 5) shows also good agreement. However LES seems to give the better predictions. At two positions there are some deficencies. The first is the jet exit. At $x/D = -0.25$ the LES predicts the same values until a height of $y/D = 0.1$. Below that point the LES prediction increases to a value of $V/U_\infty = 0.23$ while the measurements have only 0.06. So the partial covering of the jet exit is not simulated like measured. Further at positions $x/D = 2$ and 4, the measurements show negativ V-velocities which cannot be prooved by all simulations. Especially the RANS models shows a strong fluid motion away from the wall. Summarizing the results, the LES is able to reproduce the gradient of the V-velocity much better than the RANS models do.

In Figure 4 the Reynold stresses are presented. In particular, the dynamic procedure is able to predict the peak position very good, while the Smagorinsky model and RANS results deviate at the most positions. Overall the nonlinear SSG model overpredicts the

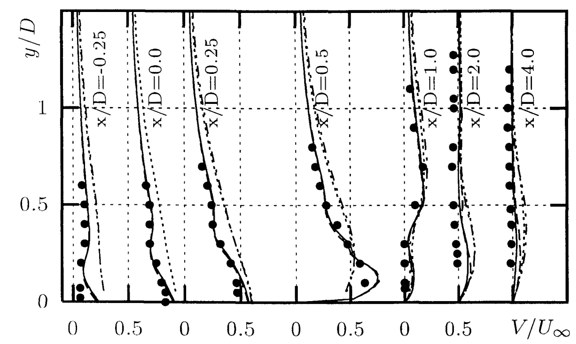

Figure 5: Profiles of mean Velocity V/U_∞ (Exp.:•; SMAG:– – –; GERM:——; JM:· · · ·; SSG:– · – ·)

shear stress at all positions, while the linear JM model is able to predict the peak values, but not the correct position. At the last three downstream positions ($x/D = 1; 2; 4$) both simulating techniques differ from the experimental data. Andreopoulos and Rodi (1984) describe this region as a high turbulent region with turbulence intensities up to 50%. Due to this the measurement errors increase up to 12% for the mean values and much higher for fluctuating quantities. From the strong discrepancies observed with Smagorinsky and SSG models, further corresponding results will not be considered for comparison of scalar field.

With regard to LES (GERM) results, at the first downstream position ($x/D = -0.25$) the $\overline{u'v'}$-correlation peak value is overpredicted, which corresponds to a misprediction of the mean U-velocity at this position. At the jet exit and further down the correlation is very good reproduced with regard to the peak position and the advantage of the LES in comparison to the RANS models appears indubitable as mentioned above.

Scalar field

With regard to mean scalar fields, Figure 6 shows the simulation results for the mixture fraction, for which the second order models for the scalar flux are used in RANS. It is obvious that both simulating techniques cannot proove the mixing above the jet exit. But the gradient is much better predicted with the LES. At these positions ($x/D = -0.25; 0$) the measured sudden increasing of the V-velocity is contradictory to the sligth increasing of the mean temperature. So it is questionable to assess numerical results when the experimental velocity and mixing fields seem to describe contradictory behaviour. At the rear pipe edge

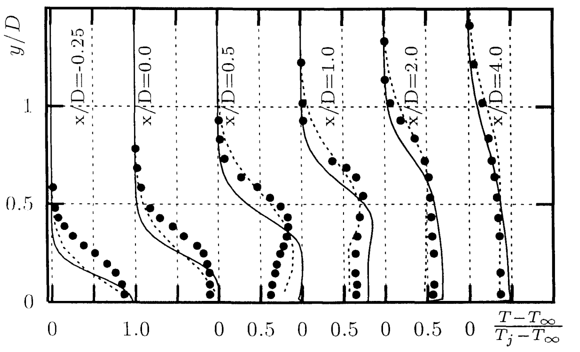

Figure 6: Profiles of mean temperature $T - T_\infty/T_j - T_\infty$ (Exp.:•; GERM:——; JM:····)

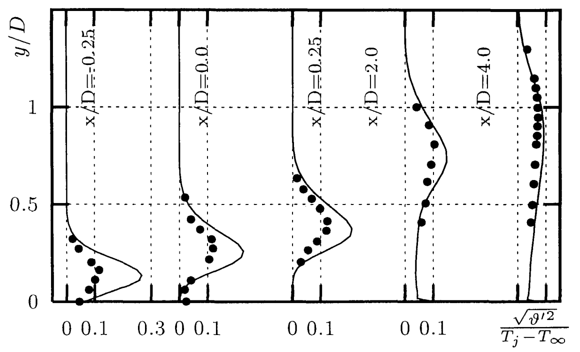

Figure 8: Profiles of rms temperature fluctuations $\sqrt{\vartheta'^2}/T_j - T_\infty$ (Exp.:•; GERM:——)

(x/D = 0.5) the mean velocity U is positive and the mean flucutations are very small, but the mean temperature profile is decreasing down to 0.5. Another questionable behaviour is shown by the position of rms-peak and gradient of the mean profile. The LES and RANS simulations show nearly the same mean profiles for the temperature. But compared with the experimental data, the simulations do not mix as far in the crossflow as the experiments do. Comparing the position of the peak postion of the rms value and the gradient of the mean value in the Figures 6 and 8 at the first downstream positions, the position of the LES is in very good agreement with the gradient of the simulations, while the experiments differ in position of peak and gradient. Furthermore the peak values of the temperature fluctuations are overpredicted by the LES at the first positions, while at the rear positions the simulations are in good agreement with the experiments.

Concerning the scalar flux predicted by LES and RANS, the velocity temperature correlation $\overline{u'\vartheta}/U_\infty(T_j - T_\infty)$ is shown in Figure 7. The correlation is overpredicted by the LES like the scalar variance, but much more than the RANS do. Again the advantage of the LES in predicting the peak position is observed. Especially at $x/D = 2$ the RANS simulations predict a change of sign, which is not prooved by the LES and the experiments.

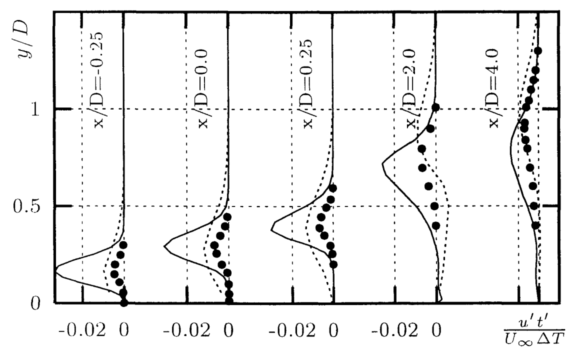

Figure 7: Profiles of $\overline{u'\vartheta'}/U_\infty(T_j - T_\infty)$ at various positions x/D and z/D=0 (Exp.:•; GERM:——; JM:····)

The results in Figures 6 and 8 underline, however, the deficiency of the eddy-diffusivity approach with constant Schmidt number for the mixing model. As shown in Kim and Moin (1989) the influence of the diffusion coefficient on the scalar fluctuations can be enormous and leads in this simulation with constant coefficient to an overprediction of the fluctuations.

CONCLUSIONS

In this work, the LES of a turbulent jet issuing perpendicular in a crossflow was simulated. The flow structures could be observed and the results show the advantage of the LES compared with RANS simulations. In our simulation it was also possible to show the influence of the crossflow to the flow in the pipe, which indicates the necessity of the simulation of the pipe flow.

The influence of the inlet conditions on the calculation time used by the implicit solver is enormous. The artificial white noise increases calculation time by a factor of 4.4. However the calculation time remains very high compared to RANS.

The flow field shows excellent agreement with the expertimental data and emphasizes the advantage of the LES compared with RANS modelling, although there are some discrepancies compared to the measurements which cannot be explained. In particular the mixture fraction fluctuation and related quantities show strong deviation. This fact needs to be investigated in detail by using advanced subgrid models for turbulence and especially for mixing.

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