Second-order modelling of variable density turbulent jets : evaluation in the near field region

Emmanuel Ruffin, R. Schiestel, Fabien Anselmet, L. Fulachier

SECOND-ORDER MODELLING OF VARIABLE DENSITY TURBULENT JETS : EVALUATION IN THE NEAR-FIELD REGION

E. RUFFIN, R. SCHIESTEL*, F. ANSELMET, L. FULACHIER
Institut de Mécanique Statistique de la Turbulence,
Unité Mixte Université d'Aix-Marseille II/CNRS N° 380033,
12, avenue Général-Leclerc, 13003 Marseille
* Institut de Mécanique des Fluides,
Unité Mixte Université d'Aix-Marseille II/CNRS N° 380034,
1, rue Honnorat, 13003 Marseille

ABSTRACT.

This paper is concerned with a complete second-order model of variable density turbulent jets. Emphasis is given here on the near-field region of the flow where it is found that the influence of the density variations is quite important resulting in a complex behaviour of both the mean and turbulent velocity fields. Particular attention has been paid to the mesh grid and the initial conditions so that quantitative comparison with the experimental data obtained in the study developed in parallel to that one at I.M.S.T. can be made. Results relative to the velocity field only will be reported herein since quite few studies have been focusing so far on the near-field region where the model shows shortcomings which may not be visible when looking at results obtained in the far-field where pseudo-similarity is attained.

INTRODUCTION.

The main purpose of this paper is to check the ability of second-order modelling in predicting variable density turbulent flows using the I.M.S.T. experimental data (see the companion paper presented at this conference by Djeridane et al.). Emphasis is given on the near-field region where the density variations are strongest. This feature significantly enhances the difficulty of refined flow modelling and may require new approaches since the mechanisms involved in turbulent energy transfers in such flows may be quite different from those encountered in constant density flows. Nevertheless, most of the models developed so far have taken advantage of the similar formalism presented by Reynolds averaged equations for constant density flows and Favre averaged ones for variable density flows to infer from usual modelling closure assumptions which are applied to that case (e.g. Gouldin et al., 1986). But recent studies (e.g. Chassaing, 1992) show that this is probably not physically justified and there is a clear need for precise comparisons of Reynolds and Favre averaged approaches of variable density flow modelling.

In addition, since this situation is often encountered in applied or industrial problems where other problems such as the flow geometry or the number of

5ème Symposium International, Paris, 7-10 septembre 1993, p. 529-536.

reacting species to consider result in the use of less refined turbulence models, it is important to study in detail the influence of density variations in a basic situation such as an axisymmetric jet flow to obtain information about the evolution of important quantities such as characteristic time or length scales, Schmidt or Prandtl turbulent numbers or the ratio R of the scalar and dynamical time scales (Fulachier et al., 1989). Indeed, though the modelling problems involved in the kinetic energy and scalar dissipation equations are not yet resolved for constant density flows, it is crucial to study them for variable density flows, and the proposals made so far are quite different (e.g. Jones, 1979; Shih et al., 1987).

Another difficulty is related to the comparison of experimental data with the model predictions since this situation has so far received little attention even for an axisymmetric jet. Most of the available results mainly concern the mean velocity or scalar field in the far-field region where approximate similarity is attained (e.g. Pitts, 1991) and the initial flow and boundary conditions are often only roughly known or quite difficult to take into account numerically. To our knowledge, the most detailed investigation is that of Panchapakesan and Lumley (1993) who measured third order moments of velocity and tested their results with a new model, but this work is limited to stations located at distances larger than 50 times the nozzle diameter.

After a short description of the numerical procedure, with emphasis given on the choice of the initial conditions and the grid mesh in order to be as close as possible to the I.M.S.T. experimental configuration, results concerning the mean velocity and some of the Reynolds stresses in the near-field region ($X/D_j < 30$, where X is the longitudinal distance from the nozzle) obtained with quite usual modelling assumptions will be reported. Possible refinements of the model will be discussed.

NUMERICAL PROCEDURE.

The code is based on a finite volume scheme for elliptic flows. It solves the second-order equations for plane or axisymmetric stationary flows in which a scalar (temperature or species concentration) may generate density gradients. The model so far includes Favre averaged versions of the continuity equation and the transport equations for momentum, the Reynolds stresses, the kinetic energy dissipation, and the scalar mean value, variance, fluxes and dissipation, as well as the equations for the local physical properties of the fluid. At the moment, these equations are modelled using quite usual assumptions and constants are those proposed by Gibson and Launder (1978). However, the additional terms related to the pressure gradients are considered. These extra terms related to the density fluctuations in the tranport equations for the turbulent stresses R_{ij} read :

$$V_{ij} = -\overline{u_i' p_{,j}} - \overline{u_j' p_{,i}} \quad (1)$$

They are modelled on the basis of the following hypothesis :

$$\overline{u_i'} = \frac{1}{\overline{\rho}} \frac{\partial \overline{\rho}}{\partial \tilde{C}} \widetilde{u_i' c'} \quad (2)$$

where C is the concentration of jet gas in ambient fluid. Buoyancy forces are so far ignored since attention is mainly paid to the near-field region.

The calculation domains are shown on figure 1 where the main different numerical regions are coloured using different grey levels : it is important to note that, for quantitative comparisons with experimental data obtained in the I.M.S.T. jet facility, the flow is slightly confined and the nozzle thickness is taken into account. The flow conditions (e.g. longitudinal velocity U_j=32m/s for helium, 12m/s for air and 10m/s for CO_2, nozzle diameter D_j=26mm, U_e=1.2m/s for air in the D_e=285mm enclosure,...) are identical to those in the experiments. Particular attention has been devoted to the grid mesh (Fig. 2) and to the initial conditions (Fig. 3). The primary (fully turbulent pipe) and secondary (fully turbulent annulus) flows are first computed on meshes radially corresponding exactly to those in the jet part of the domain, using the same second-order code, since it appeared that this is essential for achieving dissipation rates compatible with the jet flow computation. For instance, figure 3 shows that when these quantities are evaluated through the usual relations from kinetic energy measurements, i.e. $\varepsilon = k^{3/2}/\ell$ (3), it takes more than $5D_j$ for the axis longitudinal velocity standard deviation to relax to an equilibrium state. Additional nodes for the nozzle thickness were also found to be essential. The spacings along the radial direction do not vary with the downstream position, whereas those along the symmetry axis do as longitudinal gradients become smoother. Calculations reported herein are obtained with 80 grid points along the symmetry axis (with X the distance from nozzle) and 72 ones along the radial direction (distance R and velocity V).

Fig. 1 : Calculation domains

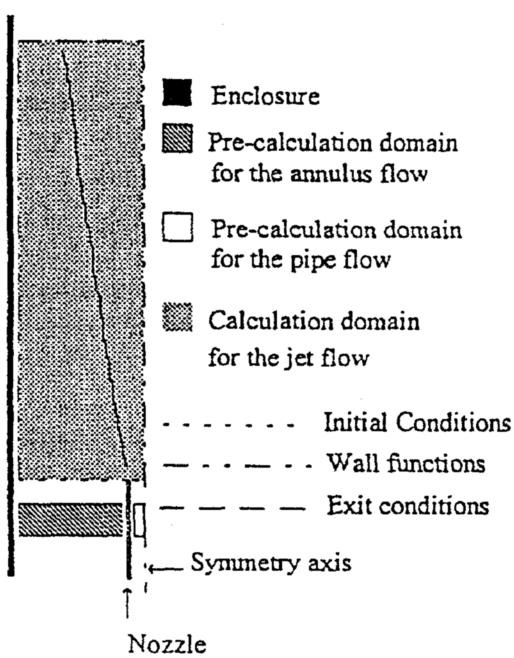


Fig. 2 : Grid disposition

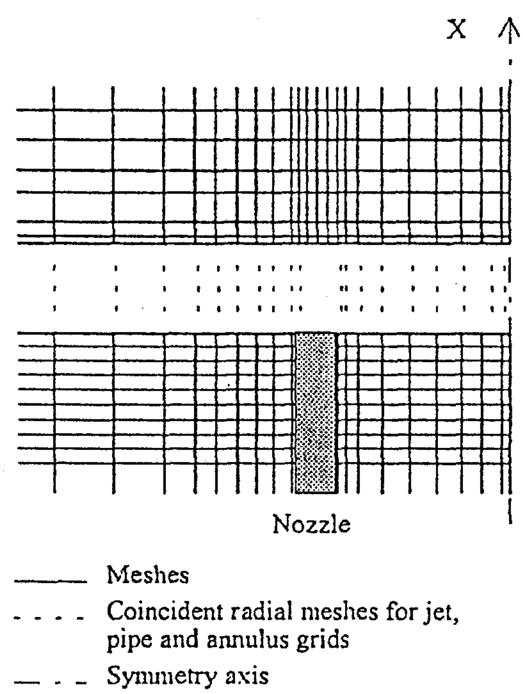
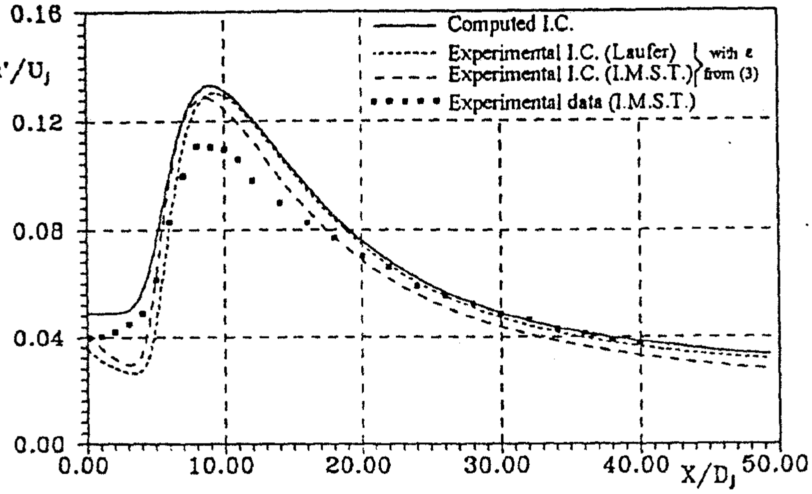


Fig. 3 : Effects of initial conditions (I.C.) on air jet calculation



Though the code computes Favre averaged quantities, comparison is made with experimental data obtained by laser-Doppler anemometry which is providing statistical values closer to Reynolds averaged than Favre averaged ones. However, the estimation of the mean Reynolds velocities from the computed ones shows that this problem can be, at least as a first step, neglected.

RESULTS AND DISCUSSION.

The streamwise evolutions of the axis mean streamwise velocities (Fig. 4), spreading of the jet (Fig. 5), streamwise u' (Fig. 6) as well as radial v' (Fig. 7) velocity standard deviations are reported for the three gases studied. It is worth noticing that, in order to have a better comparison of the various quantities computed with those measured, the raw data will be presented all along this paper. Indeed, normalization with the initial flow mean velocity U_j seems better if one really wants to study the various problems involved in the model and to avoid error compensating effects that could result from the computation of, for instance, local turbulence intensities. For mean velocities (Fig. 4), the well known shortcomings of second-order models are clearly visible for the air flow, resulting in an overestimation of the rate of velocity decay. For CO_2 (density 1.5 times larger than that of air), this feature is even more important, whereas, for helium (density 7 times smaller than that of air) the relative behaviour is opposite. Gouldin et al. (1986) 's computations of a propane jet (density twice smaller than that of air) with a slightly different second-order model are in good agreement with ours. The calculated spreading rates (Fig. 5) of the CO_2 and helium jets are sligthly different from the experimental findings but the air jet one is in relatively good agreement. The calculation gives values of spreading rates that are not distinctly different for the three jets. However experimental data indicate a larger spreading rate for the helium jet and a smaller one for the CO_2 jet. At this time, this experimental trend still needs to be better analyzed since data from various other studies (e.g. Panchapakesan and Lumley, 1993 ; Sahr and Gokalp, 1991) suggest that other parameters such as the Reynolds number and the jet exit conditions may affect the evolution of the velocity half-widths almost as much as the density difference does.

However, the very-near field region is well represented for the three gases. The relatively poor results for this parameter reflect those obtained for the axis mean streamwise velocities.

Fig. 4 : Evolutions of the mean longitudinal velocity on the jet centerline.

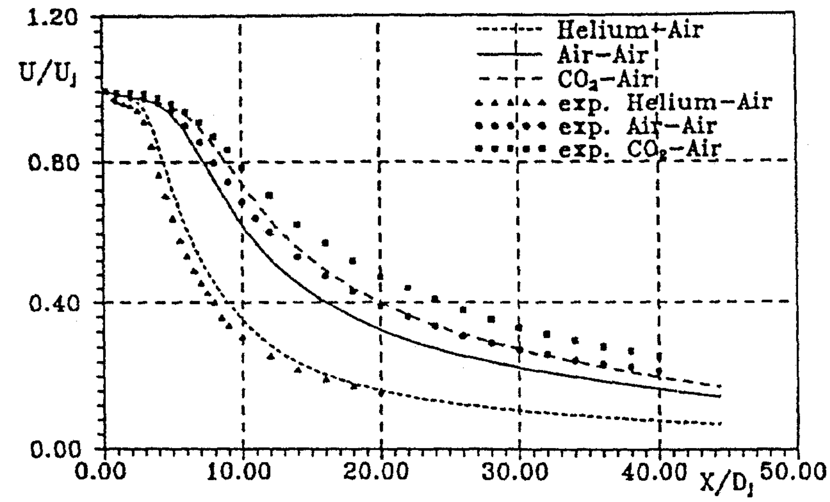
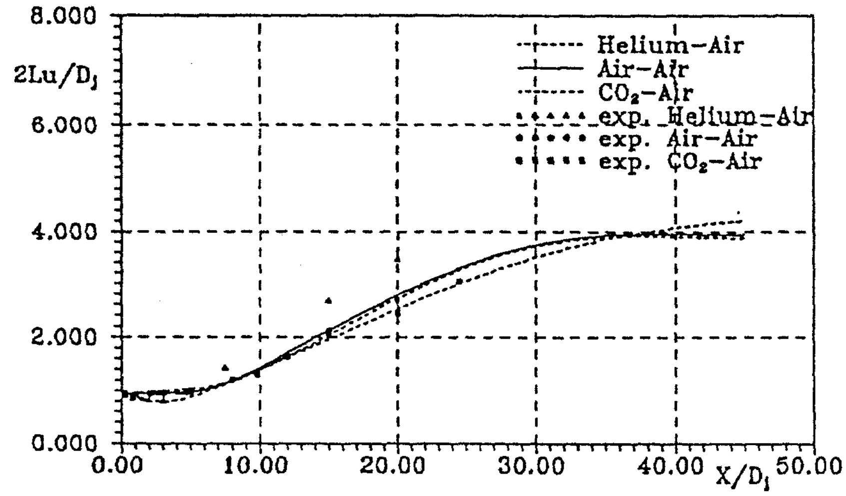


Fig. 5 : Evolutions of the velocity half-width on the jet centerline.



Results relative to the turbulent field (Figs. 6 and 7) show deviations from the experimental data globally similar to those previously discussed for the mean field. However, the radial velocity standard deviations are in better agreement with experiments than the longitudinal ones. It is obvious that, for the helium jet, the code cannot at the moment take into account the sudden development of the flow in the very first stations ($X/D_j < 6$). It is also interesting to note that, in this region, quite large skewness and flatness factors for u and v are found experimentally, especially for helium, with the departure from gaussianity being significantly larger for u than for v. One can think that this latter behaviour is also characterisic of a turbulent field quite different from usual ones that the code cannot so far take into account.

Fig. 6 : Evolutions of the longitudinal velocity standard deviation on the jet centerline.

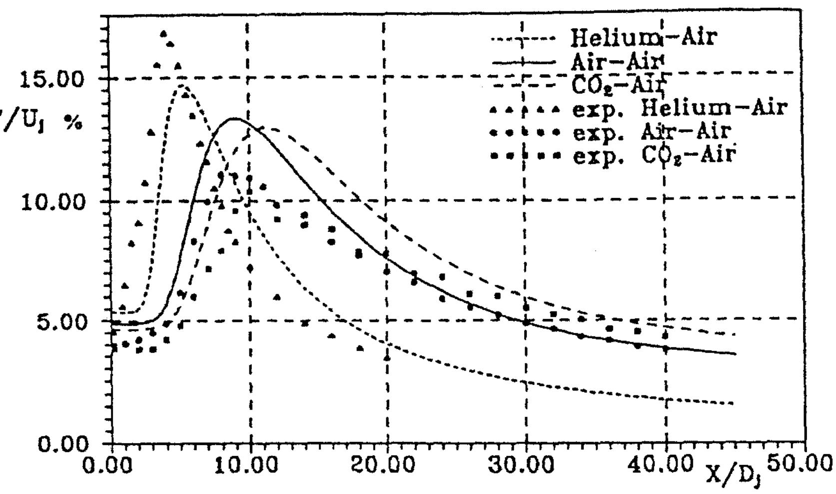
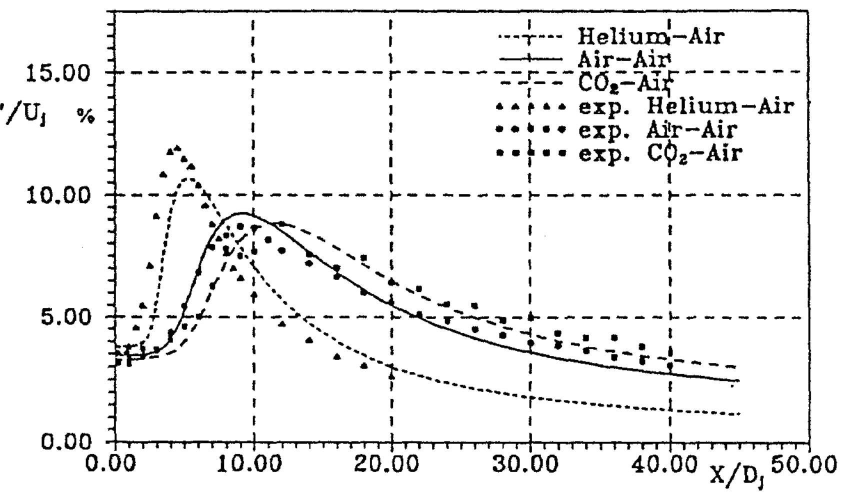


Fig. 7 : Evolutions of the radial velocity standard deviation on the jet centerline.



Radial distributions of the Reynolds shear stress <uv> at three stations X/D_j are presented on figures 8, 9 and 10 for the CO_2, air and helium jets respectively. For all of these distributions, the positions of the peaks are fairly well predicted but their amplitudes are, here again, overestimated for CO_2 and air and underestimated for helium. In addition, the radial expansions of these quantities are also significantly underestimated for helium and overestimated for CO_2 and air. These findings are also quite similar to those reported by Gouldin et al. (1986) for propane, who present turbulent quantities for the station X/D_j=30.

Fig. 8 : Radial distributions of the Reynolds stress for CO_2-Air jet.

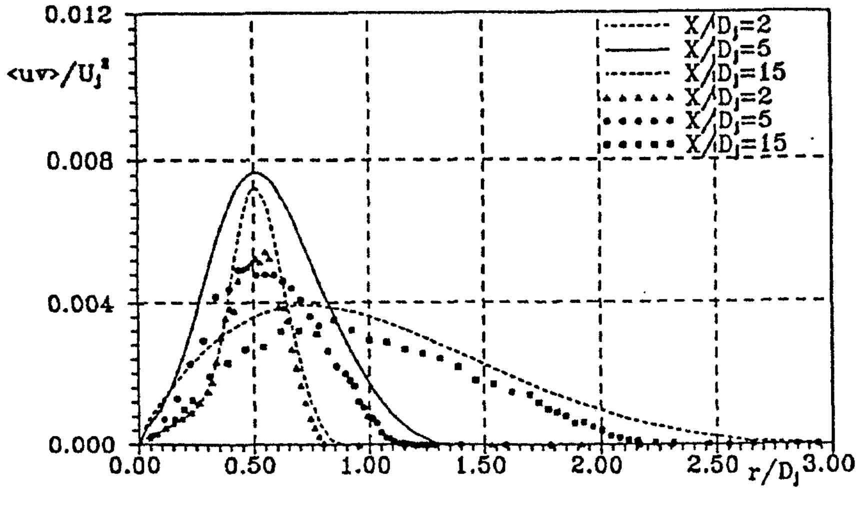


Fig. 9 : Radial distributions of the Reynolds stress for Air-Air jet.

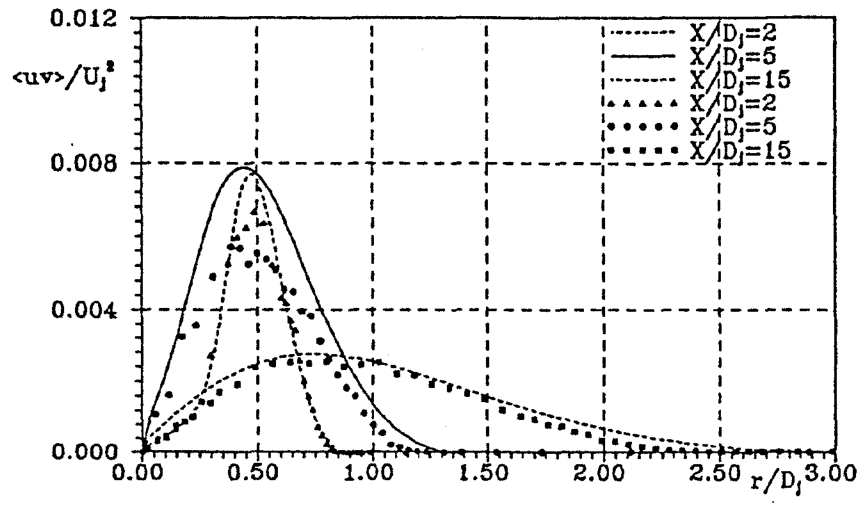
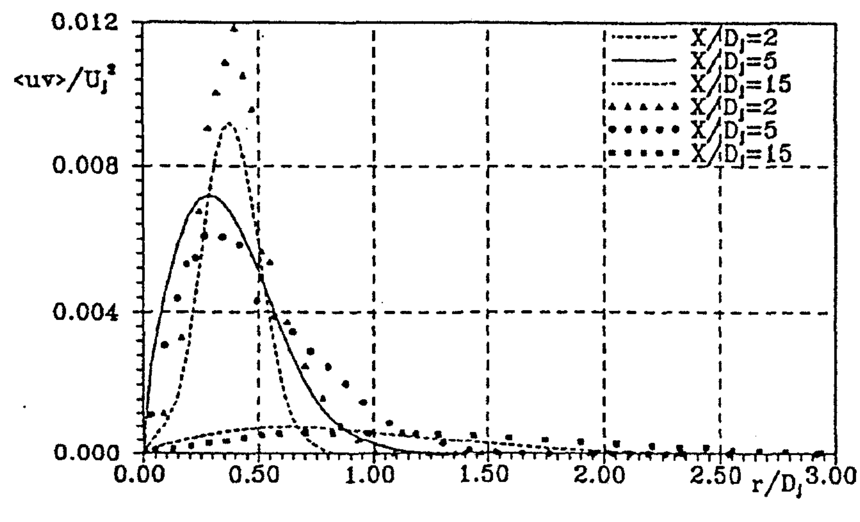


Fig. 10 : Radial distributions of the Reynolds stress for Helium-Air jet.



CONCLUSION.

Results reported herein confirm that the usual second-order model is not very efficient for predicting the development of pure air jets and this is particularly obvious in the near-field where detailed results such as those reported here are usually not presented since attention is mainly paid to the self-preserving region. As a consequence, though the relative effects of density variations have the right trend for all the quantities reported here, the code cannot predict with good accuracy the near-field development of CO_2, air and helium jets. However, before focusing on the shortcomings of the modelling with respect to the effects of density, it seems essential to improve those for the air jet. Thus, new models such as those proposed by Launder (1989) for the redistribution terms of the Reynolds stress equations and the corresponding ones for the scalar fluxes, or the development towards the improvement of the modelling of the third order moments involved in the turbulent diffusion terms (e.g. Panchapakesan and Lumley, 1993), are worth being tested. Nevertheless, the present model seems already efficient enough for studying, for instance, the influence of density variations on turbulent characteristic time and length scales which are important for lower order models such as those used in the modelling of turbulent combustion since, to our knowledge, such information is not available at the moment.

ACKNOWLEDGEMENTS.

Financial support from Electricité de France, Gaz de France, Société Nationale de Construction de Moteurs d'Avions, Institut National de l'Environnement Industriel et des Risques and Conseil Régional Provence-Alpes-Cote d'Azur (access to the computer center of Institut Méditerranéen de Technologie) for both the numerical and experimental aspects of this work is gratefully acknowledged.

REFERENCES.

CHASSAING, P. 1992 2nd French Workshop on Var. Dens. Turb. Flows.
DJERIDANE, T., AMIELH, M., ANSELMET, F. and FULACHIER, L. 1993 Companion experimental paper presented at this conference.
FULACHIER, L., BORGHI, R., ANSELMET, F. and PARANTHOEN, P. 1989 J. Fluid Mech., vol. 203.
GIBSON, M.M. and LAUNDER, B.E. 1978 J. Fluid Mech., vol. 86.
GOULDIN, F.C., SCHEFER, R.W., JOHNSON, S.C. and KOLLMANN, W. 1986 Prog. Energy Comb. Sci., vol. 12.
JONES, W.P. 1979 VKI Lecture Series, n° 2.
LAUNDER, B.E. 1989 Int. J. Heat Fluid Flow, vol. 10, n° 4.
LAUFER, J. 1953 NACA Report vol. 1174.
PANCHAPAKESAN, N.R. and LUMLEY, J.L. 1993 J. Fluid Mech., vol. 246.
PITTS, W.M. 1991 Experiments in Fluids, vol. 11, n° 5.
SAHR, B. and GOKALP, I. 1991 In Proc. Congrès français de Mécanique, vol. 2.
SHIH, T.H., LUMLEY, J.L. and JANICKA, J. 1987 J. Fluid Mech., vol. 180.