TURBULENT REACTING FLOW IN A DUMP COMBUSTOR: SOME SPECIFIC ASPECTS RELATED TO THE MODELLING OF TURBULENT TRANSPORTS

Phuc Danh NGUYEN - Pascal BRUEL

Centre National de la Recherche Scientifique
Laboratoire de Combustion et de Détonique
Site du CEAT
43, route de l'Aérodrome
86036 Poitiers Cedex - FRANCE
Tel.: (+33) 5 49 36 60 89, Fax: (+33) 5 49 36 60 64
E-mail: nguyen@ensma.fr

Extended Abstract to be presented at the 19th ICDERS
Hakone, Japan, July 27 - August 1, 2003.

Key Words: premixed combustion, coherent motion, turbulence modelling.

Abstract

The development of systems of aeronautical propulsion able to meet the forthcoming drastic certification on low level of pollutants emission partly relies on the development of new concepts of combustion chambers based for instance on the Lean Premixed Prevaporized (LPP) technology [5]. In such type of combustion chambers, both large scale coherent motion and turbulence contribute to the flow unsteadiness and only the modelling approaches able to deal with this peculiarity can be used to participate in the development of these systems. In that respect, the choice appears to be "limited" to either the Large-Eddy Simulation (LES) [3][4] which involves the resolution of unsteady space averaged governing equations or the Semi-Deterministic Approach (SDA) [7][8][9][11][12] which stretches the capability of one-point Reynolds Averaged Navier Stokes approach by explicitly discriminating in the flow unsteadiness between the coherent and the stochastic motion. In that framework, the present study proposes an experimental methodology aimed at assessing the intrinsic coherence of a classical turbulence model in the case of a turbulent premixed propane-air flame stabilised by a symmetrical backward-facing step, a dump combustor that can be considered as a highly simplified LPP system.

The great interest of such a flow is that it features simultaneously large scale coherent motion as well as turbulence [1] and thus can be used to study combustion instabilities [6][10] as well as to develop and test new turbulent combustion modelling that will benefit from the relative simplicity of the flow geometry [2] while yielding results that will be useful for the development of the real LPP systems. Our objective here is to pinpoint the fact that the conclusions concerning the "performance" of a given turbulence model (here a classical $k-\varepsilon$ model) can be drawn in a sound way only if the conditions of application of the model are realised. In the case of a flow unsteadiness for which the coherent motion plays an important role as it is the case for LPP systems, this implies in particular that the turbulence model has to be applied to model solely the transports that take their source in the stochastic fluctuations. Consequently, as far as the experimental data are concerned, this means that a specific data processing has to be carried out in order to extract the Reynolds stresses associated with the stochastic motion. This requirement being fullfilled, the predictive capabilities of the model or its coherence can be examined. Along these lines, we propose a simple experimental methodology aimed at permitting such a "fair" turbulence model testing. At any point M within the flow, the coherence of the turbulence model will be assessed by comparing the modelled values $(\overline{u_s'^2})_M^{k-\varepsilon}$ and $(\overline{v_s'^2})_M^{k-\varepsilon}$ to the measured ones. The modelled values will be determined from the experiments by applying the following 5-step procedure:

1. Simultaneous measurement of the streamwise and the transverse component of the velocity with a 4-beam LDV system at point M.

2. Measurements of the velocity components in the neighbourhood of M in order to be able to compute $(\partial\overline{u}/\partial y)_M$ and $(\partial\overline{v}/\partial x)_M$.

3. Use at point M, of the SDA that introduces the following triple decompositions: $u(t) = \overline{u} + u'_s(t) + u'_p(t)$ and $v(t) = \overline{v} + v'_s(t) + v'_p(t)$ to extract $u'_s(t)$ and $v'_s(t)$ and then calculation of the shear stress $(\overline{u'_s v'_s})_M$ associated to the stochastic motion.

4. Evaluation of the turbulent kinetic viscosity by: $(\nu_t)_M = -(\overline{u'_s v'_s})_M / \left(\partial\overline{u}/\partial y + \partial\overline{v}/\partial x\right)_M$

5. Calculation of the "modelled" Reynolds stresses according to the following expressions:

$$(\overline{u'^2_s})^{k-\varepsilon}_M = -2(\nu_t)_M(\frac{\partial\overline{u}}{\partial y})_M + \frac{2}{3}k_M \text{ and } (\overline{v'^2_s})^{k-\varepsilon}_M = -2(\nu_t)_M(\frac{\partial\overline{v}}{\partial x})_M + \frac{2}{3}k_M \text{ where } k_M = \frac{1}{2}\left(\overline{u'^2_s} + 2\overline{v'^2_s}\right)_M \quad (1)$$

Figure 1 presents a schematic view of the flow configuration considered as well as an example of the shape of the instantaneous flame brushes and Table 1 lists the related flow parameters.

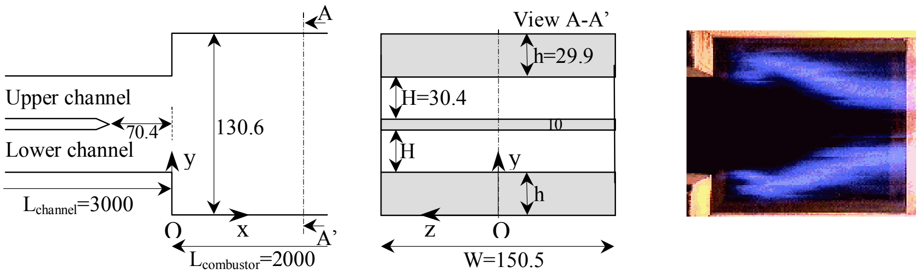

Figure 1: Characteristic dimensions (in mm) of the combustor and instantaneous flame brushes with time exposure = $1/1000$ s.

Case	Stream	$Re = U_{bulk}H/\nu_0$	Q g/s	U_{bulk} m/s	Φ	Thermal Power (kW)
c_1	upper	25000	65	11	0.75	110
	lower	25000	65	11	0.75	110

Table 1: Main parameters of the test cases (atmospheric pressure, temperature of the incoming flows = 276 ± 10 K; systematic error in $Q = \pm 1$ g/s, in $Re = \pm 2\%$, in $U_{bulk} = \pm 1.5\%$, and in $\Phi = \pm 0.025$).

Figure 2 gives, at two different locations in the combustor, the transverse profiles of the turbulent kinematic viscosity normalized by the molecular kinetic viscosity ν_0 of the fresh mixture calculated either by using the stochastic or the total shear stress. These results show that the use of the total velocity fluctuations to compute ν_t leads to an important overestimation of the turbulent kinematic viscosity coefficient when compared to the values obtained when only the stochastic shear stress $(\overline{u'_s v'_s})$ is considered.

The results presented in Figures 3 and 4 demonstrate that a fair agreement is obtained between the values computed by the model and those obtained directly from the experimental measurements (Figs. 3.c and d - Figs. 4.c and d) provided that only the stochastic contribution is considered in the comparison. The contrast is clear with the poorer quality of the agreement between measured and modelled values presented in Figs. 3.a and b and Figs. 4.a and b where the total velocity fluctuations is used without extraction of the sole contribution of the stochastic motion. Thus, these results suggest that a numerical simulation of such reacting flow, based on

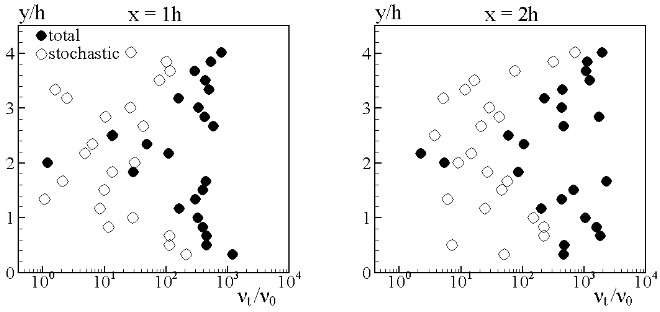

Figure 2: Profiles of the turbulent kinematic viscosity normalized by molecular kinematic viscosity of fresh mixture at two streamwise abscissa $x = 1h, 2h$.

a "simple" turbulence model could produce accurate results if both the calculations and the comparisons with experiments were carried out by considering only the stochastic motion.

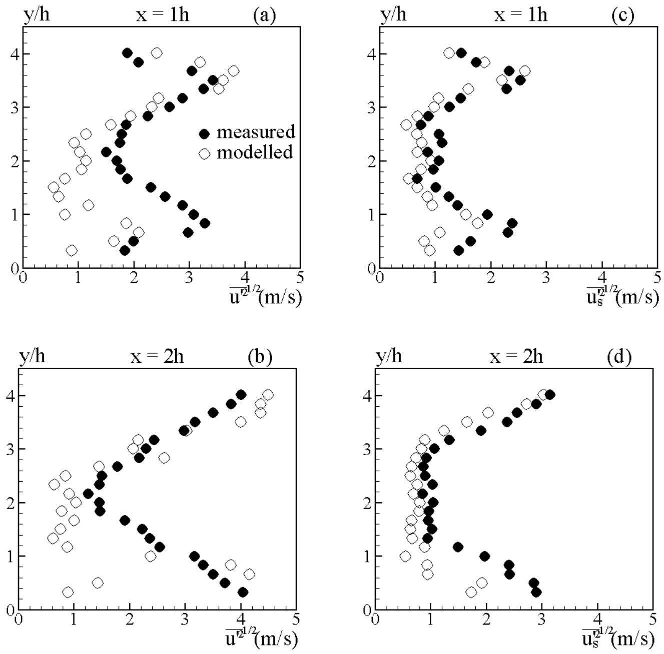

Figure 3: Profiles of the streamwise velocity fluctuations (total u', stochastic u'_s) measured and modelled at two streamwise abscissa $x = 1h, 2h$.

Acknowledgments: Phuc Danh NGUYEN has been granted a scholarship by the Région Poitou-Charentes.

References

[1] Besson, M., Bruel, P., Champion, J.L., and Deshaies, B. Experimental analysis of combusting flows developing over a plane symmetric expansion, Journal of Thermophysics and Heat Transfer, 14(1), 59-67, 2000.

[2] Bigot, P., Champion, M. and Garréton-Bruguières D. Modelling a turbulent reactive flow with variable equivalence ratio: application to a flame stabilized by symmetrical backward-facing steps. Combust. Sci. Tech. 158:299-303, 2000.

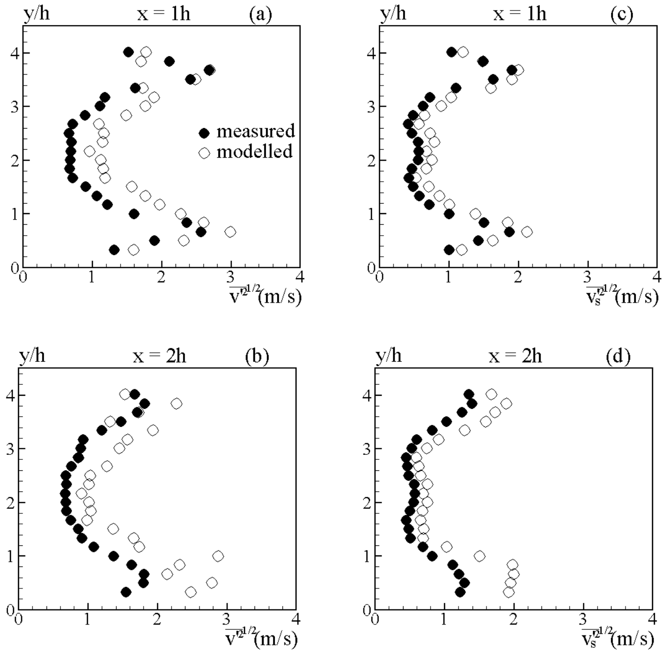

Figure 4: Profiles of the transverse velocity fluctuations (total v', stochastic v'_s) measured and modelled at two streamwise abscissa $x = 1h, 2h$.

[3] Colin, O., Ducros, F., Veynante, D. and Poinsot, T. A thickened flame model for large eddy simulations of a turbulent premixed combustion. Physics of Fluids, 12(7):1843-1863, 2000.

[4] Cook, A. and Riley, J. Subgrid scale modeling for turbulent reacting flows. Combustion and Flame, 112:593-606, 1998.

[5] Correa, S.M. Power generation and aeropropulsion gas turbines: from combustion science to combustion technology. Twenty-Seventh Symposium (International) on Combustion. 1793-1807, 1998.

[6] De Zilwa, S.R.N., Uhm, J.H. and Withelaw, J.H. Combustion oscillations close to the lean flammability limit. Combust. Sci. Tech. 160:231-258, 2000.

[7] Ha Minh, H., and Kourta, A. Semi-deterministic turbulence modelling for flows dominated by strong organized structures. 9^{th} Symposium On Turbulent Shear Flows, Paper 10-5, Kyoto, Japan, 1993.

[8] Hussain, A.K.M.F. and Reynolds, W.C. The mechanics of an organized wave in a turbulent shear flow. Part 1. J. Fluid Mech. 41(2), 241-258, 1970.

[9] Hussain, A.K.M.F. and Reynolds, W.C. The mechanics of an organized wave in a turbulent shear flow. Part 2: experimental results. J. Fluid Mech. 54(2), 241-261, 1972.

[10] Keller, J.O., Vaneveld, L., Korschelt, D., Hubbard, G.L., Ghoniem, A.F., Daily, J.W. and Oppenheim, A.K. Mechanism of instabilities in turbulent combustion leading to flashback. AIAA 20(2):254-262, 1982.

[11] Louedin, O. and Billet, G. Study of energy transfers in a transiant high speed flow with 2D large eddy simulation based on temporal filter, First AFOSR International Conference on DNS and LES, 1997, Ruston, USA

[12] Nguyen, P.D. and Bruel P. Turbulent reacting flow in a dump combustor: experimental determination of the influence of an inlet equivalence ratio difference on the contribution of the coherent and stochastic motions to the velocity field dynamics. AIAA paper 2003-0958, 41^{st} Aerospace Sciences Meeting and Exhibit, 2003, Reno, USA.