On the impact of large–scale coherent structures on scalar mixing in swirling jets

J. Fröhlich[†,*], M. García-Villalba[‡], W. Rodi[‡]

[†]Institute for Technical Chemistry and Polymer Chemistry,
University of Karlsruhe, 76128 Karlsruhe, Germany
[‡]Institute for Hydromechanics, University of Karlsruhe, 76128 Karlsruhe, Germany
[*]Email: froehlich@ict.uni-karlsruhe.de

ABSTRACT

The paper presents large eddy simulations of co-annular swirling jets into an open domain. In each of the jets a passive scalar is introduced and its transport is computed. If the exit of the pilot jet is retracted strong coherent flow structures are generated. Average and instantaneous fields are discussed. A conditional averaging technique is devised and applied to velocity and scalars. The results show the strong impact of the coherent structures on the mixing process.

INTRODUCTION AND CONFIGURATION

Swirling annular and co–annular jets are widely used in combustion devices such as gas turbine burners to stabilize the flame by means of a swirl–induced recirculation zone. Previous experimental and numerical studies have demonstrated, however, that such flows are often prone to fluid mechanical instabilities generating large–scale coherent vortical structures [9,2,11]. These have a substantial impact on the mixing of scalar quantities such as fuel and oxidizer or hot and cold gas. This process hence substantially impacts on the combustion, possibly triggering highly detrimental combustion instabilities [10].

The paper presents results of large eddy simulations (LES) of such turbulent flows in the constant–density case, i.e. without combustion, and focuses on the pure mixing process. The entire simulation model, consisting of numerical discretization scheme, choice of grid, subgrid–scale modelling and boundary conditions, has been validated in previous work [7,4]. In these

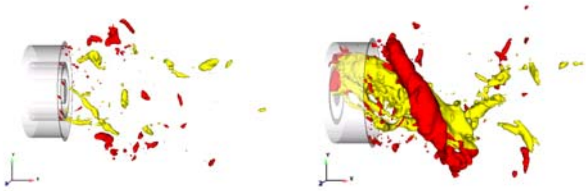

Fig. 1. Visualization of coherent vortex structures by means of iso-surfaces of instantaneous pressure perturbation. Left: no retraction, right: with retraction. Light colour: structures in the inner shear layer exhibiting a small angle with the $x-$axis, darker colour: structures in the outer shear layer, exhibiting a larger angel with the $x-$axis.

studies the generation of coherent structures (CS) was investigated together with their dependence on various aspects. The strongest structures were observed in simulations with the pilot jet retracted into a surrounding tube, so that this case is considered here. In the case without retraction which is taken for comparison, the CS are destroyed by a pilot jet [5]. Both cases are illustrated by snapshots in Fig.1. The present paper is devoted to the interaction between the

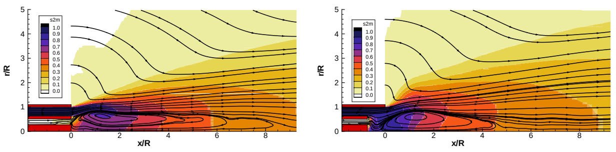

Fig. 2. Two-dimensional streamlines and mean concentration $\langle S_2 \rangle$ in the centerplane. Left: no retraction, right: with retraction.

large–scale coherent structures and the scalar mixing process.

The geometry, shown in Fig. 1, features two annular jets exiting into still ambient. The outer main jet accounts for 90% and the inner jet for 10% of the mass flux. The Reynolds number is $Re_b = 81000$, based on the bulk velocity of the main jet and its outer radius R. The total swirl number is $S = 0.93$, the swirl number of the pilot jet alone is 2 at $x/R = -0.73$. All conditions are identical for both cases, apart from the retraction of the inner jet to $x_{pilot} = -0.73R$ in the second case. Geometry and parameters correspond to an experiment conducted at the University of Karlsruhe [1]. To investigate the mixing processes, two scalars were introduced, S_1 in the inner and S_2 in the outer jet. An additional equation is solved for each of them using an eddy diffusion model with turbulent Schmidt number of 0.6 [3]. The origin of the $x-$coordinate in streamwise direction is located at the end of the outer tube (see Fig. 2).

RESULTS FOR AVERAGE AND INSTANTANEOUS FLOW

Fig. 2 shows two-dimensional streamlines in the centerplane ($x - r-$plane) for both cases. With retraction, the average recirculation zone does not reach upstream to the exit of the jets and is shorter and broader. Also, the spreading angle of the jet is larger than in the reference case. Details of the flow field are discussed in [8]. With retraction, the mean concentration of S_2 close to the axis is substantially larger and also increased at the outer edge, i.e. around $x/R \approx 1$, $r/R \approx 2$.

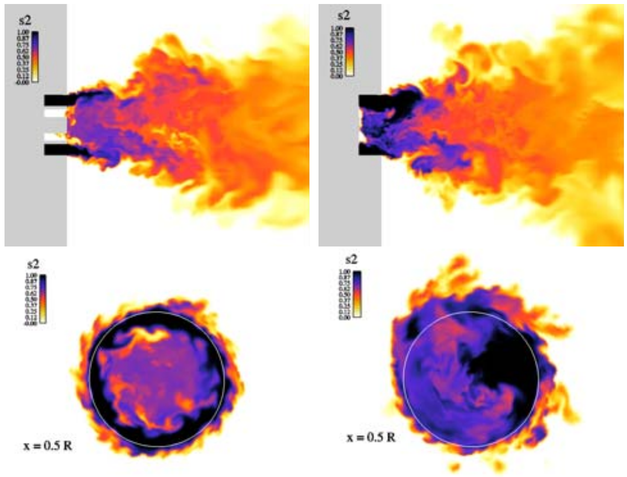

Fig. 3. Snapshots of instantaneous concentration. Top: centerplane, bottom: $x = 0.5R$. Left: no retraction, right: with retraction. The thin white circle is located at $r = R$.

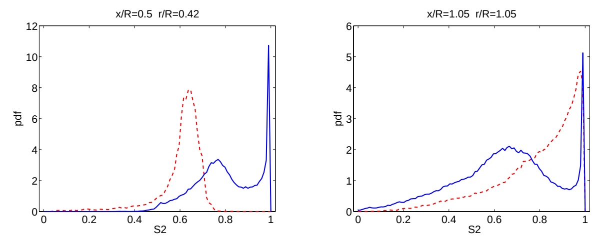

Fig. 4. PDF of scalar S_2 at two different positions. Left: $x/R = 0.5$, $r/R = 0.42$, right: $x/R = 1.05$, $r/R = 1.05$. - - - - no retraction, —— with retraction.

The coherent structures visualized in Fig. 1 substantially impact on the scalar mixing as shown in Fig. 3. Without retraction, the distribution is more symmetric in the centerplane and regular in circumferential direction in the lower plot. With retraction, large spots of high concentration appear in plots at $x/R = const.$ reflected by asymmetry in the centerplane plot. The spots are generated by the coherent structures visible in the right plot of Fig. 1. It has previously been found that they are correlated with a local excess in axial velocity [6] and this brings along undiluted scalar from the jet exit as shown by corresponding plots in planes $x = const.$ (not reproduced here).

This issue has been investigated also by means of the probability density function (PDF) of both scalars at various points. Fig. 4 shows two representative plots. The dashed line corresponds to the reference case and the continuous line to the case with retraction. The left plot was generated for a point in the inner structure. Without retraction, the concentration S_2 is fairly uniform as reflected by the narrow shape of the PDF. With retraction, the coherent structures are related to almost unmixed scalar during some instants while at other instants more diluted flow is present leading to a bimodal shape of the PDF. Similar observations are made at the outer border of the jet in the right plot of Fig. 4. The point of investigation is the same for both curves but the spreading angle of the jet is different in both cases. Hence, the jet is somewhat more remote from the point in the case without retraction. Further downstream, i.e. for $x > 2R$, the shape of the PDF from both cases is similar, but mean and variance still differ.

CONDITIONAL AVERAGING

The coherent structures observed in Fig. 1 rotate around the axis at a relatively constant rate. They are however not totally stable due to the high Reynolds number and can, for example, disintegrate into several structures or change their shape to a certain extent. It has been shown that the inner structures trigger the outer ones [5] so that the following conditional averaging strategy was devised. Due to the cylindrical symmetry of the geometry all angular positions are statistically equivalent. In over 180 stored flow fields the position of the strongest inner structure was detected and its center assigned zero angular coordinate. The resulting rotated fields of velocity and scalars were ensemble averaged and are identified by a tilde in the following. This procedure was applied for the case with retraction only since in the reference case the observed structures are very weak.

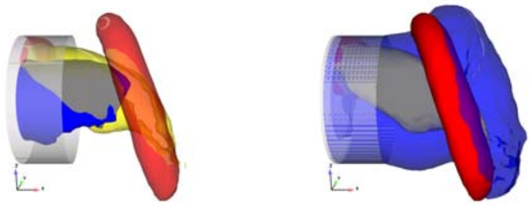

Fig. 5. Conditional averages of flow field and scalars for the retracted case. In both graphs an iso-surface of $\widetilde{p} - \langle p \rangle$ showing the inner and the outer vortex structure is depicted. The left plot also shows an iso-surface of $\widetilde{S_1}$ and the right plot an iso-surface of $\widetilde{S_2}$.

Fig. 5 provides the conditionally averaged vortex structures by means of pressure-perturbation iso-surfaces, similarly to Fig. 1. Included in the two plots are iso-surfaces of $\tilde{S}_1$ (left) and $\tilde{S}_2$ (right). They demonstrate how the coherent vortices influence the concentration of the scalar quantities. The maximum of $\tilde{S}_1$ is found in the interiour of the inner structure while $\tilde{S}_2$ has small values there. Due to its position of intrusion, S_1 essentially depends on the inner structures. The mixing of S_2 with the ambient fluid, on the other hand, is determined by the outer structures as evidenced by the second graph in Fig. 5. The distortion of the iso-surface of its conditionally averaged concentration by the outer structure is very well visible.

In a further step it was investigated to which extent the coherent structures contribute to the fluctuations of the scalar. This is illustrated in Fig. 6. The top graph shows the total fluctuations $\langle (S_2 - \langle S_2 \rangle)^2 \rangle$. Fluctuations generated by highly ordered regular structures are determined as $\langle (\widetilde{S_2} - \langle S_2 \rangle)^2 \rangle$. The bottom plot in Fig. 6 shows the ratio of these two quantities. In almost the entire region with $x < 0$, more than 40% of the fluctuations result from organized motion. The fluctuations themselves are not very strong, though, as visible in the right plot of the figure. Another maximum of the ratio is observed in the outer shear layer with 30-40% around $x/R = 0.2 \ldots 1$ and $r/R \approx 1.2$ due to the outer structures. Here, also the fluctuations attain large values.

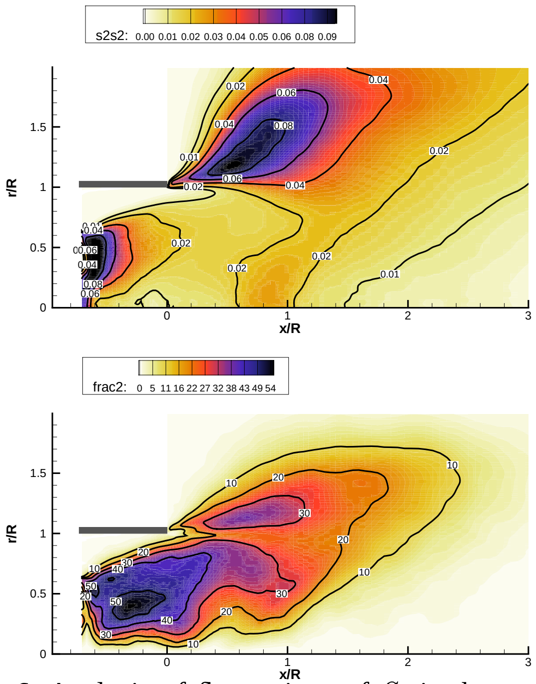

Fig. 6. Analysis of fluctuations of S_2 in the center-plane for the retracted case. Top: total fluctuations, bottom: percentage of fluctuations generated by conditionally averaged structures.

Conclusions

The analysis of instantaneous and statistical data demonstrates the strong impact of the coherent structures generated by retraction of the pilot jet on the mixing process. In a reacting flow this would alter considerably the entire combustion process. The technique devised for conditional averaging yields smooth and reliable data which characterize the regular part of large-scale features in the velocity and scalar field. Note that this procedure can also be applied to non-swirling flows of round jets since the same arguments given in the text hold for such configurations as well.

Acknowledgments: This work was supported by the German Research Foundation through SFB 606, www.sfb606.uni-karlsruhe.de. The references of the authors can be obtained there. The calculations were carried out on the HP XC6000 Cluster of the University of Karlsruhe Computer Centre.

BIBLIOGRAPHY

[1] C. Bender and H. Büchner. Noise emissions from a premixed swirl combustor. In *Proc. 12th International Congress on Sound and Vibration, Lisbon, Portugal*, 2005.

[2] C. M. Coats. Coherent structures in combustion. *Prog. Energy and Comb. Sci.*, 22:427–509, 1996.

[3] J. Fröhlich, J. Denev, and H. Bockhorn. Large eddy simulation of a jet in crossflow. In *Proc. 4th ECCOMAS Conference, Jyväskylä, Finland*, 2004.

[4] M. García-Villalba. *Large eddy simulation of turbulent swirling jets*. PhD thesis, Univ. Karlsruhe. In prep., 2006.

[5] M. García-Villalba and J. Fröhlich. On the sensitivity of a free annular swirling jet to the level of swirl and a pilot jet. In W. Rodi and M. Mulas, editors, *Engineering Turbulence Modelling and Experiments*, volume 6, pages 845–854. Elsevier, 2005.

[6] M. García-Villalba, J. Fröhlich, and W. Rodi. Identification and analysis of coherent structures in the near field of a turbulent unconfined annular swirling jet using large eddy simulation. under review for Physics of Fluids.

[7] M. García-Villalba, J. Fröhlich, and W. Rodi. On inflow boundary conditions for large eddy simulation of turbulent swirling jets. In *Proc. 21st Int. Congress of Theoretical and Applied Mechanics. Warsaw. Poland*, 2004.

[8] M. García-Villalba, J. Fröhlich, W. Rodi, O. Petsch, and H. Büchner. Large eddy simulation of flow instabilities in co–annular swirling jets. In E. Lamballais, B.J. Geurts, O. Métais, and R. Friedrich, editors, *Direct and Large-Eddy Simulation VI*. Kluwer Academic, 2006.

[9] A.K. Gupta, D.G. Lilley, and N. Syred. *Swirl Flows*. Abacus Press, 1984.

[10] C. Külsheimer and H. Büchner. Combustion dynamics of turbulent swirling flames. *Combustion and Flame*, 131:70–84, 2002.

[11] O. Lucca-Negro and T. O'Doherty. Vortex breakdown: a review. *Prog. Energy and Comb. Sci.*, 27:431–481, 2001.