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COMPUTATIONAL STUDIES OF TURBULENT CROSS-FLOW JET USING LES

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Rezumat. *Interacţiunea dintre un jet turbulent şi un fluid care se mişcă liber într-o conductă este studiată computaţional folosind metoda Large-Eddy Simulation (LES). Efectul raportului vitezelor asupra amestecului turbulent este subiectul de investigaţie în acest studiu. Metoda LES este potrivită pentru calculul asistat de calculator al fluidelor turbulente şi poate evidenţia toate structurile fluidului turbulent şi în particular a jetului care împinge fluidul liber. Analiza a arătat că raportul vitezelor este unul dintre factorii care influenţează şi controlează amestecul turbulent. Interacţiunea dintre jet şi fluidul liber generează vârtejuri de formă inelară de diferite dimensiuni. Drept consecinţă, dimensiunea vârtejurilor inelare creşte cu creşterea raportului vitezelor celor două fluide. Concluzia acestui studiu este că pentru un amestec turbulent eficient este necesar un raport mare al celor două viteze.*

Abstract. *The interaction between a turbulent jet and free stream flow is computationally studied using the large-eddy simulation (LES) approach. The effect of the blowing-ratio on the turbulent mixing is also subject of investigation in this research. The study revealed that the LES approach is suitable for the computation of highly-turbulent flows and able to capture all the flow structures of the jet in cross-flow. The analysis showed that the blowing-ratio is one of the parameters that control the turbulent mixing. Thus, the increase of the blowing-ratio causes a deeper penetration of the jet into the free stream flow and hence, an increased turbulent mixing. The interaction between the jet and free stream flow causes a sequence of vortex rings of different length-scales. Thus, larger vortex rings were observed for higher blowing –ratios. A concluding remarks of the present research is that high-turbulent mixing requires higher blowing-ratios.*

Keywords: cross-flow jet, blowing-ratio, vortex ring, large-eddy simulation

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1. Introduction

The cross-flow jet has been used in many engineering applications such as cooling jet in turbo machinery, cooling of electronic components, turbulent mixing. Nowadays, the cavity flow is used for flame stabilization in supersonic combustion propulsion systems such as scramjets [1]. The cross-flow impinging jet is a canonical problem in fluid dynamics. However, in spite of the simple geometry, the cross-flow jet exhibits a highly-complex fluid dynamics including horseshoe vortex pair, shear layer, counter-rotating vortices, wake vortices and hanging vortices [2-19]. The interaction between the cross-flow jet and free-stream flow impacts the turbulent mixing and flow characteristics [6-8, 12]. The blowing-ratio (R) is the parameter that define the fluid dynamics of the jet in cross-flow [6]. The blowing ratio is defined as the ratio between the speed of the jet and free-stream flow. The blowing ratio impacts the boundary-layer flow and flow separation. Previous studies concerned the jet in cross-flow and showed that the blowing-ratio governs the turbulent mixing. A schematic of jet in cross-flow, for supersonic scramjet propulsion is shown in Figure 1.

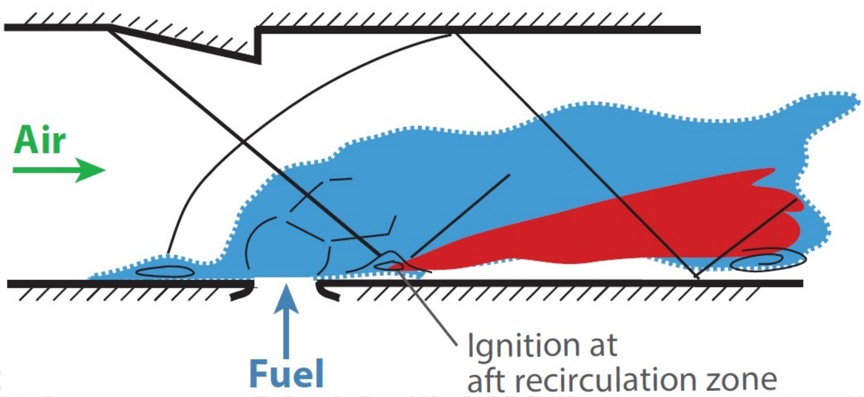

Figure 1. Fuel injection scheme for scramjet combustion [1]

Figure 2 presents the schematic of the cross-flow jet. The computation of the jet in cross-flow poses significant challenges due to the complex fluid dynamics such as horseshoe vortices, jet shear-layer and wake vortices as shown in Figure 2. Therefore, advanced high-fidelity computational method must be sought for the computation of these flows. Previous studies showed that capturing the shear-layer and counter-rotating vortices represents a computational challenge.

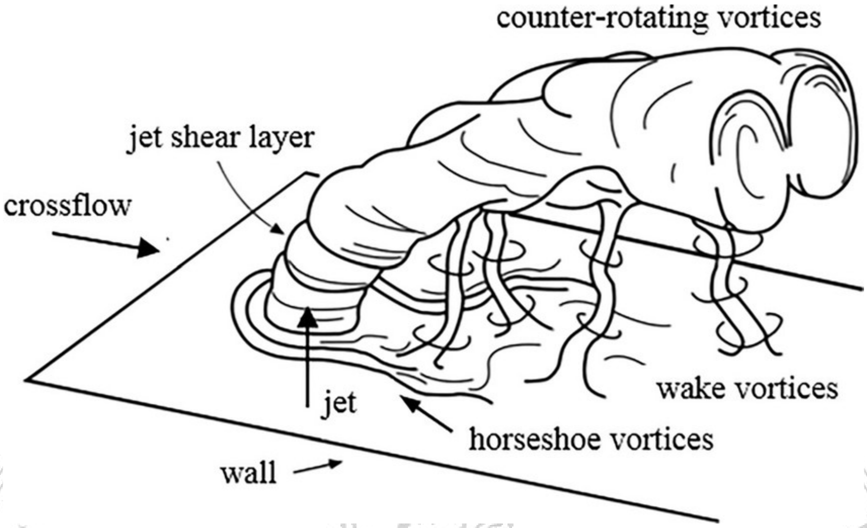

Figure 2. Jet in cross-flow [5]

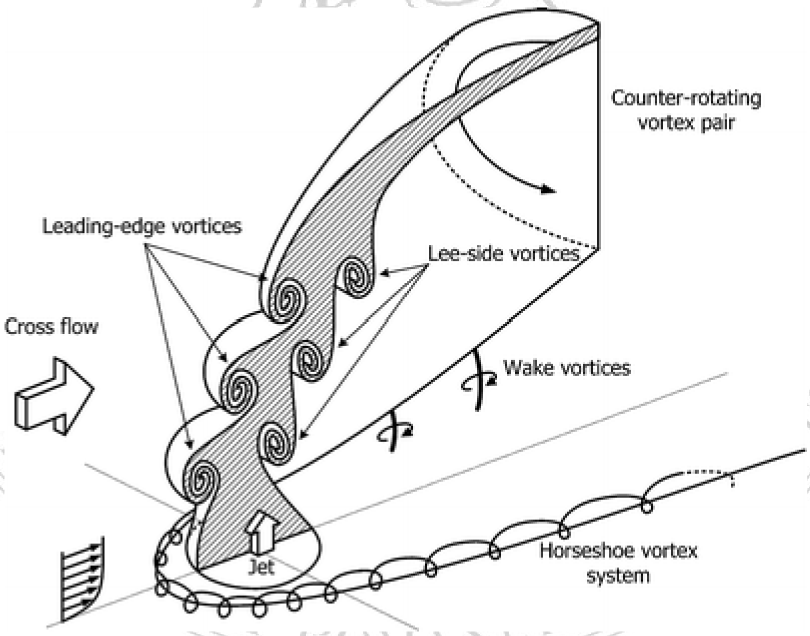

Figure 3. Jet in cross-flow [6]

Figure 3 presents a schematic of the flow structures inside the impinging jet. The schematic reveals the presence of the leading-edge vortices and horseshoe vortices as well the counter-rotating pair of vortices. It is the goal of the developed model and study to compute and capture these complex flow structures.

2. Background

In the past computational methods were used for the computation of cross-flow impinging jets [2-17]. Thus, computational methods using the Reynolds-averaged Navier-Stokes (RANS) equations were used for the computation of cross-flow impinging jets. However, the cross flow impinging jet is transient phenomenon and thus, RANS methods are not suitable for this kind of computations. Therefore, for the computation of jet in cross-flow, we need to employ numerical methods that can compute the transient nature of the turbulent flow. Numerical methods such as direct numerical simulations (DNS) provide the most accurate solution. However, the DNS approach poses significant limitations due to the fact that the required grid size of the computational domain is proportional to the Reynolds number $\mathrm{Re}^{9/4}$ and thus, it is limited only to low Reynolds number flows. On the other hand, the large-eddy simulation (LES) approach overcomes these issues since it is independent of Reynolds number. Previous studies showed that LES is a suitable approach for the computation of large Reynolds number flows.

3. Modeling

The governing equations of large-eddy simulations (LES) are the filtered Navier-Stokes equations, given by the equations (1) and (2)

$$\frac{\partial \overline{u}_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial \overline{u_i}}{\partial t} + \frac{\partial}{\partial x_j}\left(\overline{u}_i \overline{u}_j\right) = -\frac{\partial \overline{p}}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} + \frac{1}{R_e}\frac{\partial^2 \overline{u}_i}{\partial x_j \partial_j} \tag{2}$$

where

$$\tau_{ij} = \overline{u_i u_j} - \overline{u_i}\,\overline{u_j} \tag{3}$$

Generally

$$\overline{u_i u_j} \neq \overline{u_i}\,\overline{u_j} \tag{4}$$

and

$$\tau_{ij} - \frac{1}{3}\tau_{kk}\delta_{ij} = 2\nu \overline{S_{ij}} \tag{5}$$

where $\overline{S_{ij}}$ is the strain rate given by the equation 6

$$\overline{S}_{ij} = \frac{1}{2}\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right) \tag{6}$$

4. Results and discussion

Figure 1 presents the 3D cross-section of the jet in cross-flow for two different blowing ratios. The analysis of the fluid flow reveals that LES can capture very well the flow structures. The analysis of the fluid flow shows that the blowing ratio causes an ejection of the boundary-layer and a lift-off of the jet, which increases with the blowing ratio. The interaction between the jet and free-stream flow causes an enhanced mixing and hence, a highly turbulent flow. The turbulent flow is dominated by the turbulent eddies of different length-scales, and this is best illustrated in Figure 2. Therefore, Figure 2 presents a detailed view of the jet in the cross-flow, for a blowing-ratio BR=1. From Figure 2, it can be seen the highly turbulent interaction between the jet and free-stream flow. Downstream the jet, due to the high-mixing, the turbulent flow dissipates and thus, small-scale vortices are generated. The analysis also reveals that the LES approach capture very well the impinging jet and shear-layer of the jet. The interaction between the jet and free-stream velocity, due to the pressure gradients at the interface between the two, generate a wrinkle of the jet and thus, vortex breakdown.

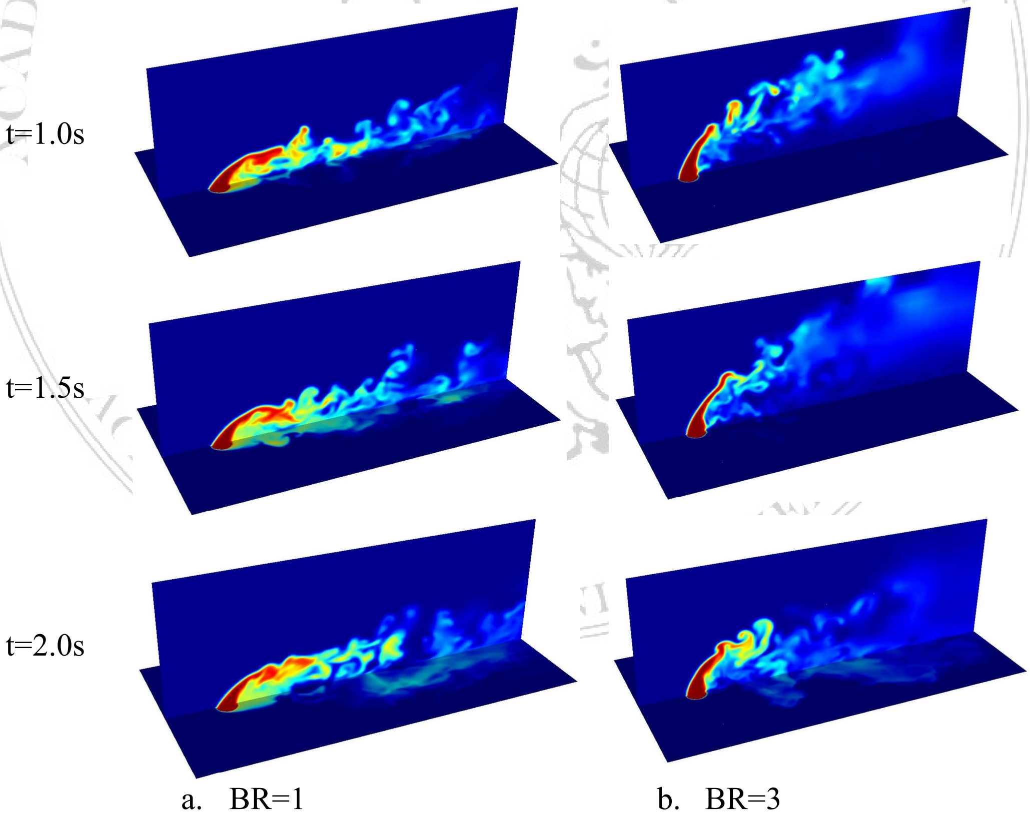

Figure 4. Jet in cross-flow; effect of the blowing-ratio

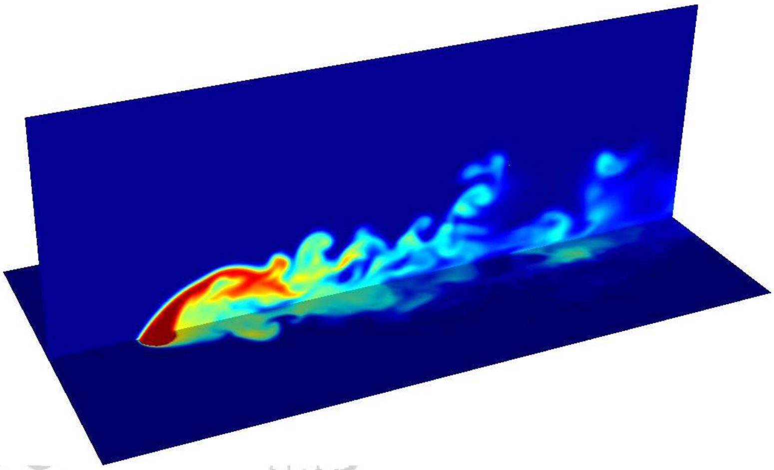

Figure 5. Jet in cross-flow; BR=1

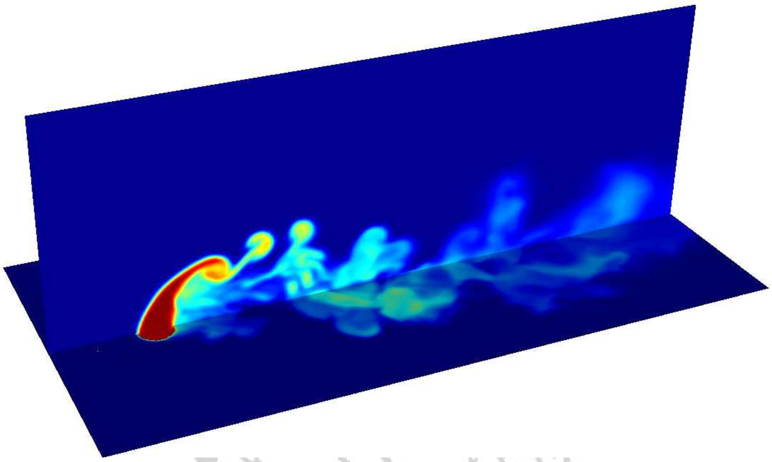

Figure 6. Jet in cross-flow; BR=2

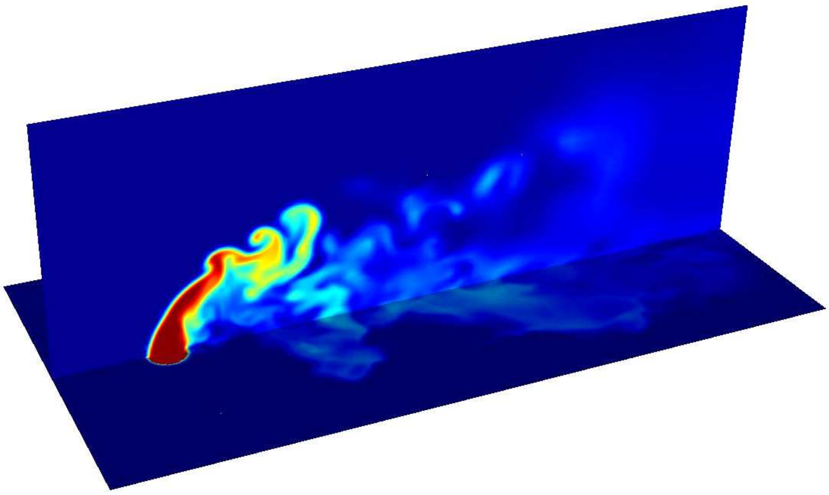

Figure 7. Jet in cross-flow; BR=3

The vortex breakdown is even better illustrated in the case of blowing-ratios BR=2 and BR=3. With the increase of the blowing-ratio, the jet penetrates higher into the free-stream flow and the interaction between the two generates higher turbulent mixing.

Figure 5 presents the fluid dynamics results of the jet in cross-flow, for two different blowing ratios at a cross-section in the middle of the orifice. The analysis of the fluid dynamics reveals the turbulent mixing between the jet and free-stream flow. The analysis also reveals that the turbulent mixing increases with the blowing-ratio. For a blowing-ratio BR=1, the cross-section of the jet presents a circular shape as shown in Figure 5. As the blowing-ratio increase the turbulent mixing increase and thus, the jet flow presents an irregular shape due to this mixing. Also, with the increase of the blowing-ratio, the jet detaches more from the wall.

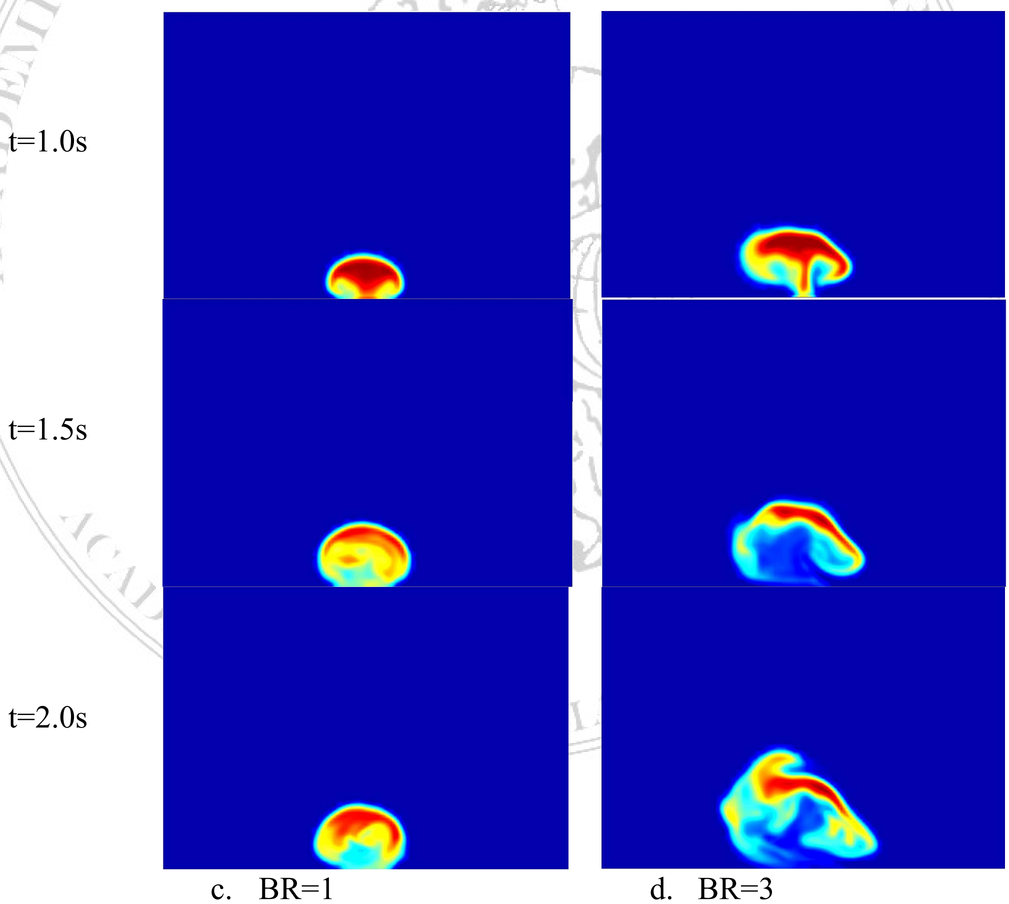

Figure 8. Jet in cross-flow; effect of the blowing-ratio

Figure 6 presents the 3D flow structures of the turbulent jet in cross-flow for two different blowing-ratios namely, BR=1 and BR=3. The analysis reveals an increase of turbulent mixing with the increase of the blowing-ratio. Thus, for a blowing-ratio, BR=3, the jet impinges higher into the free-stream flow and a higher mixing is observed. The analysis also reveals that the LES approach can capture very well the wake vortices as shown in Figure 6b, at instant t=2.0s. Also a higher blowing ratio can sustain longer the turbulent mixing.

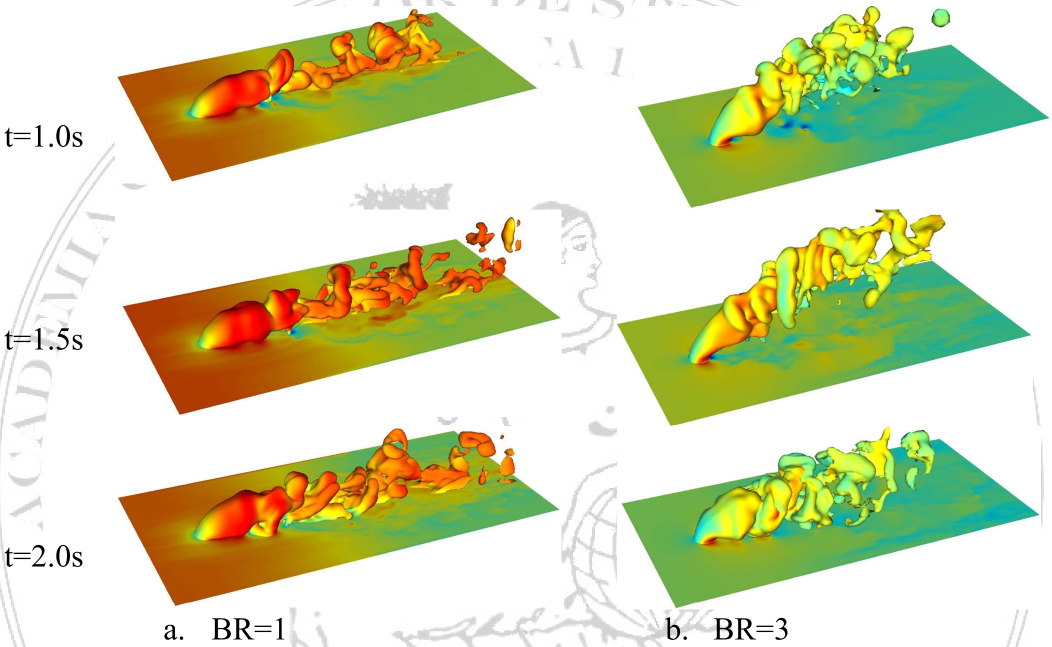

Figure 9. Jet in cross-flow; effect of the blowing-ratio

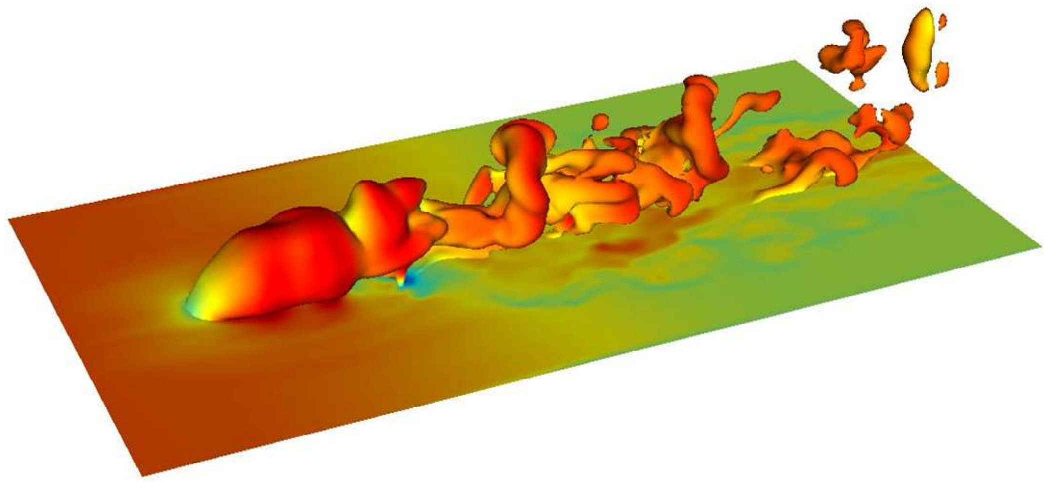

Figure 10. Jet in cross-flow; BR=1

A better understanding of the fluid dynamics of jet in cross-flow can be obtained from the analysis of results in Figures 8 and 9, for blowing-ratios BR=2 and BR=3. Thus, for a blowing-ratio the jet penetrates deeper into the free-stream flow and thus, a detachment from the boundary-layer. For higher blowing-ratios, the jet shear layer exhibits a smaller hydraulic diameter. However, the O-ring vortices are more distinguishable for higher blowing-ratios.

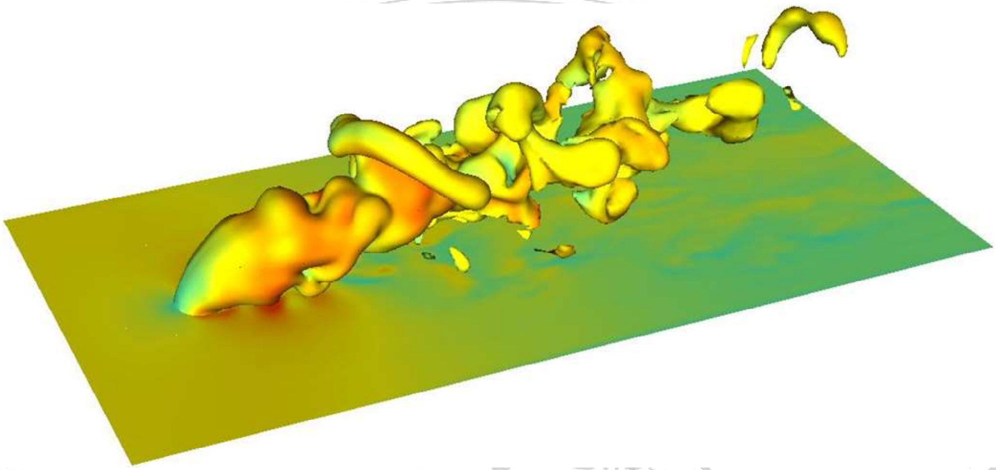

Figure 11. Jet in cross-flow; BR=2

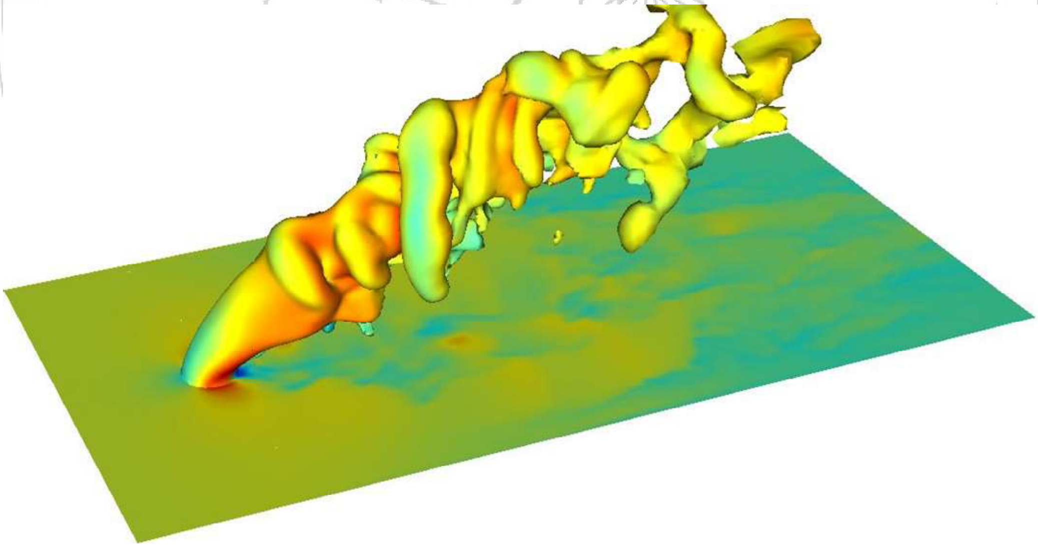

Figure 12. Jet in cross-flow; BR=3

The analysis of the fluid dynamics of jet in cross-flow, Figures 8 and 9, reveals the impact of the jet and its interaction with the free stream on the boundary-layer. Therefore, a significant turbulent mixing is observed in the boundary-layer region, which dissipates farther from the injection region of jet.

Conclusions

In the present research an efficient computational approach, large-eddy simulation (LES), is developed for the computations of large Reynolds number flows. The developed model is used for the numerical computations of the cross-flow impinging jet. The study concerned the effect of the blowing-ratio on the turbulent mixing. The analysis of the turbulent jet in cross-flow reveals that the increase of the blowing-ratio causes an increase in the turbulent mixing through a larger interaction between the impinging jet and free stream flow. The impinging jet also causes a detachment of the boundary-layer. The interaction between the jet and cross-flow results into a breakdown of the jet and thus, it causes a wrinkle of the shear-layer. Thus, for a highly-turbulent mixing, higher blowing-ratios are desired.

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