LES AND PLIF INVESTIGATION OF COHERENT STRUCTURES IN A TURBULENT PLANE WALL JET

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ABSTRACT

Coherent structures inside a turbulent wall jet were visually investigated using smoke flow visualization and Large Eddy Simulation. Distinct outer-backward hairpin structures and inner-forward hairpin structures were observed. The backward structures appeared in the outer jet region, with the characteristic angle in the range of 50 to 60. Inside the boundary layer, forward structures were captured with a characteristic angle in the range of 12 to 15 degrees. A strong upwash is created between the legs of the hairpins in the outer jet region, raising the high-momentum flow below the hairpins upward. Similarly upwash is created between the legs of boundary layer hairpins also. The kinking of the linear vortex filaments found in the outer jet region occurs delayed, when compared the filaments found in the boundary layer region. The height and span of the backward structures became larger in the direction of the flow.

INTRODUCTION

Turbulence is one of the prime unsolved problems of fluid dynamics. One of many such turbulent flows is the turbulent wall jet flow, which is formed when a jet of fluid faces a solid wall as the side boundary, and incorporates complex flow mechanisms, like free shear flow and wall bounded shear flow, coexisting. The integrated presence of both jet flow and boundary flow could result in a pattern of flow frame work and mechanics, which are significantly different from those found individually in boundary layer flow or free jet flow. This work concentrates on the existence, nature and the trend of occurrence of the coherent structures (turbulent flow structures) within a plane turbulent wall jet. The understanding of the structures of these flow structures will pave way for identifying the mechanism of turbulence involved and also facilitate in the development of an analytical model of wall jet turbulence. The wall jet is a flow which is both pragmatically essential and integrally intriguing. The most frequent engineering applications calling attention to wall jets are detected in the cooling, heating, demisting and drying of surfaces. An expressly relevant precedent is the injection of wall jets parallel to the inner surface of a combustion chamber, devised to protect it from the hot combustion products. A wall jet is also developed as a consequence of jet transgression on a surface. This occurs, for example, in the context of heating or annealing of metal and glass plates during manufacture. In all these applications, the turbulent structure of the wall jet, eminently that close to the surface is a crucial concern to the jet's thermal performance.

HISTORY

The presence of coherent structures inside zero-pressure gradient turbulent boundary layer was visually studied by Head & Bandyopadhyay (1979) and detailed results on the existence of hairpin shaped vortex pairs were presented. These results directed for further work in this direction and many new hypotheses evolved with qualitative findings that substantiated the existence of hairpin structures in turbulent boundary flow and are responsible for many turbulent phenomena to occur. Some vital works performed on the properties of the hairpin structures followed the work of Head & Bandyopadhyay and were majorly carried out by A. E. Perry, between 1980 and 1998. A. E. Perry's works provided a strong support for attached- eddy hypothesis, a hypothesis which enforces the importance of the existence of these flow structures and their contribution to the turbulent characteristics of the flow. Following the observation of forward lent hairpin structures in turbulent boundary layers, similar hairpin structure were observed in free jet and were noted to be lent backward. Subsequently the presence of such hairpin structures in the outer jet region (free shear flow region) of wall jet were brought to light by the LES study carried out by Takafumi Nishino, Seonghyeon Hahn and KarimShariff (2010). Later the results of an experimental study by Dhamotharan V (2011) stated that the experiment (two point correlation and flow visualization) as a crucial testimony for the subsistence of hairpin structures in a plane wall jet.(However, a clear description about the structure's properties, with reference to their extension inside the boundary layer along the wall, was not clearly declared. While Takafumi Nishino, Seonghyeon Hahn and KarimShariff (2010) presented the data to support the presence of hairpin structures in the outer jet region of wall jet, some key questions like, What kind of vertical structures exist in the inner shear layer (boundary layer) of the wall jet, Whether there are any forward tilted hairpin structure like those observed in flat- plate boundary layer flows, were also posed. This work was driven with answering these questions as the objective.

EXPERIMENTAL SETUP AND FLOW VISUALIZATION

A nozzle with exit dimensions 40 cm x 1 cm was connected to a blower exit, to generate a plane turbulent jet. The exit velocity of the jet was set at 5 m/s resulting in an exit Reynolds number of 4000. The exit span of the nozzle was much larger than its height and hence the jet can be assumed to be two dimensional. Flow visualization was done using Plane Laser Induced Florescence (PLIF) with 30 mW green laser and glycerine smoke. Initially the smoke was injected along with the jet-stream. The laser sheet was placed normal to both the wall and flow span as represented in Figure 1.

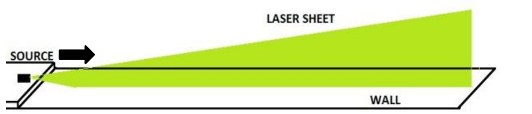
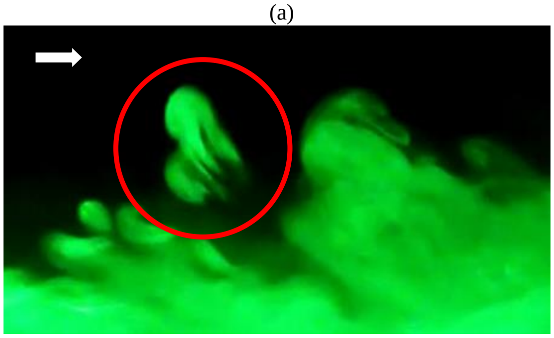


Figure 1. Initial laser orientation.

From the flow visualization images in Figure 2, an apparent view of backward tilted Hairpin structures were noted in the outer jet region. However, the subsequent layers were cloaked, revealing no clear sight of the near wall structures. Few images show some hairpin structure with detached roots (Figure 2(b)), subsequently giving rise to the need to reconsider the implications given by Attached Eddy Hypothesis (ATH).

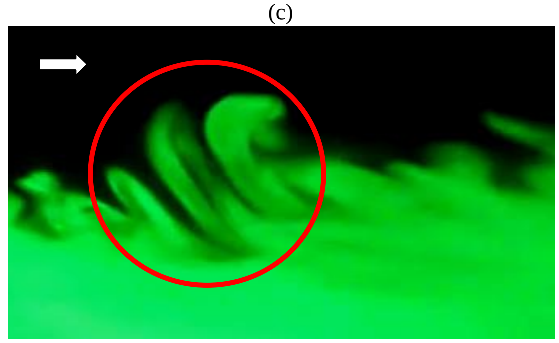
Then, predictably, to visualize the shape of the turbulent structure in the near wall region, the location of the smoke injection was altered and directed tangential to the wall, through a slit, which was proximal to the jet-source on the wall.

(a)



(b)

(c)



(d)

Figure 2. Outer- jet backward tilted hairpin structures (marked in red circle).

Subsequently, there emerged an eddy envelope at a certain distance from the jet exit, which was observed to have a shape as found in Figure 3, with its forward slant closer to the wall, subtending around 12 degrees with the downstream direction and backward slant away from the wall at about 55 degrees with the upstream direction.

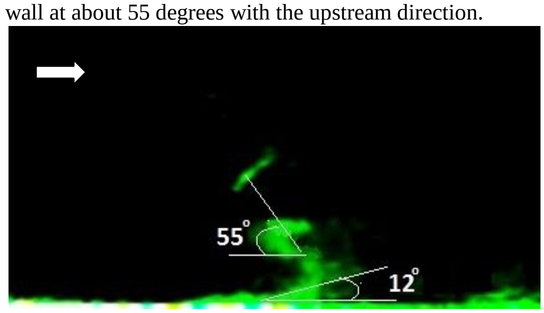


Figure 3. Eddy envelope showing inclination angles.

Having found the angles, the laser sheet was consequently placed with the inclination of 12 degrees, followed by 55 degrees as depicted in Figure 4, with an anticipation of witnessing the hairpin loop shape of the eddy structure.

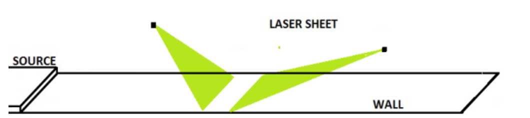
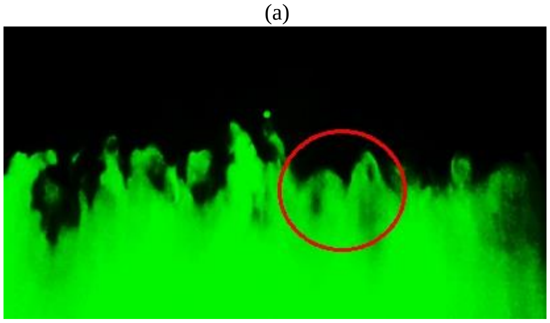


Figure 4. Inclined laser orientation.

The images from this configuration revealed distinct Hairpin structures in the boundary layer and the jet regions. The images in Figure 5(taken with laser sheet incidence of 55 degrees and smoke injected along with the jet-stream) substantiate hairpin like eddies in the outer jet region. It can also be noted that the roots of these hairpins are submerged into the jet-stream.

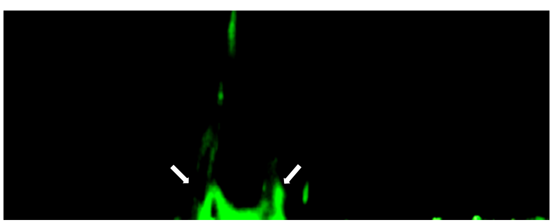
(a)



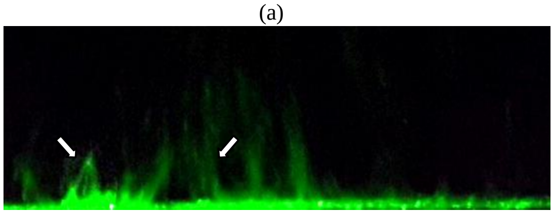
(b)

Figure 5. Outer jet hairpin structures with 55 degrees laser incidence (marked in red circle).

Images (taken with laser incidence of 12 degrees and smoke through near wall injection) in Figure 6 illustrate scarcely distributed near wall hairpin structures.



(a)



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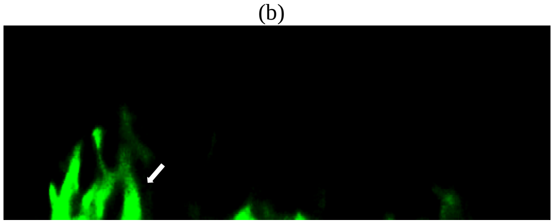

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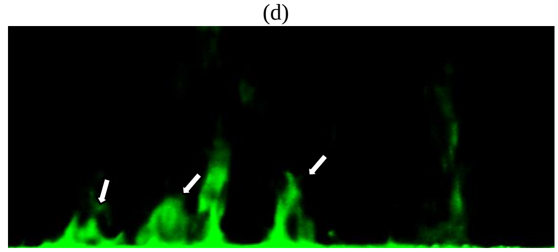
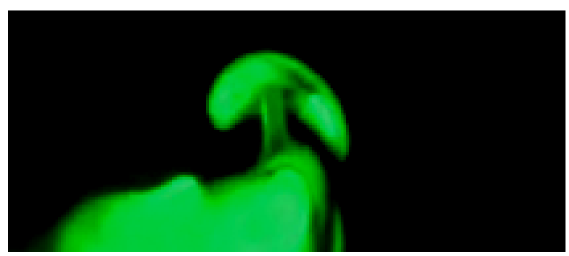


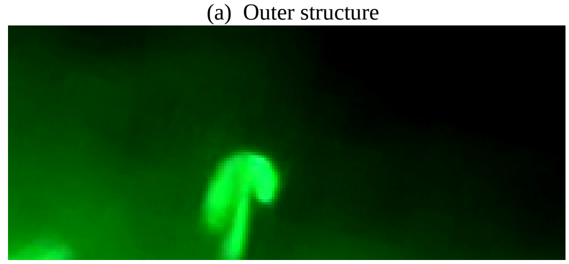
(e)

Figure 6. Boundary layer hairpin structures with 12 degrees laser incidence (pointed with white arrow).

It is observed (in Figure 5 and 6) that the outer hairpins are dominant and -have their roots submerged in the jet-stream. However, the inner (near wall) hairpins are small and rooted to the wall. Further, to scrutinize the cross sections of the hairpin structures, the laser sheets were placed with a supplementary angle of inclination for the previously mentioned angles (55 and 12 degrees). From these images, the cross section of the hairpin structures appeared similar to cross section of a mushroom cloud. Additionally, to measure the height and width of both the backward and forward structures, a scale was placed parallel to the laser sheet plane. To substantiate the observations from flow visualizations, Large Eddy Simulation was performed.



(a) Outer structure



(b) Inner structure

Figure 7. Images from complimentary angle inclined laser orientation. (showing the cross section of the structures).

LARGE EDDY SIMULATION

LES of the turbulent wall jet was implemented using commercial CFD software FLUENT 14. The domain's inlet height and span are same as in the experiment. The height and length of the domain are 60 cm and 90 cm respectively. The computational domain was meshed using 4 million brick elements. The simulation was carried out with a jet velocity of 20m/s using Smagorinsky-Lilly model. Q-criterion (the second invariant of velocity gradient tensor), at a level of 0.04, colored by instantaneous velocity magnitude, was used for the visualization of the turbulent structures. In the outer jet region, backward facing hairpin structures appeared as shown in Figure 8 and were identified to subtend to an inclination similar to the angle observed in the flow visualization. It appeared as if the roots of these hairpins were detached.

Even though the outer structures were clearly demarcated as shown in Figure 9, the inner layers were imperceptible. Hence, Q-criterion visualization was confined to the near wall region, where stratified and distorted forward lent hairpin structures appeared proximal to the wall as shown in Figure 10.

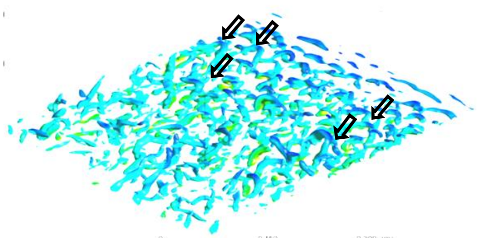


Figure 8. Three dimensional view of the LES result clearly showing the backward hairpins (marked with black arrows).

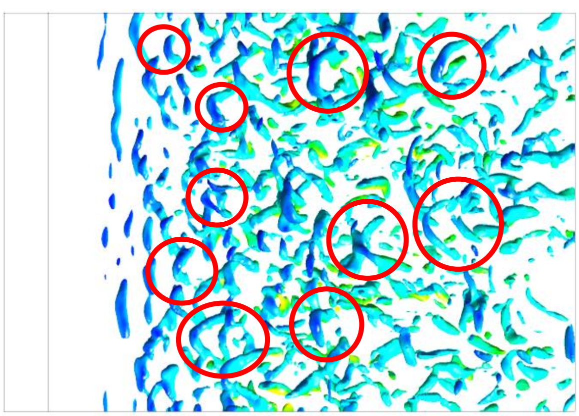


Figure 9. Backward hairpin structures (marked with red circles).

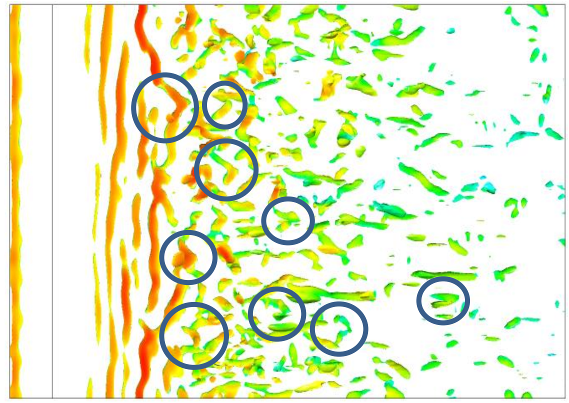
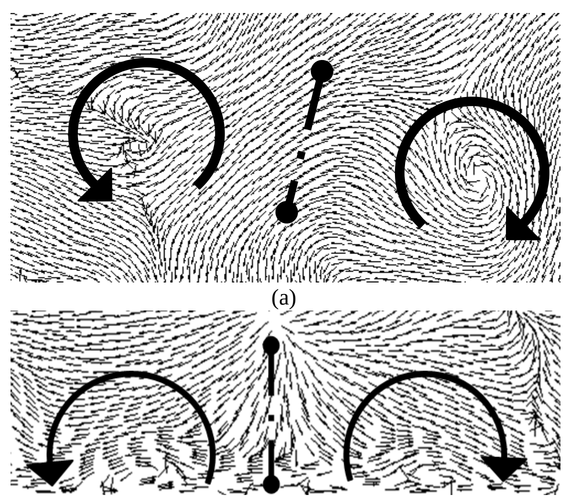


Figure 10. Forward Hairpin structures (marked with blue circles).

Local induced velocity vector along the cross sectional plane of the hairpin structures shown in Figure 11, shows the presence of strong upwash between the legs of both the backward structures (Figure 10(a)) and forward structures(Figure 10(b)), which has resulted in the high momentum flow being pulled upward. The height and width of the backward hairpins were observed to become larger when measured along the flow direction.



(a)

(b)

Figure 11. Tangential induced velocity vectors along a plane through the cross section of the hairpin structures (marked with blue circles).

It can also be noted that, the kinking of the linear vortex filament in the outer jet region happens delayed, when compared to the filaments in the boundary layer region.

NOTABLE DISCUSSIONS

(i). Some pictures from flow visualizations taken with low expose time reveal the direction of curl due the local circulation for both outer and inner structure concurring with the former identification of the hairpin structures in the outer and inner shear layers as illustrated in Figure 12.

(ii). Both flow visualization and LES results displays similar structure shape and size for both outer and inner hairpin structure as shown in Figure 13. The outer structures are mostly found to have a ***U***- shaped hairpin vortex filament, while the inner structures are mostly found to possess a ***V***-shaped hairpin vortex filament.

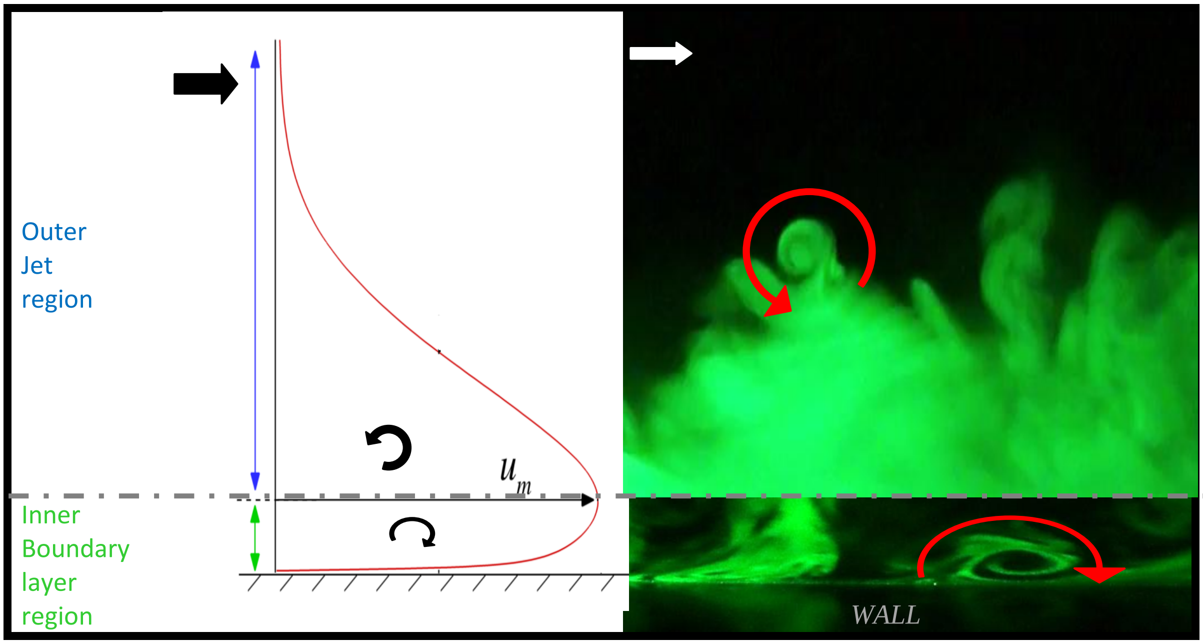
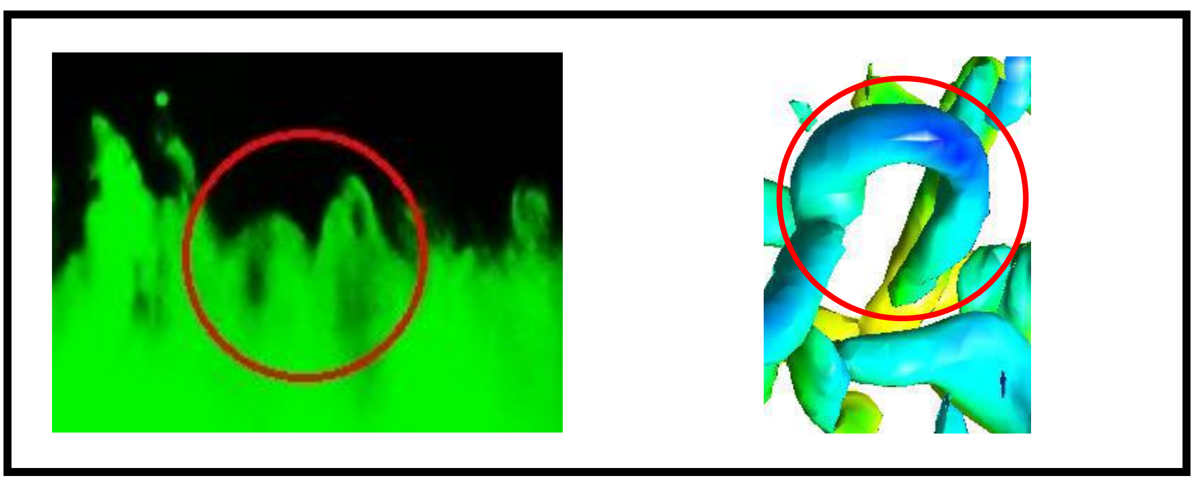
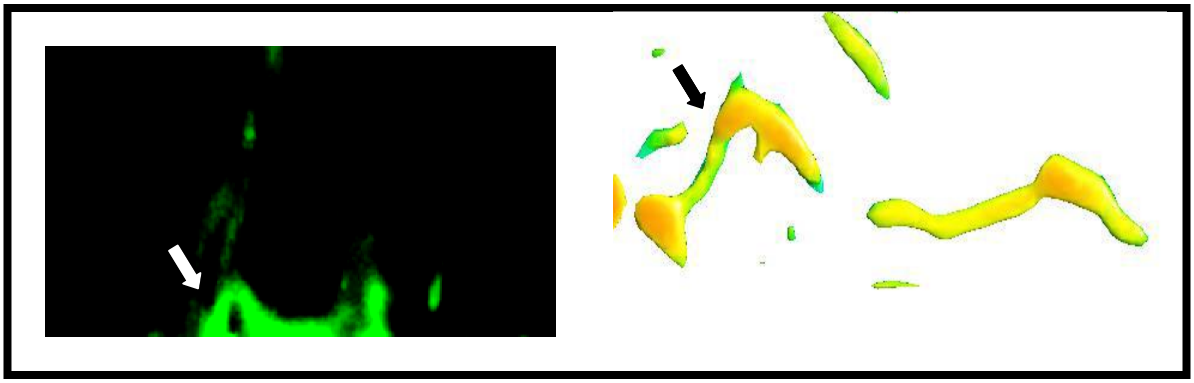


Figure 12. Curl of flow in the outer and inner shear regions.

(iii). The cross section of the hairpin structures observed in flow visualization and LES results are consistent and distinctly show the upwash between therir legs (Figure 14).

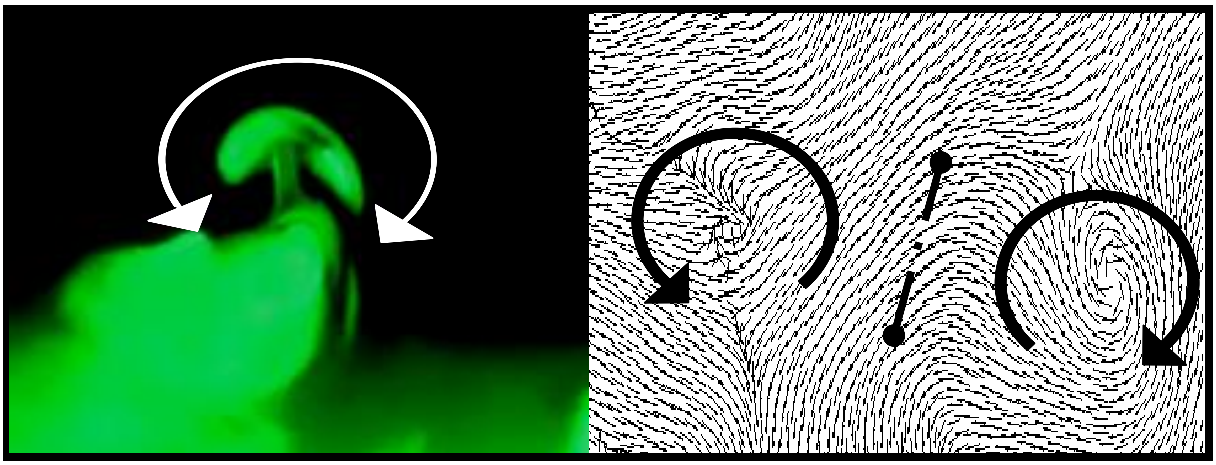


(a)

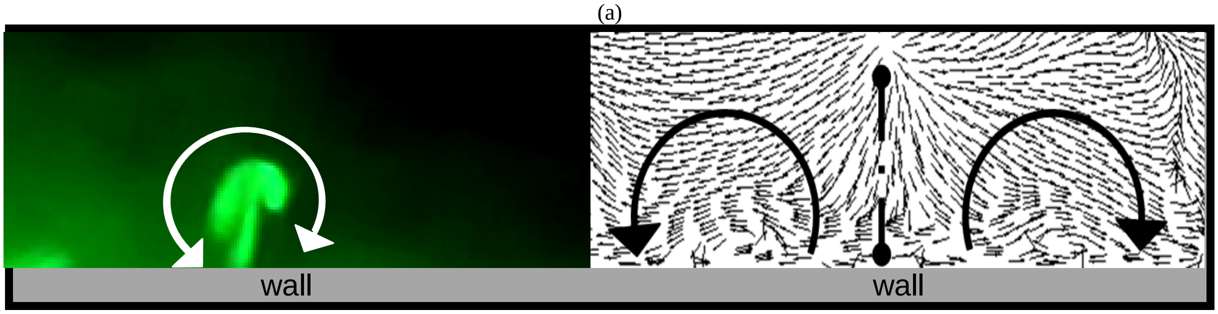


(b)

Figure 13. Flow visualization (left) and LES (right) results compared; (a) outer structure (enclosed with circles), (b) inner structures (indicated with arrows).



(a)



(b)

Figure 14. Cross section of hairpin structures; (a) outer structure, (b) inner structures.

CONCLUSION

- The experiments and LES reveal the presence of coherent backward tilted structures in the outer jet regime and forward tilted structures in the boundary layer region of the wall jet. In addition they emphasize the fact that the forward and the backward structures exist distinctly.

- The angle subtended by the outer structure with the wall is about 50 to 60 degrees with roots submerged in the jet-stream and could be detached.

- The inner hairpin structures are scarce and the angle subtended by it with the wall is about 12 to 15 degrees, with its root attached to the wall.

- There is a strong upwash created, between the legs of both backward and forward hairpins, pulling the high momentum flow below it upwards.

- As the presence of detached hairpins in the jet region is highly probable, it directs the requirement of improved Attached Eddy Hypothesis (AEH) for better insight into their properties.

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