

# The detailed structure and behavior of discrete cooling jets in a turbine

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**ABSTRACT:** Three-dimensional jets are an efficient way of cooling the walls of modern high-pressure turbines. Introduced in the external flow that develops around the turbine blade, they are associated with a set of vortex structures. The purpose of this paper is to underline the respective origin and importance of these structures, with reference to both experimental and numerical results. Steady and unsteady vortices will be analyzed. Recommendations for numerical simulations will be proposed from these observations.

We have emphasized the complexity of the flow structures of a 3D jet introduced in a cross flow, using results from a Navier-Stokes simulation. We have observed that the familiar kidney vortices  $\Omega_1$  are strongly influenced by the flow behavior in the orifice or very close to it. A 3D separation occurs on the walls of the injection tube under the influence of the static pressure field; this pressure field is itself induced by the kidney vortices. The fluid particles are then collected in two groups separated by their localization with respect to this separation line; the two groups have very different trajectories.

The boundary layer of the cross flow generates two vortices in the upstream region of the jet. They belong to a complex set of flow singularities that depends on the injection ratio and the neighboring jets. They may collect both a part of the jet material. The trajectory of the lip vortex follows closely the jet boundary; thereby it is the most upstream manifestation of the jet. The horseshoe vortex intercepts the jet boundary in the region of the minimum of static pressure. This is also the localization of tornados, which eject the wall material in the jet wake. The downstream wake is dominated close to the wall by a vortex  $\Omega_5$  that mimics the horseshoe vortex. It is induced in the crossflow boundary layer by the secondary flow imposed by the kidney vortices. One branch is reintroduced in the jet lee-side, while the second branch develops close to the wall in the downstream direction.

The unsteady behavior is an important characteristic of the 3D jet. While the upstream boundary is dominated by a set of Kelvin-Helmoltz-like vortices, the jet wake transports small tornadoes that seem to connect the  $\Omega_5$  vortex to the jet wake.

All these flow characteristics request a lot of caution in the numerical simulation of the 3D jets. The mesh must be fine enough in order to capture all the local flow structures. In other case, the solution will still verify the topological law. This means that a completely different solution could be obtained: think for instance to an unsteady simulation that would miss the lip vortex, and the direction of rotation of the vortices could be wrong.

A good numerical simulation could not be performed without a set of local experimental results. We know for instance that detailed field measurements are necessary in order to validate the choice of the turbulence model, particularly for the wake region. We have shown also that the surface visualizations are invaluable for a proper understanding of the flow behavior. If they are used with a good knowledge of the topological laws, and with 3D numerical simulations, they allow an access to a 3D understanding of the flow behavior.

Finally, we have given the formula of the vorticity flux. This equation emphasizes the strong coupling with the pressure field, and the role of surface topological singularities. This is a key point that underlines the necessity of an accurate pressure prediction on a wall in order to expect a good simulation of the 3D flow structures in the 3D jet environment.