The Flow Structures and Mixing Characteristics of Variable Density Vortex Rings Produced by a Supersonic Jet

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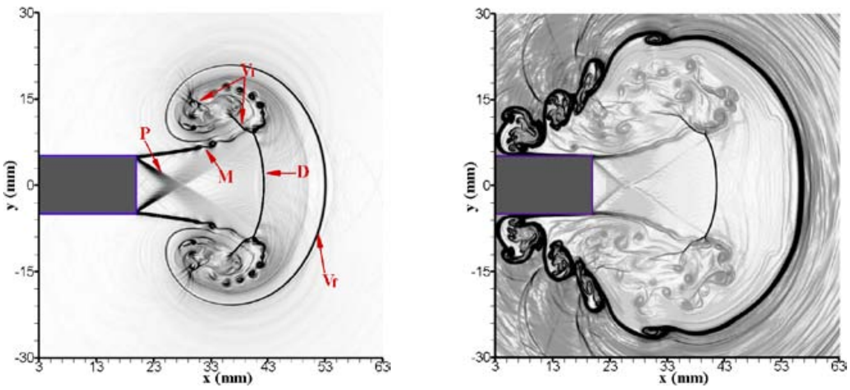
Summary: Large eddy simulation (LES) has been used to simulate the initial flow field of variable density of a supersonic jet. The different structures and mixing characteristics of two cases with different Atwood numbers have been shown, which can provide some important guide for relative engineering design.

Laminar supersonic pulse jets have been investigated for years. Although their main flow structures have been known, however, the detail flow phenomena including shock wave-vortexlet interactions, turbulent mixing and ring sound etc. are still not clear so far. In this paper, the 2-D LES governing equations with mixing fraction equation included are used for investigating the mixing characteristics of a pulse jet flow with different densities. The stretched-vortex model is used as the subgrid model. The inviscid derivatives are discretized using a high-order WENO/TCD scheme [1]. The fourth-order Runge-Kutta scheme is used for the time integration. Supersonic laminar inflow boundary conditions are enforced. The ambient gas is chosen to be standard, its velocity, density and pressure are u_0=0 (rest), ρ=1.156kg/m^3 and p_0=1.0atm, respectively. The Mach number and pressure of the jet flow are Ma=1.4 and p=1.4atm, respectively. Its density has been chosen to be ρ=1.156kg/m^3 (density ratio with ambient gas is 1:1, Atwood number At=0, called case 1) and ρ=0.224kg/m^3 (density ratio become 1:5.16, At=0.675, case 2).

Fig.1 shows the instantaneous numerical schlieren images of initial jet flow field of (a) case 1 and (b) case 2. It is clear that, the main initial jet flow structures of both cases are similar, which include the main vortex ring, mixing layers, diaphragm shock and vortex-induced shock etc., and some interesting and complicated phenomena, like the shock-vortex interactions, turbulence transition and mixing etc. However, for case 1, due to the same density of jet flow and ambient gases, the external front of the main vortex ring generated by the supersonic jet is stable and looks like a mushroom cap (Fig.1.a). The rotation of its vortex core engulfs both ambient and jet flow into its core area. For case 2, its ring front expanded at a higher speed compared to case1 due to a larger Atwood number. And under the effects of Rayleigh-Taylor (R-T) instability, the front loses its stability quickly at its back and rolls up to form unstable vortexes (Fig.1.b). The engulfment effect of vortex core affects mainly the flow within the vortex ring other than the ambient gases in case 1.



(a) Case 1, t=0.134ms (b) Case 2, t=0.101ms

Fig.1 The instantaneous numerical schlieren images of (a) 1:1 density ratio and (b) 1:5.16 density ratio. (P: Prandl-Meyer, M: Mixing layer, D: Diaphragm shock, V_i: vortex-induced shock, V_f: Vortex ring front)

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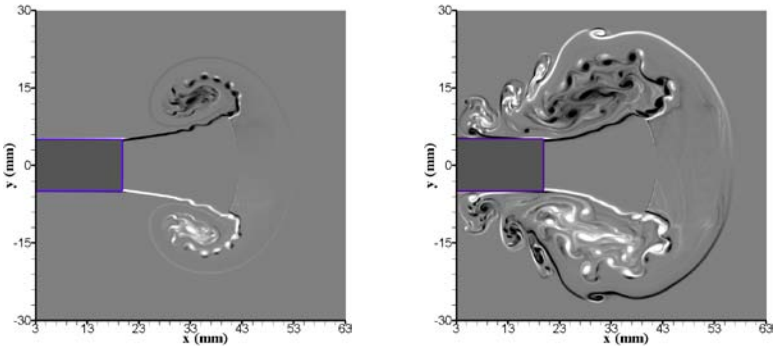
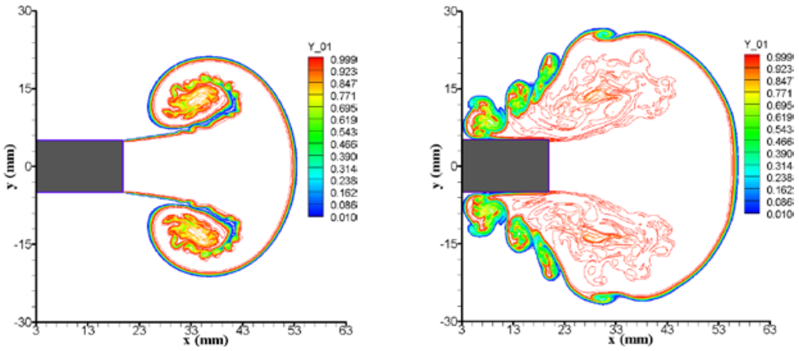
The instantaneous vorticity contours of both cases are illustrated in Fig.2. It is clear that the diaphragm shock (shown in Fig.1) can accelerate the instability of the shear layer (Fig.2). The vortexes lose their shape after the interaction with the diaphragm shock, then break down and become turbulent under the effects of the vortex-induce shock and tangential tensile forces of the circular shear layer, during their engulfment into the core. However, for case 2, the ring front loses its stable firstly at the highest location of the ring, and become fully turbulent near the jet (Fig.2.b).



(a) Case 1, t=0.134ms (b) Case 2, t=0.101ms

Fig.2 The instantaneous vorticity contour of both cases.

Fig.3 presents the instantaneous mixture fraction distribution of both cases. The red color area means the pure jet gas, and the blue for the ambient gas. The different locations of mixing areas of two cases are obvious. For case 1, the ambient gas entrained into the vortex core by trailing shear layer and mix fast with the ejected gas inside the ring occurs due to the vortices distortion and turbulent breakup, however, due to the limited amount of entrained ambient gas, there are mainly the jet gas around the core(Fig.3.a). However, in case 2, the vortex ring surrounds the jet exit, and loses its stability at the back, which obstructs the engulfment of ambient gas into the core, thus the mixing occurs only at the back front of the ring, but the amount of entrained gas are more than that of case 1, therefore, its mixture fraction become smaller, which means it has better mixing efficiency.



(a) Case 1 at t=0.134ms (b) Case 2 at t=0.101ms

Fig.3 The instantaneous mass fraction contours of both cases.

CONCLUSIONS

The flow structure and mixing characteristics of variable density vortex rings, which are produced by a supersonic jet with Mach number Ma=1.4 and pressure p=1.4atm, have been investigated numerically. Our results show that, for a high Atwood number, the vortex ring loses its stable, engulfs and mixes ambient gas at the back of its front, however, for a zero Atwood number, the above process occurs mainly at its core.

References

[1] Hill D. J., Pullin D. I.: Hybrid Tuned Center-Difference-WENO Method for Large Eddy Simulations in the Presence of Strong Shocks. *J. Comput. Phys.* ***194***:435-450, 1999.