A NUMERICAL STUDY OF FLOW DYNAMICS IN THE STARTING PHASES OF SUBSONIC AND SUPERSONIC ROUND JETS

by

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2015AMZ8217

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Submitted

in fulfillment of the requirements of the degree of Doctor of Philosphy

to the

INDIAN INSTITUTE OF TECHNOLOGY DELHI

September 2021

Numerical investigation of the flow dynamics in the starting phases of laminar, axisymmetric, continuously blowing compressible jets is performed. The effect of jet Reynolds number (Re_j), jet Mach number (M_j), pressure-ratio ($\frac{p_j}{p_a}$) and velocity ratio ($\frac{U_a}{U_j}$) on the different starting flow structures and their flow dynamics is explored. The Navier Stokes solver employs the novel *PVU-M+J* scheme developed in this study for the simulations of the compressible jets. The *PVU-M+J* scheme is a variant of the existing *PVU-M+* scheme (Hasan et al.; 2015). The simulations show the starting flow structures obtained for the limiting case of a top-hat profile at the orifice/short nozzle exit. Core bow shock is formed in the inviscid core of the transonic/supersonic jets for sustaining the supersonic flow-field in the primary vortex ring (*PVR*). The embedded shock (*ES*) and vortex induced shock (*VIS*) are also found to sustain the evolving *PVR* in the supersonic jets and at high magnitudes of $\frac{U_a}{U_j}$ these shocks may even cease to form inside the *PVR* which has shrinked to a circular shape. The formation of Kelvin-Helmholtz vortices (*KHV*) leads to the pinch-off of the *PVR* from the trailing shear layer which is also responsible for the quasi-constancy of the *PVR* circulation. For supersonic jets with $\frac{p_j}{p_a} \leq 1$, *KHV* entrained into *PVR* interact with the *ES* to cause a shock-vortex interaction which results in the appearance of multiple *VIS*. It is established that the different events of interaction of *KHV* with the *ES* inside the *PVR* after the pinch-off are a manifestation of two factors; (i) the constraint imposed on the *PVR* by quasi time-invariance of circulation around a material curve enclosing the *PVR* and, (ii) the requirement of spatially-cyclic property distribution inside the *PVR*. In the under-expanded jets ($\frac{p_j}{p_a} > 1$), the investigation of the shock-shear layer-vortex interaction (*SSVI*) shows that the refracted oblique shock portion, across the shear layer, inside the *PVR* evolves in response to the vorticity dynamics prevailing in the evolving *PVR*. This is found to be the main reason for the observed oblique shock refraction in *SSVI*. For under-expanded jets, apart from Mach-reflection time-scale of the *CRVR* pattern formation is also governed by the initial strength of the slip-stream which in turn is regulated by all the four parameters *i.e.* Re_j, M_j, $\frac{p_j}{p_a}$ and $\frac{U_a}{U_j}$. If the slip-stream strength is very low, the CRVR formation is completely suppressed. While for high magnitudes of slip-stream strength there is formation of multiple *CRVR*s. The *CRVR* evolution involves the rolling of *CRVR* over the *PVR* periphery followed by the shock-vortex interaction between *CRVR* and vortex induced shock (*VIS*) of the *PVR*. In the under-expanded jets, *PVR* and *CRVR* circulations attain quasi-constancy as the *CRVR* starts to roll over the *PVR* periphery. The *PVR* circulation is shown to attain quasi-constancy even in the absence of its pinch-off (detachement) from the shear layer. The slip-stream strength is found to govern the magnitude of *CRVR* circulation. New type of discontinuities (induced shocks and vortex sheet) are observed inside the *CRVR*s generated from medium/high strength slip-streams. The self roll-up of *CRVR* causes the formation of the transient spiral stagnation point and the vortex sheet which leads to the formation of the transient saddle stagnation point. The formation of induced shocks inside these *CRVR*s is due to the combination of two different constraints *i.e.* (a) cyclic distribution of fluid properties inside the *CRVR* and (b) quasi-constancy of the *CRVR* circulation. The shock-vortex interaction between *CRVR* and *VIS* is shown to be a weak shock-strong vortex interaction which occurs under the constraint of quasi-constancy of net-circulation enclosing both vortex rings (*i.e.* *PVR* & *CRVR*) and causes the weakening of *VIS*. The vorticity analysis of under-expanded jets with co-flow shows that with increase in co-flow ($\frac{U_a}{U_j} > 0.15$), the PVR circulation attains quasi-constancy owing to the PVR pinch-off and shock-vortex interaction between KHV and ES. While, at low velocity ratio ($0 \leq \frac{U_a}{U_j} \leq 0.15$), the quasi-constancy of PVR is attained due to the occurrence of shock-shear layer-vortex interaction (SSVI).

References

N. Hasan, S. M. Khan, and F. Shameem, A new flux-based scheme for compressible flows *Comp. & Fluids* **119**, 58-86 (2015).