Inlet Unstart Induced by a Jet Injection
• Carbon dioxide sublimation curve crosses isentropic flow condition curve of the Mach 5 tunnel.
• Typical PLRS image taken at the end of the tunnel test time depicts complex flow features (e.g. turbulent boundary layer, shockwave, slip line, etc.).
• Experimental setup including a Mach 5 wind tunnel, pressure sensors and PLRS imaging system.
• Splitter plate is placed to split freestream flow into two/three separated flows.
• Region of interest of each case (Case I through Case V) and configuration of the splitter plates.
• The height of the flow passage (ROI) in each the case is 18.5 mm (40 mm depth).
Result I:
Jet Injection of various jet upstream pressures with and without shock train
• PLRS images depicting thick turbulent boundary layer on the bottom wall and thin laminar boundary layer on the upper surface (beneath the splitter plate).
• Strong shockwave, reflected on the bottom wall, is seen in Case II, while a weak shock appears at the splitter plate tip in Case I.
• PLRS images taken 120 ms after triggering the jet injection valve.
• The flow structures are steady (20 ms ~ 1 sec): jet injection duration ~ 1 sec.
Tunnel unstart observed with 550 psi jet upstream pressure (slow ~ 200 ms) and 600 psi jet (fast ~ 20 ms).
• The arrival time of pressure rise at S1 relative to the pressure jump at S8 is indicated: earlier pressure rise with higher jet pressure.
Arrival time of pressure rise is plotted as a function of jet upstream pressure in Case I and Case II.

As the jet upstream pressure increases, the pressure wave propagation (through boundary layer on the bottom wall) accelerates while the arrival time at S6 does not have explicit correlation with the jet pressure.
Pressure wave propagation speed between S6 and S3 is shown as a function of jet upstream pressure.

In the downstream of incident shock reflection point (between S3 and S2 in Case II), pressure wave propagation speed is slower than that of Case I.

Propagation speeds between S3 and S1 are approximately 15 m/s in Case I and 30 m/s in Case II with 450 psi – 550 psi jet pressure.
The incident shock reflection slows down the pressure rise propagation downstream (pressure build-up) while it accelerates overcoming the local high pressure.
Result II:
Effect of turbulent boundary layer on the unstart procedure
Appearance of Unstart Shock

- Unstart shock originating in the vicinity of the jet appears on the surface where turbulent boundary layer pre-exists before the jet injection.
Sand papers attached on both splitter plates in Case V provide thicker turbulent boundary layers on the plate surfaces, while they are initially thin laminar boundary layer in Case IV.
Formation of a compression wave near the jet (16 ~ 17 ms after the jet injection), a standing wave at the inlet (18 ~ 54 ms), and unstart of the tunnel at 55 ms.
Fluctuation of the Compression Wave
Internal Flow Simulation:

Itaru Hataue (Fluid Dynamics Research 5 (1989) 217-234)

Density Contour (Incident shock-boundary layer interaction)

- Dual compression wave structure is seen in an internal flow simulation.

Ma = 3, Re = 10^5

Ma = 3, Re = 10^7

Ma = 3, Re = 10^5, without turbulence

Ma = 3, Re = 10^5, with turbulence
Boundary layers and shocks, interacting each other near the inlet, stand steady during 16 ~ 24 ms after the jet injection, and the tunnel unstarts at 25 ms.

The unstart in Case V occurs earlier in comparison with Case IV.
Conclusion

• Jet injection into the Mach 5 free stream flow induces a moving or standing shock (compression wave) depending on jet pressure.

• **Incident shock reflection** on tunnel wall delays (behind the shock) or accelerates (in front of the shock) pressure wave propagation on the wall triggered by the jet injection.

• **Unstart shock** originating in the vicinity of the jet appears on the surface where turbulent boundary layer pre-exists before the jet injection.

• Generation of turbulent boundary layer on tunnel surfaces accelerates unstart procedure: 55 ms with minimal boundary layer (Case IV) and 25 ms in the presence of turbulent boundary layer on both surfaces generated by sand papers (Case V).