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# Multi-Species Subsonic Inlet Boundary Condition Formulation with RCS and SRP Applications

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**Abstract**: A description of a model and boundary condition implementation required for simulating the influence of Hypersonic or Supersonic Retro Propulsion (SRP) jets and Reaction Control Systems (RCS) of planetary entry vehicles using Laura 5 is provided. A subsonic reacting boundary condition is required to accurately simulate the jet effects with the surrounding vehicle environment. The paper presents the mathematical implementation of the model and discusses results for test cases with RCS and SRP jets to show the code capabilities.

**Introduction:** Controlled entry or reentry into planetary atmospheres is one of the space exploration challenges that needs to be mastered for space missions with higher mass payloads. Guided lifting entry can be achieved with the use of Reaction Control Systems (RCS) such as those designed for Mars Science Laboratory (MSL) and Orion Crew Exploration Vehicle (CEV). RCS jets will be used for vehicle guidance maneuvers and attitude corrections. Heat load management is also a major task in a design of entry and reentry vehicles, more specifically for human missions. The heat load is the result of the dissipation of hypersonic or supersonic kinetic energy during the deceleration. The vehicle performance improves by reducing the vehicle drag and the aerothermal loads by the means of active flow control such as Hypersonic or Supersonic Retro Propulsion (SRP) mechanism. SRP changes the external flowfields of entry vehicles for spacecraft deceleration by weakening shock system with opposing jets.

The jet effects on the vehicle environment depends on nozzle throat and exit conditions. Throat condition must be accurately obtained for both RCS and SRP systems to correctly predict jet exit condition. Therefore, one must be able to simulate the entire nozzle system from its chamber, which normally is subsonic. This is a favorable approach compare to separately obtaining the internal nozzle solution and superimposing a somewhat averaged throat condition in a hypersonic flow solver, which was used primarily for MSL calculations (Ref.1). The subsonic chamber condition, which is often consists of multi-species gas mixture, requires some special mathematical and numerical treatments. This paper presents details of these treatments and discusses the boundary condition implementation in the Laura 5 code (Ref. 2).

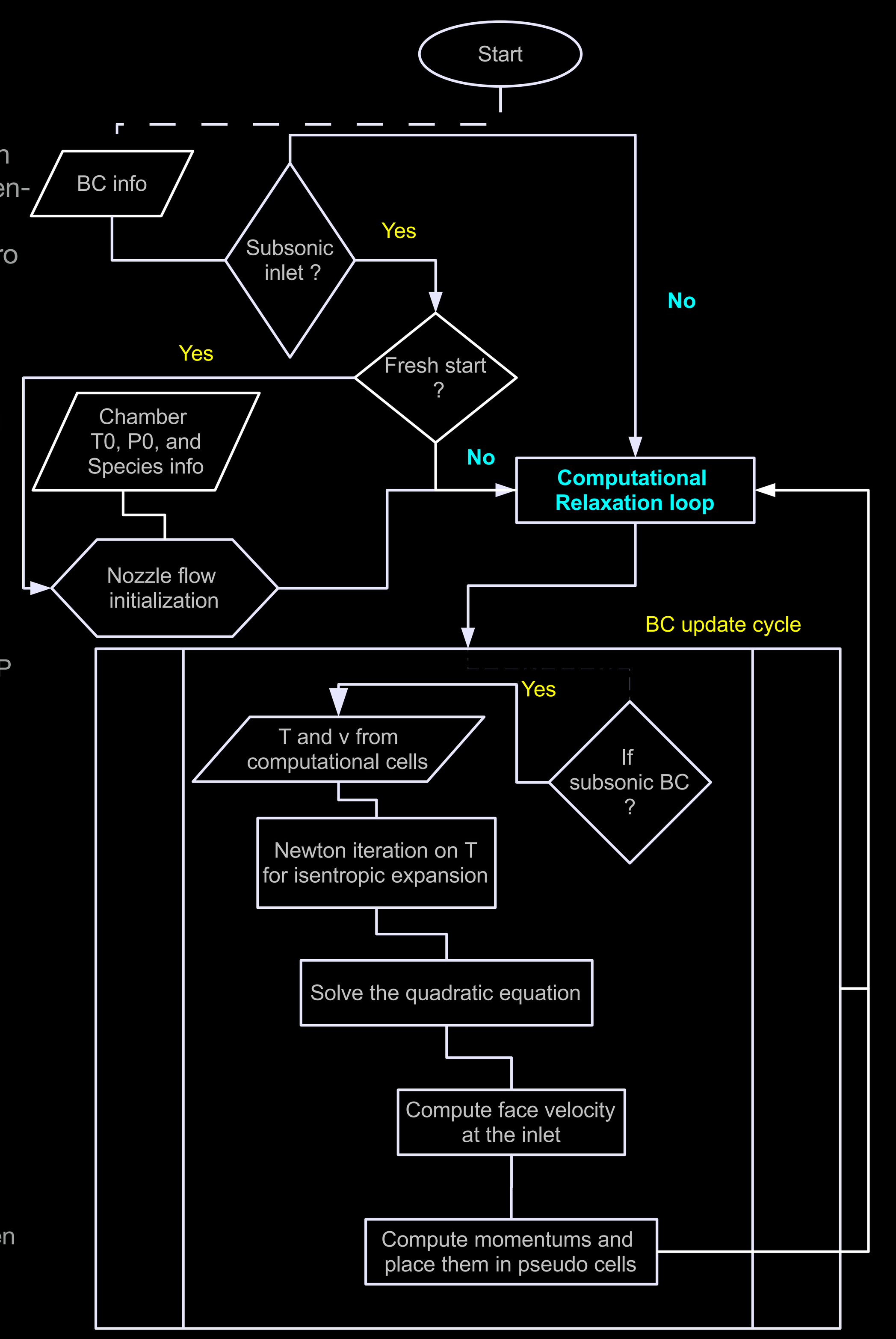


**Figure 2.** Solution procedure flowchart.

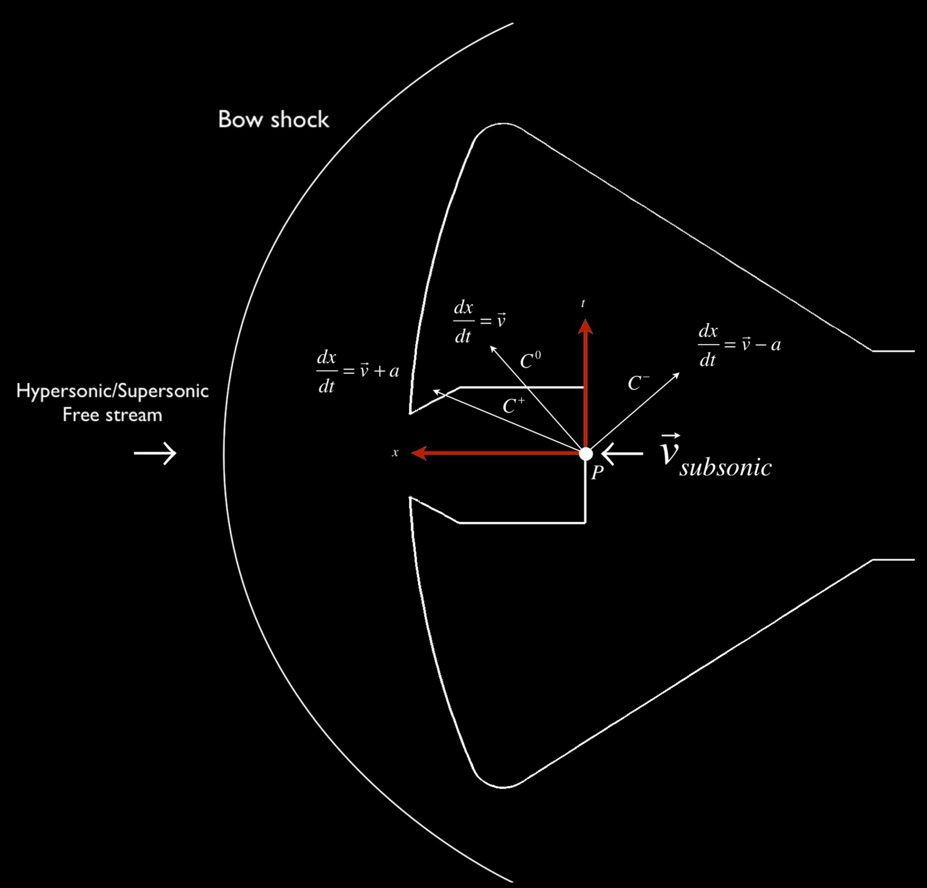


**Figure 1.** Schematic of subsonic inflow boundary condition.

**Mathematical Formulation:** Consider a subsonic boundary condition and the Riemann characteristics at point P shown schematically in Figure 1. Due to the negative slope of C-minus characteristic, one of the flowfield variables must be imposed numerically at point P to correctly prescribe the subsonic inflow condition at the boundary. For multi-species gas mixture, the C-minus characteristic line is defined as:

Riemann characteristic with negative slope — Frozen speed of sound — Total normal velocity on the inlet face

$$C^- = v_\perp - 2a/\beta \qquad (1)$$

$$\beta = \frac{\partial P}{\partial \rho E} = \frac{\sum_{i=1}^{ns} \rho_i R_i}{\rho C_v}$$

For thermal equilibrium condition, which is assumed at the nozzle chamber, the frozen speed of sound, *a*, is given as

$$a^2 = \sum_{s=1}^{ns} \frac{\rho_s}{\rho}\gamma_s + \beta(H - v_\perp^2) \qquad (2)$$

pressure jacobian, $\frac{\partial P}{\partial \rho_s}$

The species *s* pressure jacobian term in Equation 2, is derived for thermal equilibrium condition by following a more general derivation approach presented in Ref. 3:

$$\gamma_s = R_s T_s + \beta \frac{u^2 + v^2 + w^2}{2} - \beta e_s \qquad (3)$$

where the energy per unit mass of species *s* is expressed as

$$e_s = h_s - R_s T_s \qquad (4)$$

By eliminating normal velocity from Equations 1 and 2, one can form a quadratic equation in terms of speed of sound, *a*:

$$(1 + \frac{4}{\beta})a^2 + 4C^- a + \beta(C^{-\,2} - H) - \sum_{s=1}^{ns} \frac{\rho_s}{\rho}\gamma_s = 0 \qquad (5)$$

Ultimately, the subsonic root of the quadratic equation defines the boundary face velocity:

$$v_\perp = C^- + 2a^*/\beta \qquad (6)$$

**Solution Procedure:** Calculation starts by imposing the total pressure and temperature at the nozzle plenum or chamber. The rest of the thermodynamic data is calculated from the imposed boundary condition and the gas mixture compositions. For multi-species jets, specific heat, enthalpy, and entropy, are calculated from their curve fit data. Similarly, the transport properties are obtained form their collision integrals.

An isentropic expansion is assumed at the nozzle chamber or the plenum and the temperature on pseudo cells are obtained using a simple Newton iteration algorithm. The other transport and thermodynamic properties are then corrected using this new static temperature. Finally, the face velocity corresponding to these thermodynamic conditions is computed using the last equation. A flowchart of this procedure is illustrated in Figure 2.

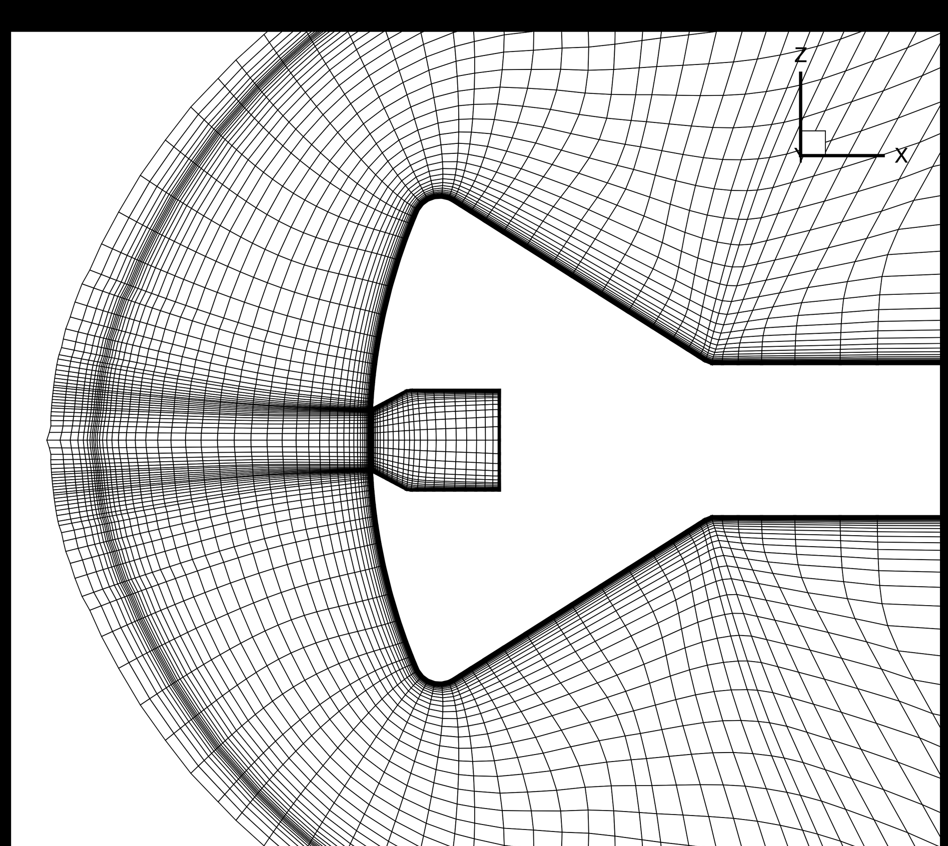

**Figure 3.** Adapted grid for the SRP case study (every third point is shown for clarity). The geometry is a 2.6% Apollo capsule with 0.5" sonic nozzle.

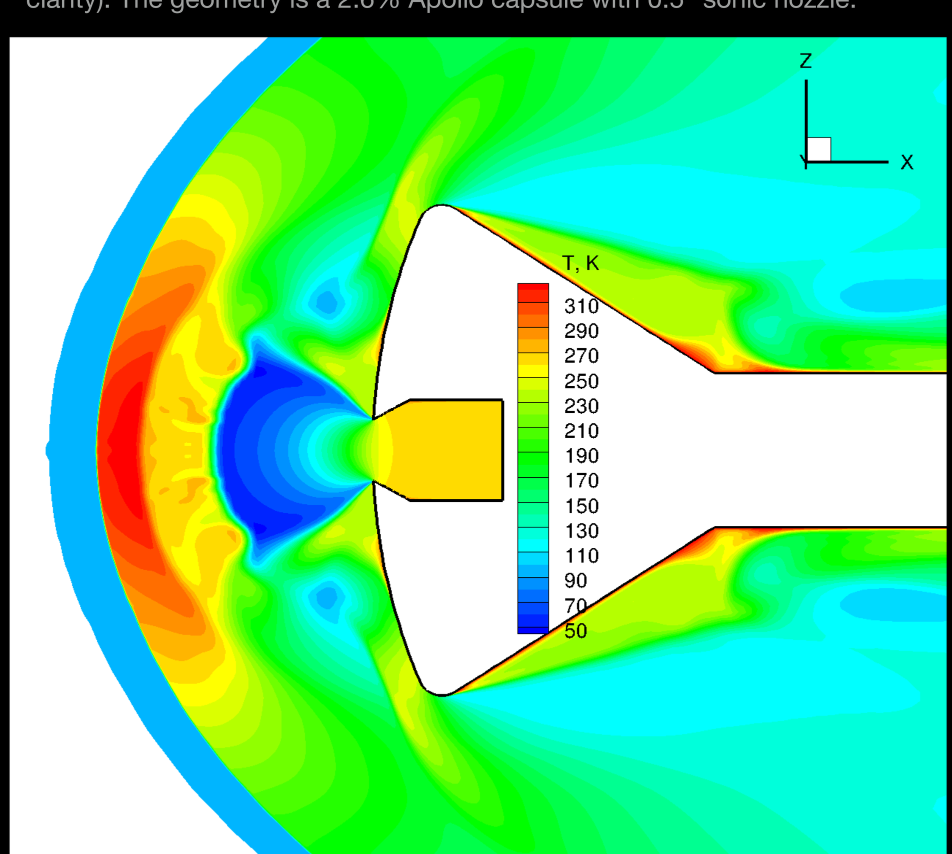


**Figure 4.** Computed temperature contour..

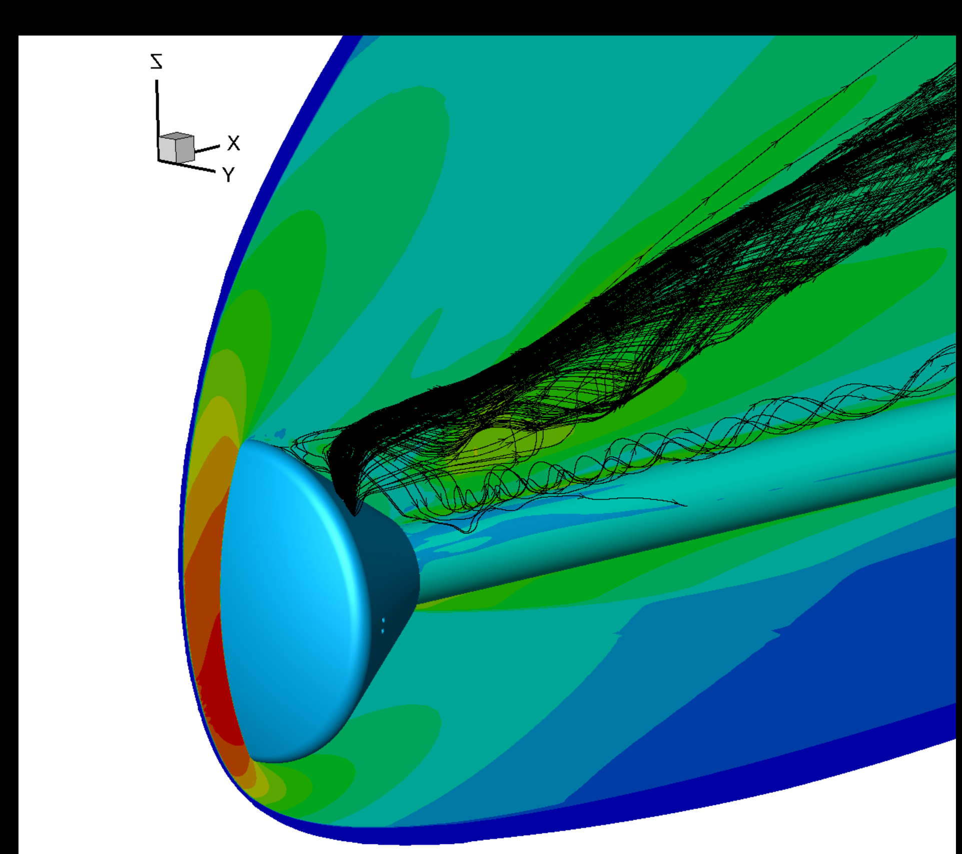

**Figure 7.** Computed Mach contour on a 5% CEV model with RCS roll jets on.

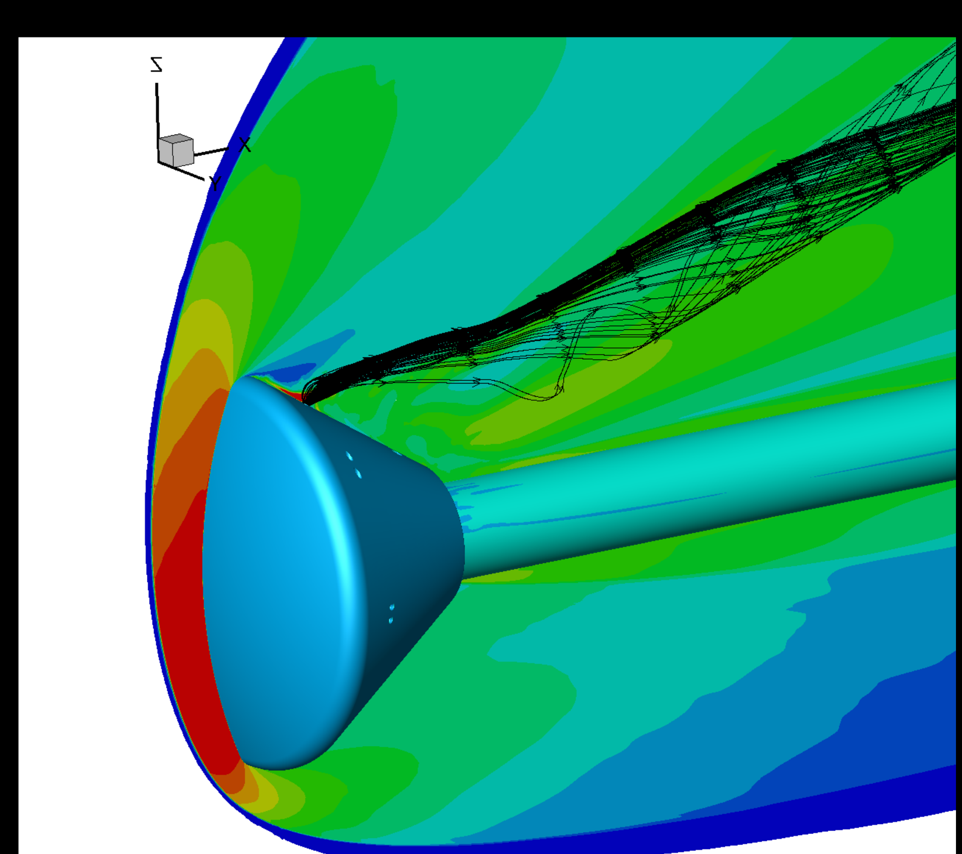

**Figure 8.** Computer temperature contour on a 5% CEV model with RCS pitch up jet on.

**Case Studies:** Test cases for SRP and RCS applications are presented here to demonstrate that the multi-species reacting characteristic boundary condition works and produces reliable result. All cases are presented here are assumed to be in laminar condition. In should be noted here that although very good agreement with experimental data is achieved, the actial flow might be turbulent and unsteady, and an accurate turbulence model is needed for a more quantitative comparison with wind tunnel and flight data,

**Table 1.** Freestream condition used in the SRP test case.

| Mach | $T_\infty, K$ | $\rho_\infty, kg/m^3$ |
|---|---|---|
| 3.48 | 97.35 | 0.15 |

**Table 2.** Chamber condition used in the SRP test case.

| Diameter, D, *inch* | $P_0, Kpa$ | $T_0, K$ | $\dot{m}, kg/sec$ |
|---|---|---|---|
| 0.5 | 719.124 | 266.11 | 0.2268 |

**Table 3.** Computed and measured shock stand off distances for the SRP test case.

| | LAURA 5 | Experiment (Ref. 8) | Diff., % |
|---|---|---|---|
| $\Delta / D$ | 0.555 | 0.54 | 2.8 |

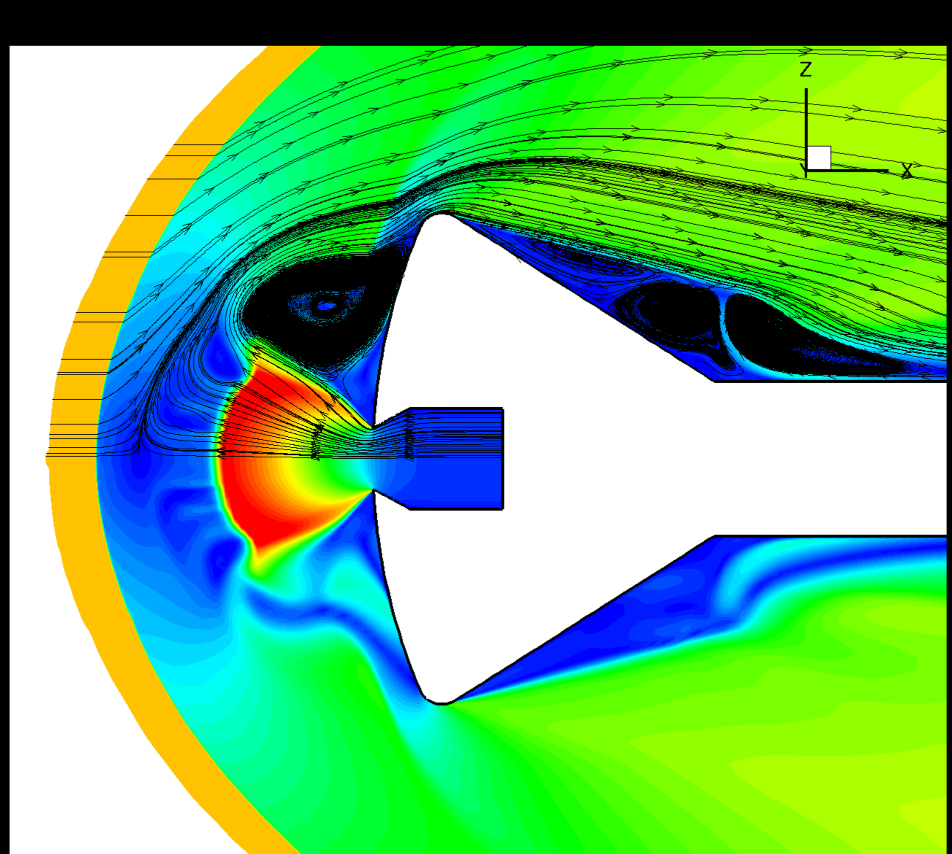

**Figure 5.** Computed Mach contour with streamlines.


**Figure 6.** Experimental Schlieren image for the SRP case study (taken from Ref. 8)

**References**

1. Dyakonov, A.A., Schenenberger, M., Scallian, W.I., Van-Norman, J.W., Novak, L.A, and Tang, C.Y., Aerodynamic Interference Due to MSL Reaction Control System, AIAA 2008-6387.
2. Mazaheri, A.R., Gnoffo, P.A., Johnston, C.O., and Kleb, B., Laura Users Manual: 5.3-46673, NASA TM, 2010.
3. Abgrall, R., Fezouli, L., and Talandier, J., An Extension of Osher's Riemann Solver for Chemical and Vibrational Non-Equilibrium Gas Flows, Int. J. Num. Meth. Fluids, vol. 14, pp.935-960, 1992.
4. Gnoffo, P.A., Gupta, R.N., and Shinn, J.L., Conservative Equations and Physical Models for Hypersonic Air Flows in Thermal and Chemical Nonequilibrium, NASA TP 2867, 1989.
5. Hayman, L.O., and McDearmon, R.W., Jet Effects on Cylindrical Aftbodies Housing Sonic and Supersonic Nozzles which Exhaust Against a Supersonic Stream at Angles of Attach From 90 to 180, NASA TN D-1016, 1962.
6. Bushnell, D.M., and Huffman, J.K., Forward Penetration of Liquid Water and Liquid Nitrogen from the Orifice at the Stagnation Point of a Hemispherically Blunted Body in Hypersonic Flow, NASA TM X-1493, 1968.
7. Jarvinen, P.O., and Adams, R.H., The Effects of Retrorockets on the Aerodynamic Characteristics of Conical Aeroshell Planetary Entry Vehicles, AIAA Paper 70-219, 1970.
8. Daso, E.O., Pitchett, V.E., Wang, T-S., Ota, D.K., Blankson, I.M., and Auslender, A.H., Dynamics of Shock Dispersion and Interactions in Supersonic Freestreams with Counterflowing Jets, AIAA J., vol. 47 (6), 2009.