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TRANSITION DELAY IN HYPERVELOCITY BOUNDARY LAYERS BY MEANS OF CO₂/ACOUSTIC INSTA

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Abstract

The potential for hypervelocity boundary layer stabilization was investigated using the concept of damping Mack's second mode disturbances by vibrational relaxation of carbon dioxide (CO₂) within the boundary layer. Experiments were carried out in the Caltech T5 hypervelocity shock tunnel and the Caltech Mach 4 Ludwig tube. The tests used 5-degree half-angle cones (at zero angle of attack) equipped near the front of the cone with an injector consisting of either discrete holes or a porous section. Gaseous CO₂, argon (Ar) and air were injected into the boundary layer and the effect on boundary layer stability was evaluated by optical visualization, heat flux measurements and numerical simulation.

In T5, tests were carried out with CO₂ in the free stream as well as injection. Injection experiments in T5 were inconclusive; however, experiments with mixtures of air/CO₂ in the free stream demonstrated a clear stabilizing effect, limiting the predicted amplification N-factors to be less than 13. During the testing activities in T5, significant improvements were made in experimental technique and data analysis. Testing in the Ludwig tube enabled optical visualization and the identification of a shear-layer like instability downstream of the injector. Experiments showed and numerical simulation confirmed that injection has a destabilizing influence beyond a critical level of injection mass flow rate. A modified injection geometry was tested in the Ludwig tube and we demonstrated that it was possible to cancel the shock wave created by injection under carefully selected conditions. However, computations indicate and experiments demonstrate that shear-layer like flow downstream of the porous wall injector is unstable and can transition to turbulence while the injected gas is mixing with the free stream. We conclude that the idea of using vibrational relaxation to delay boundary layer transition is a sound concept but there are significant practical issues to be resolved to minimize the flow disturbance associated with introducing the vibrationally-active gas into the boundary layer.

1 Introduction

This project explored the potential for influencing the location of transition from laminar to turbulent flow within the boundary layer on hypervelocity vehicles by modifying the gas composition of the boundary layer. For hypervelocity boundary layers on smooth slender bodies, the main mechanism of boundary layer transition is the high-frequency instability (usually referred to as the “second mode”) discovered by Mack in the 1960s [1, 2]. Motivations for the present project was based on previous studies that showed a significant increase in measured transition location [3–5] in CO₂ atmospheres as compared to air as well as a substantial decrease in computed [6] instability growth rates when physical and chemical nonequilibrium effects were included. The peculiar effectiveness of CO₂ in delaying hypervelocity boundary transition was conjectured by Fujii and Hornung [7] to be due to vibrational relaxation time in CO₂ being comparable to typical second mode instability periods. This idea is substantiated by the computations [8] that predict significant damping of high frequency acoustic waves in CO₂ as compared to air or nitrogen (N₂) flows. The dynamics of acoustic waves in a uniform flow are distinct from that of second-mode instability waves in hypervelocity boundary layers but there are sufficient similarities to make this analogy useful. The second mode disturbances are essentially inviscid and couple thermodynamic and velocity fluctuations through locally isentropic motion.

With this background and motivation, it was proposed by Leyva et al. [9] that injection of CO₂ into the boundary layer through the cone surface might be an effective transition control strategy if sufficient CO₂ could be injected and mixed with the free stream while maintaining laminar flow. Earlier work on this project (2007-2009) sponsored by the AFOSR was exploratory and focused on discrete injection (holes) through the forebody of a 5-degree half-angle cone [10, 11] sparsely instrumented with surface-mount thermocouples to detect transition based on heat flux changes. Following these preliminary studies, a new cone model was constructed with a much greater density of thermocouples and the effect of injection schemes on transition location was examined [11] with preference for distributed injection using sintered porous metal that conformed to the shape of the cone. Linear stability computations by Wagnild et al [12] demonstrated the potential stabilizing effects of CO₂ in the free stream, the potential destabilizing nature of localized injection of CO₂, and the potential benefits of injection spread over the entire cone surface.

The present project was a continuation of this earlier work, initially focusing on experimental studies in T5 using the densely instrumented cone and sintered metal injectors. In addition to the experimental studies in T5, during 2010-13, we worked with collaborators at the University of Minnesota (Candler, Johnson and Wagnild) on the analysis of the mean flow and boundary layer stability. The students, visitors and postdoctoral scholars supported by this project are given in Appendix A; significant collaborations carried out as part of this project are given in Appendix B; and publications that resulted from the project are described in Appendix C.

After carrying out the experimental studies in T5 during the first two years (2010-2012) of the current contract, we fabricated and tested a smaller model of the T5 cone in the Caltech Mach 4 Ludwig tube to examine strategies for injection and mixing within the boundary layer. The last two years (2013-2014) focused on experiments and analysis of the Ludwig tube experiments as well as reanalysis of T5 data. We collaborated with Fedorov of MIPT (through an EOARD grant) to examine the effect of surface geometry changes on the instability of flow within and downstream of the porous injectors of the type used in previous T5 testing. In the Ludwig tube testing, we have used a new electronic mass flow rate control system and high-speed schlieren visualization to examine the effect of geometry and flow rate on the flow stability. We also performed a linear

stability analysis on flow with injection under Ludwig tube conditions. We have identified as a critical issue the instability in the shear flow between the low momentum injected gas and the free-stream flow.

2 T5 Studies

Hypervelocity (3000-4000 m/s) experiments with CO₂ and argon injection were performed in T5 in FY2011. A 1-m long, 5-degree half-angle cone is instrumented with 80 Type E surface-junction thermocouples to measure heat transfer as a proxy for laminar to turbulent transition. A porous metal injector section shown in Figure 1 located 13 cm downstream from the cone tip allows gas injection into the boundary layer surrounding the cone. Tests were performed in air with reservoir conditions of 10 MJ/kg enthalpy and 55 MPa. The results were compared to tests with no injection and a smooth injector section. Full details of the test facility, operating conditions, methods of analysis and complete discussion of all results from T5 testing for this project are provided in Jewell’s PhD thesis [13] and supplemental material available online from Caltech at <http://thesis.library.caltech.edu/8433/>.



Figure 1: Porous metal injector used in T5 injection study. Pore size is on the order of 1 μm .

The surface-mounted thermocouple data are analyzed to obtain instantaneous and fluctuating heat flux along the surface of the cone. Transition to turbulent flow is identified by a rapid increase in both the average and fluctuating heat flux expressed as the root mean square (rms) of the time series recorded during the test time. Test times are on the average of 1.5 to 2 ms in T5 and data are recorded at 200 kHz, allowing sufficient temporal resolution to obtain a reliable indication of transition over a period of at least 5-10 flow times over the cone surface. An example of average and rms heat flux data are shown in Figure 2 for a test in air. Using the analysis method described in Chapter 3 of Jewell [13], the onset of transition is 0.51 m from the tip of the cone, where $Re_x = 4.2 \times 10^6$.

The result of the injection experiments¹ in T5 are given in Figure 3. These show a weak trend of increasing transition distance with increasing injection rate, reaching a maximum at a mass flow ratio (injected/boundary layer) of 0.02 and then decreasing with further increase in CO₂ injection mass flow rate. At the maximum mass flow rate tested, CO₂ does not appear to have any effect on transition distance. Argon injection conditions into air at similar mass flow rates transitioned at a distance that was about 80% of the transition distance for any CO₂ injection or no-injection conditions. The discrepancy between the Ar and CO₂ results at the lowest injection levels indicates an issue with repeatability in tunnel operation, which in hindsight is due to a lack of consistent

¹Note that the mass flow rates shown in this figure are substantially lower (by up to a factor of 30) than those originally reported in an earlier paper [14] due to errors in estimating the mass flow rate. This issue and subsequent work to obtain better estimates is discussed at length in Chapter 7 (see Table 7.4 for corrected mass flows) of Jewell [13].

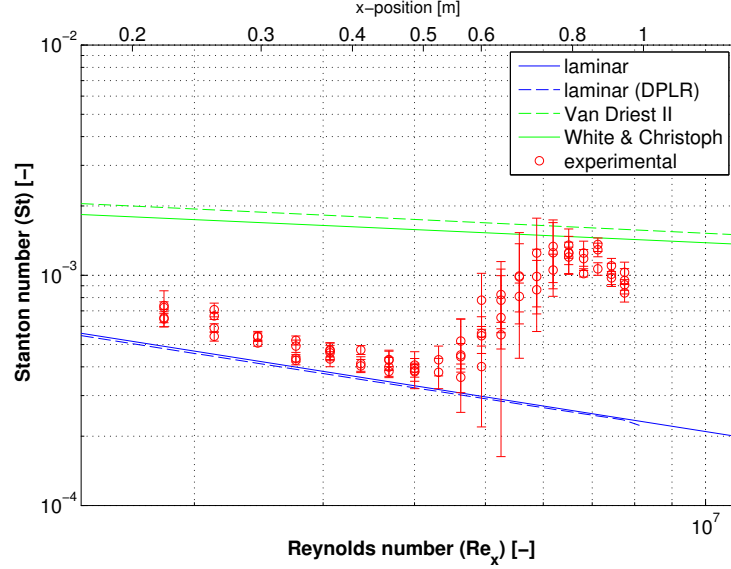


Figure 2: Nondimensional heat flux (Stanton Number) as a function of distance and Reynolds number along the generator of the cone for T5 test 2744, air at 7.7 MJ/kg. The boundary layer edge velocity is 3541 m/s and the edge temperature is 1260 K.

cleanliness in the shock tube and control of tunnel operation conditions. All experiments with injection in T5 were performed prior to the adoption of the current tunnel-cleaning protocol that we learned is needed to obtain reliable transition location measurements. Although the uncertainty ranges shown on each of the data points reflects the known measurement errors, these do not reflect uncontrolled effects of cleanliness that significantly influence transition location.

Given all the limitations on the T5 injection tests, the results are at best inconclusive. The value of the data is limited by the lack of direct measurement of injection mass flow rate as well as variations in tunnel performance and cleanliness that will cause substantial uncontrolled variability in the transition location. In any case, the injection flow rates achieved in these experiments are extremely low compared to what is anticipated from computations [12, 13, 16] to be necessary for significant boundary layer stabilization. This is a consequence of the very high mass flux in the hypervelocity boundary layer compared to what can be readily achieved with our porous injector and reasonable CO₂ supply pressures. Based on our present understanding, it would be very surprising to obtain any significant stabilization effect at these mass flow rate ratios due to damping by vibrational relaxation.

Due to the limitations of the test section in T5, it was not possible to directly observe the injection process while simultaneously measuring changes in heat flux, which made it difficult to directly determine the effect of injection on boundary layer stability immediately downstream of the injection. At the same time, other work in T5 measuring instability waves using the focused laser differential interferometer technique demonstrated [15] the importance of carefully cleaning the tunnel in order to obtain repeatable results.

The initial tests in T5 were important for identifying key issues and clearly defining future research needs. As a consequence, the program direction was altered to focus on obtaining higher quality data in T5 without injection and a separate program of injection experiments in the Ludwig tube to enable the direct observation of the fluid mechanics of the interaction of the injection with the

boundary layer. These experiments are described in Section 3.

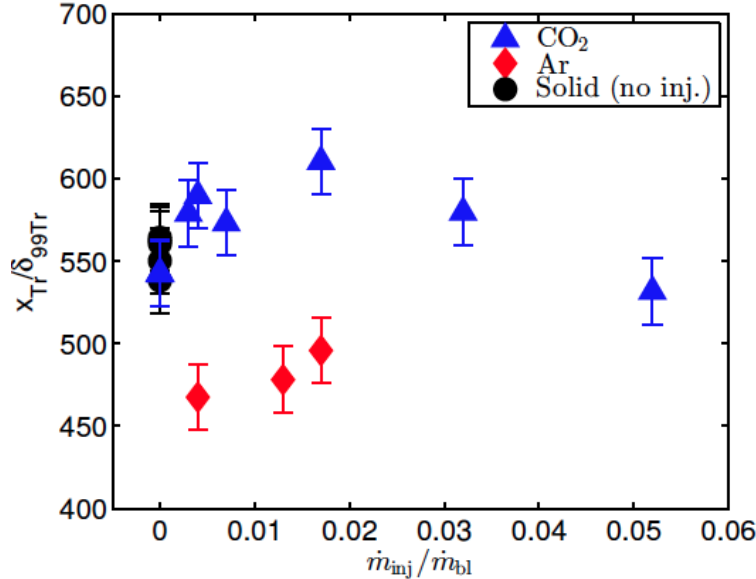


Figure 3: Normalized transition location x_{Tr}/δ_{99Tr} as a function of gas injection mass flow (estimated - see the discussion in Jewell [13]) for experiments in T5 with air as a test gas.

Further research in T5 in FY2012 and FY2013 concentrated on understanding the transition process in thoroughly mixed gases rather than flows with injection in order to eliminate the complexities introduced by injection. Unlike earlier testing in T5, active mixing of air and CO₂ was carried out in a separate mixing tank rather than relying on diffusion within the shock tube. The active mixing and use of high-purity gases are part of a series of efforts to improve the repeatability of transition data with air-CO₂ mixtures. A rigorous cleaning procedure for the tunnel in between shots was also developed at this time in order to reduce variability between experiments and improve flow quality. Four CO₂/air free-stream gas mixtures were used with reservoir pressures between 55 and 60 MPa. These mixtures consisted of 0.0 (all air), 0.5, 0.75, and 1.0 CO₂ by mass fraction. For tests at an reservoir enthalpy of 9.2 MJ/kg, transition delays of up to 30% in terms of x -location, 38% in terms of edge Reynolds number, and 140% in terms of the Reynolds number evaluated at reference conditions were documented in CO₂ flow compared with similar experiments in air.

These improvements together with much high density of instrumentation and improved data analysis make the resulting transition location data much more suitable for validating stability computations than earlier work in T5. Transition locations in air flow at these conditions are consistent with computed N-factors between 8 and 10, significantly higher than previously believed for reflected shock tunnel flow. Results of simulations carried out at Caltech with the U. Minnesota STABL software suite are presented in Figure 4. Computations at Caltech and Minnesota using the critical N-factor method of predicting boundary layer transition [16] in mixtures with CO₂ show a significant effect increase in predicted transition distance when vibrational relaxation is included in the simulation. The magnitude of the effect of vibrational damping on transition distance is predicted to be strongly dependent on the mass fraction of CO₂ and reservoir enthalpy with a minimum concentration of CO₂ of 50% (by mass) and reservoir enthalpy greater than 7 MJ/kg required to obtain significant effects.

In other work, time- and spatially-resolved heat transfer traces were obtained and used to interpret

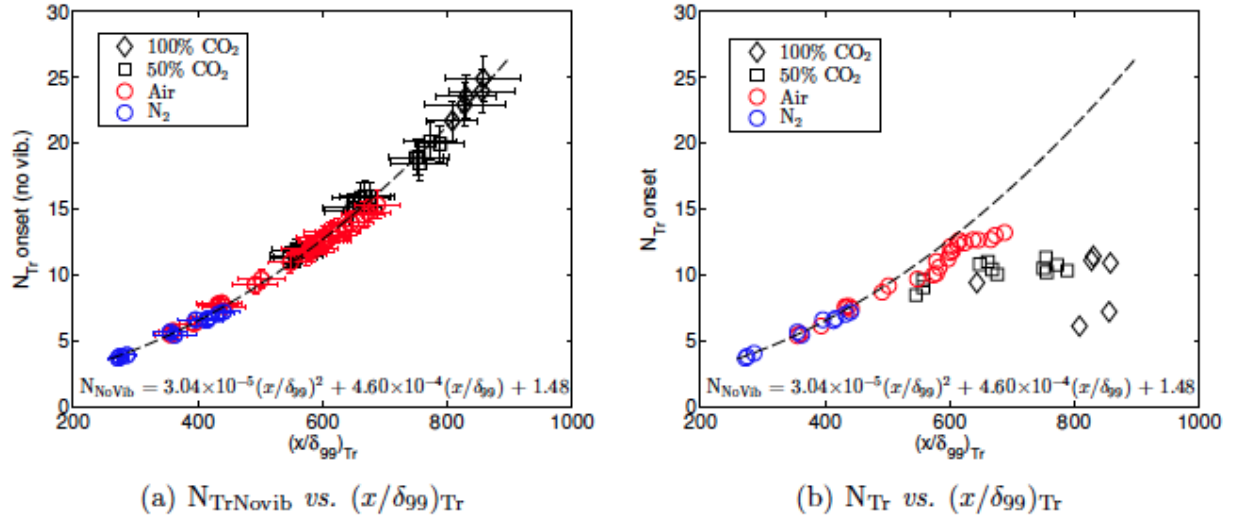


Figure 4: Comparison of computed N-factor at transition with normalized transition distance. (a) computed without considering vibrational effects; (b) computed with vibrational effects. The dashed line is the fit to the results shown in a).

the transition process. Turbulent spots are observed propagating in heat flux “movies” of the developed cone surface (Figure 5) and used to calculate spot convection rates. The spot propagation speed and spreading rate are generally consistent with past supersonic and hypersonic experiments, as well as with computational results.

3 Ludwig tube Studies

Experiments began in the Caltech Mach 4 Ludwig tube in FY2012 and continue today to better understand the fluid dynamics of injection in supersonic flow. We also began testing methods to reduce the disturbance to the flow by shaping the injector section as proposed by Fedorov. A scale model of the T5 cone with interchangeable injector sections was used in the Ludwig tube with free-stream conditions $M = 4$, $T_\infty = 70$ K, and $P_\infty = 1335$ Pa. The cone model with both injectors used is shown in Figure 6. The conical injector is the same used in the T5 study and the cylindrical injector is intended to reduce the disturbance to the external flow when the injection rate is properly adjusted or “tuned” to eliminate visible compression or expansion waves at the front of the injection section.

Injection mass flow rates are reported as $m = \dot{m}_{inj}/\dot{m}_{BL}$ where $\dot{m}_{BL}$ is the mass flow rate of the incoming boundary layer at the beginning of the injector as calculated using the similarity solution of Lees. Experiments with injection of both CO₂ and air were performed. Figure 7 shows long (30 μ s) exposure schlieren images for four different cases with air injection using the conical injector. Without injection the boundary layer is observed to be laminar for almost the entire length of the cone, but injection causes a rapid transition to turbulence almost immediately for all cases examined. Injection also creates an oblique shock wave that propagates into the external flow.

Injection with the cylindrical injector does not cause immediate transition. Figure 8 shows four cases with air injection with the cylindrical injector. For cases with high injection mass flow rates an oblique shock forms at the beginning of the injector as in cases with the conical injector. At

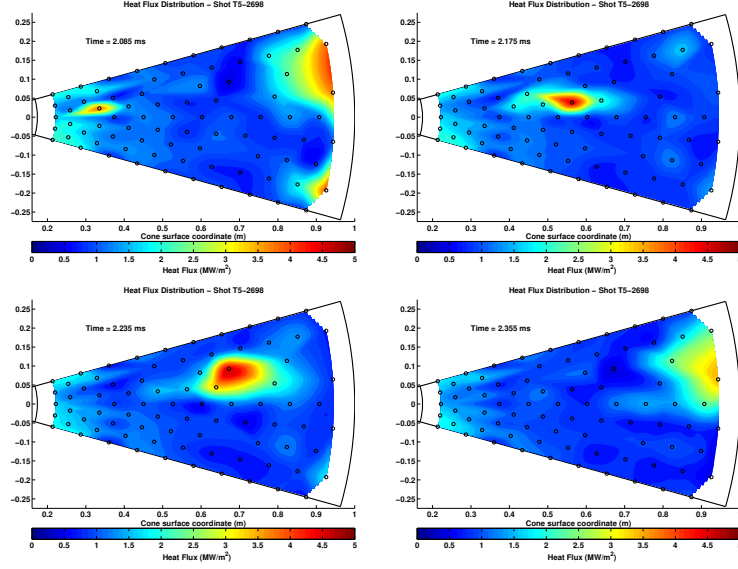


Figure 5: Surface heat flux Visualization of a turbulent spot in T5 test 2698. The test gas is air with a boundary layer edge velocity of 3668 m/s and edge temperature of 1407 K.

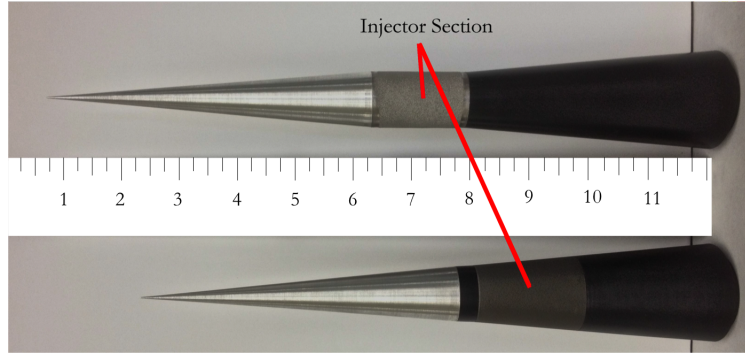


Figure 6: Cylindrical (top) and conical (bottom) injector assemblies used in the Ludwig tube study. The injector portion of the conical injector assembly was also used in the T5 study.

$m = 0.5$, the injection rate is “tuned” and produces a minimal disturbance to the exterior flow.

Unfortunately, the injection layer downstream of the injector is observed for the cylindrical injector to be unstable for all mass flow rates. A transition location can be determined from schlieren images by finding where the injection layer edge ceases to be a sharp change in contrast in the image and becomes a smooth gradient broadening in extent with increasing downstream distance. The transition location is observed to be unsteady, which we believe is due to tunnel noise. The transition Reynolds numbers correspond to a computed N-factor of 5 to 6, which is consistent with a high free-stream turbulence level. To address this issue, the upstream diaphragm in the Ludwig tube was replaced in FY2014 by a fast-acting valve which has reduced the noise level in the free stream by a factor of 3-4.

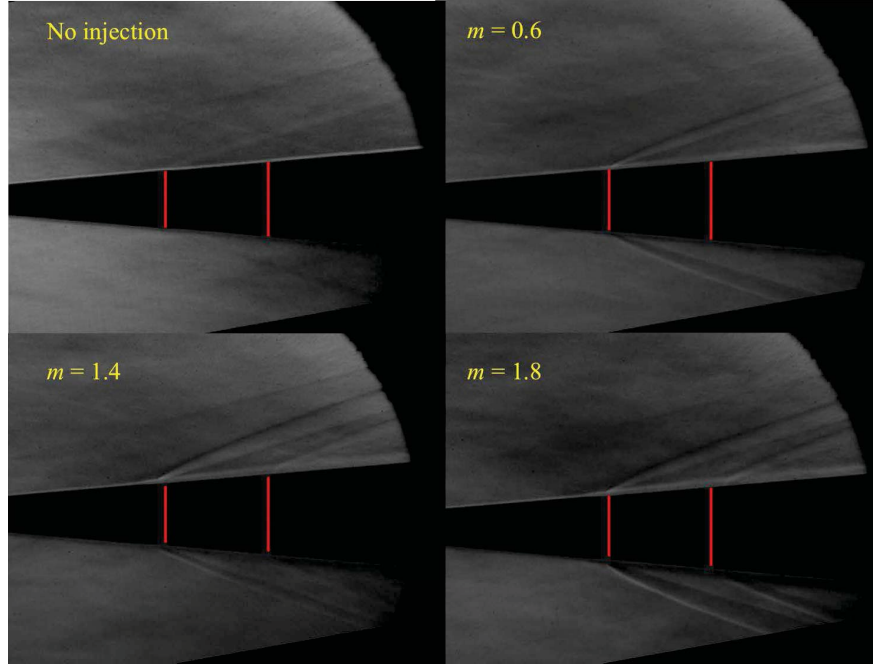


Figure 7: Long-exposure schlieren images from conical injector experiments using air.

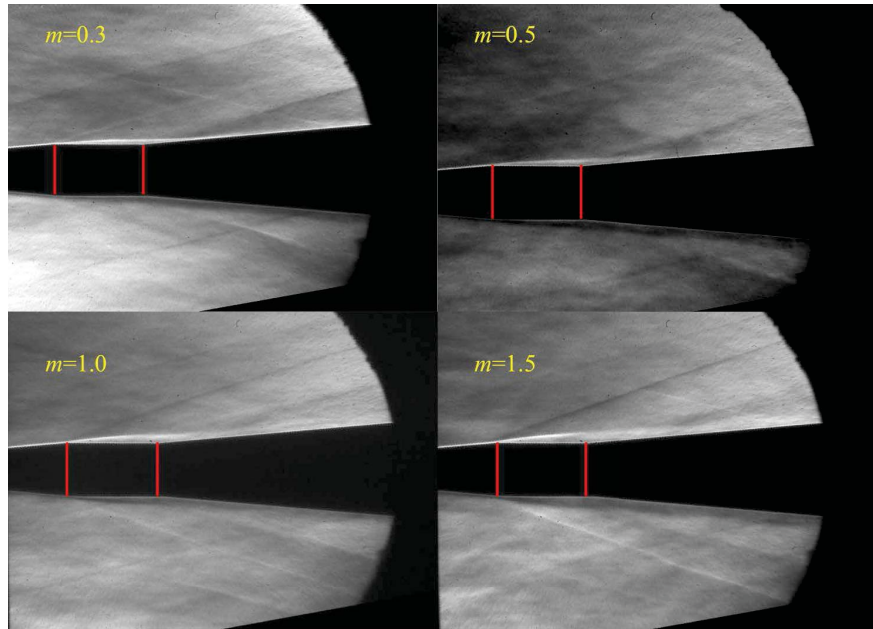


Figure 8: Long-exposure schlieren images from cylindrical injector experiments using air.

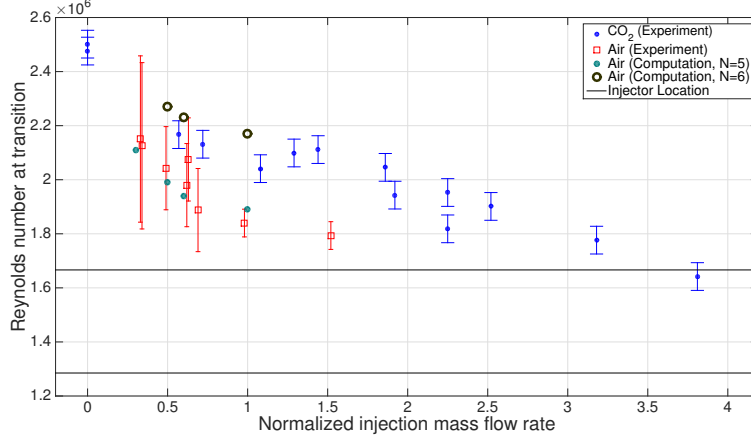


Figure 9: Experimental and computational (based on a critical N-factor of 5 or 6) mean transition Reynolds number for various injection rates with the cylindrical injector. Transition is observed near the end of the viewing window with zero injection.

A pulsed laser light source was used to capture schlieren images with a very short (40 ns) exposure time to study the instability created by injection. One such image for the tuned injection case is shown in Figure 10. The instability appears to be akin to either shear layer breakdown or perhaps second-mode rope waves in hypersonic boundary layers. Images are of sufficient quality to determine the spatial wavelength of the instability waves. An algorithm samples along a line in each image in the injection layer and produces a power spectrum of intensity. Spectra from 500 images are averaged together for each case. Figure 11 shows the calculated spectra for the tuned case ($m = 0.6$) and from a case with a much higher injection rate, and therefore a much thicker injection layer. Both spectra exhibit a strong peak at a wavenumber corresponding to a wavelength of approximately 6 mm. This wavelength is independent of the injection layer thickness, suggesting that the underlying instability is perhaps not related to Mack’s second mode.

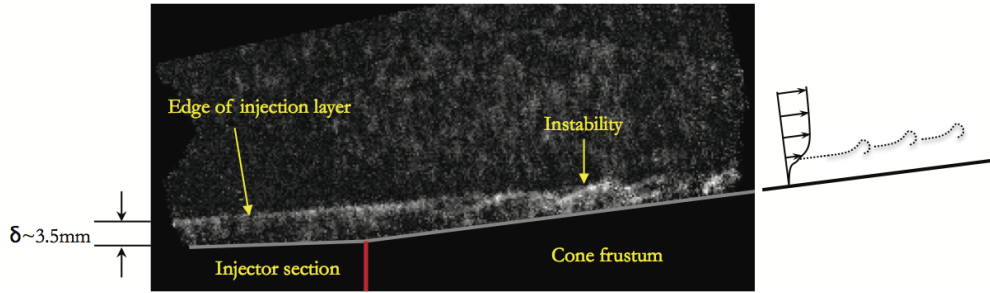


Figure 10: Schlieren image from a test with 40 ns exposure with $m = 0.6$. The rear of the injector is marked with a vertical line. A sketch on the right shows the velocity profile and the resulting production of vorticity. The instability of the injection layer is clearly visible downstream of the injector.

3.1 Stability Computations

Computations examining the stability characteristics of the flow with injection in the Ludwig tube began in FY2013 and are ongoing. The mean boundary layer profile is computed using a shock-capturing Navier-Stokes solver that is included in the STABL stability software suite developed at the University of Minnesota [6, 17, 18]. This program uses the Data Parallel Line Relaxation

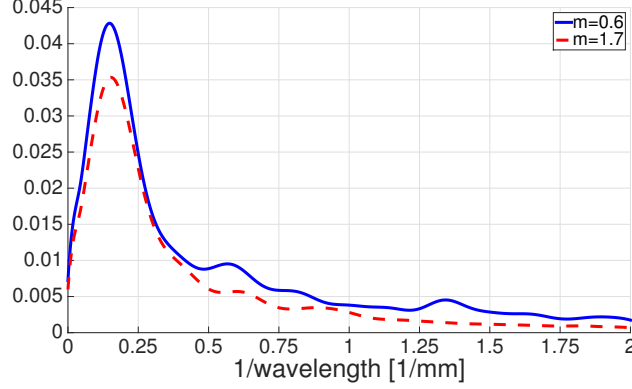


Figure 11: Averaged PSDs for cases with $m = 0.6$ and $m = 1.7$.

(DPLR) method to obtain steady-state solutions of the Navier-Stokes equations. Conditions in the computations match those of the experiments in Section 3. Stability characteristics are determined by separate software tools (developed by Bitter at Caltech) which implement a locally-parallel stability analysis using the shooting method developed by Mack [1]. N-factors for 2D waves and 3D waves at the most unstable oblique angle are shown in Figure 12. N-factors for 3D waves are much larger than for 2D waves, indicating that the first mode instability plays an important role in the transition process for flows with injection at Mach 4. This had not been reported by other researchers. These computations also confirm that injection has a destabilizing effect on the boundary layer even in the cylindrical case. Fedorov et al [19] also carried out mean flow and stability computations for the same geometry but using T5 free-stream conditions. They also concluded that injection was destabilizing and proposed that using acoustic absorption by porous material downstream of the injection section could be beneficial.

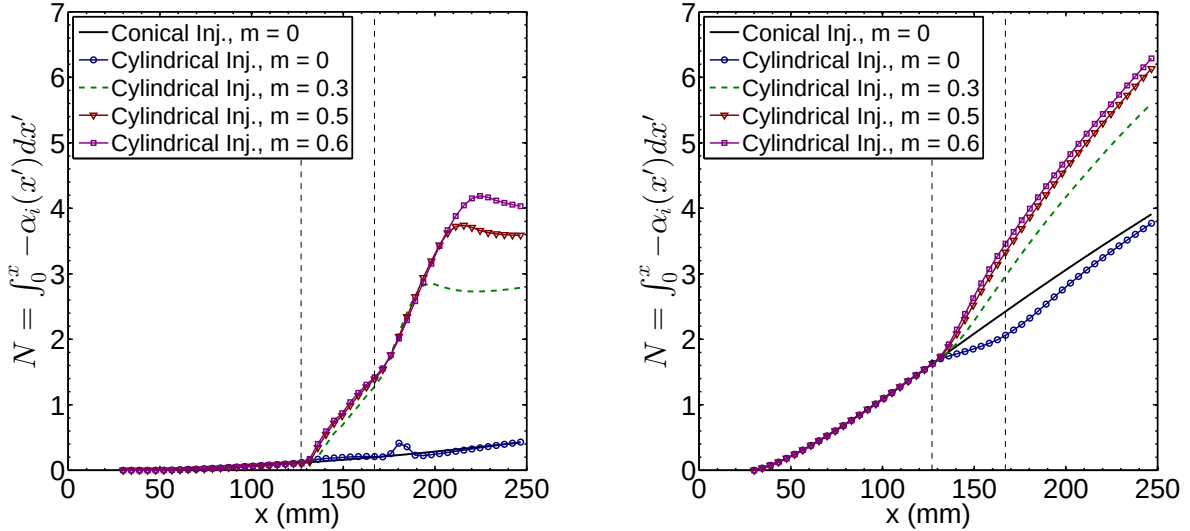


Figure 12: N-Factor diagrams for various injection rates. Left: 2D waves, Right: 3D waves with $\beta = 220$.

The most amplified wavenumbers from the stability analysis can be compared with values determined experimentally in Section 3. The taller peak in Fig. 13 corresponds to first mode waves, which grow monotonically in amplitude and decrease slightly in wavenumber as x increases. The

second peak at about $1/\lambda = 0.16/\text{mm}$ corresponds to second-mode waves which grow mainly over the injector and slightly downstream from it, but stop growing farther downstream.

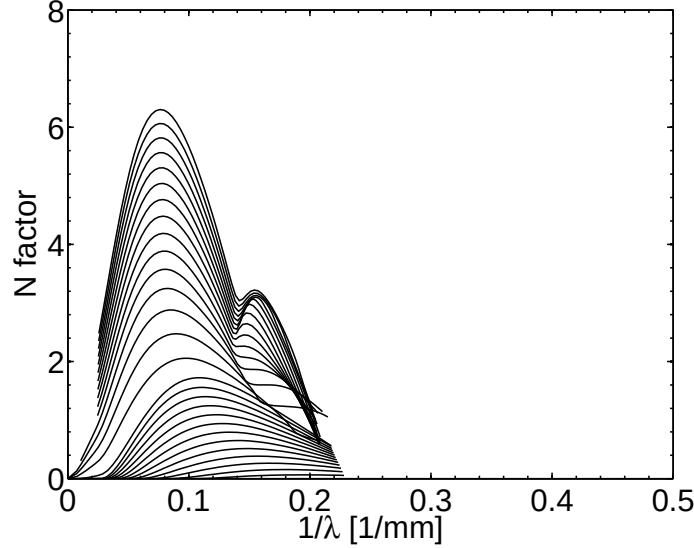


Figure 13: Mode amplification as a function of wavenumber for the cylindrical injector, $m = 0.6$, $\beta = 220$. Each line corresponds to a different streamwise location x , with frequency parameterizing the curves.

4 Summary and Conclusions

This project explored the possibilities for delaying boundary layer transition in hypersonic flow by injecting CO_2 into the boundary layer. This was motivated by observations that CO_2 is known to absorb acoustic energy in the frequency range of the Mack second-mode instability by energy exchange between vibrational/rotational modes and translational motion of the molecules. CO_2 in the boundary layer in a hypersonic flow could therefore reduce the strength of Mack second-mode waves and delay the onset of transition associated with the growth and breakdown of the second mode. Computations of boundary layer stability confirmed the potential stabilizing effect of CO_2 in the free stream but indicated that injection over a limited range of the cone surface was destabilizing.

Experiments were performed in the T5 hypervelocity shock tunnel to test various schemes of injecting CO_2 into the boundary layer on a cone through a porous material. The experiments with injection were inconclusive. Several issues were identified and addressed in later portions of the project. These include direct measurement of the injection mass flow rate as well the importance of shock tunnel cleanliness in obtaining repeatable transition location measurements. Improved procedures for estimating free-stream and boundary layer edge conditions and associated uncertainties were developed based on using two-dimensional, reacting-flow computations of the gas expansion the nozzle with an averaging procedure to account for nonuniform conditions for the flow at the tip of the cone.

Additional experiments in T5 re-examined the effect of free-stream composition alone to avoid the complications of injection. Using a careful experimental protocol, experiments with air- CO_2 test gases and no injection show a significant increase in boundary layer transition distance with increasing CO_2 content and conclusively demonstrate the importance of including vibrational damping

effects when predicting critical N-factors in hypervelocity flows. These experiments also obtained high-quality times series measurements of heat flux over the cone surface that were used to visualize and quantify turbulent spot propagation. Examination of the present and past data on transition with statistical methods indicated that the most significant parameter affecting transition is not reservoir enthalpy but reservoir pressure.

Experiments were conducted in the Caltech Mach 4 Ludwieg tube using a scale model of the cone used in the T5 study to examine the fluid dynamics of injection without non-equilibrium effects. Immediate transition with injection using a conical injector was observed for all injection rates. The effect of shaping the injector according to a proposal by Fedorov was also examined. Injection with a cylindrical injector does not cause immediate transition and the injection rate can be tuned to minimize the disturbance to the external flow. However, the injection layer downstream of injection is still observed to be unstable and we identify the characterization of this instability as a critical issue for future study. Preliminary experimental and computational analysis suggest that the primary instability at Mach 4 cold flow is not caused by Mack's second mode but is instead a result of the first mode, or Tollmein-Schlichting waves. This is new finding and is in contrast to the results of Fedorov and Soudakov for T5 conditions, who found that instability was due to the modes that were similar to the second (and higher) Mack modes.

In conclusion, we have explored with both experiment and computation the idea of using vibrational relaxation to delay boundary layer transition on a slender body in hypervelocity flow. The concept has a sound physical basis that can be explained using simple models of molecular energy exchange. We have shown that with appropriate experimental protocols, it is possible to carry out repeatable transition experiments in a reflected shock tunnel. For pre-mixed air/CO₂ flows, we have demonstrated significant increases in transition location (compared to pure air) when expressed in terms of transition distance normalized by boundary layer thickness or in terms of transition location Reynolds number. However, using porous wall injectors creates an unstable shear layer downstream of the injector section even when wall shaping is used to minimize the free stream disturbance associated with flow displacement. Further research is needed on injection techniques that will to minimize the flow disturbance associated with introducing the vibrationally-active gas into the boundary layer. Maintaining laminar flow while obtaining significant concentrations of mixed fluid in the boundary layer is the challenge.

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A Students Supported

A.1 Ph.D.

- Joseph Jewell, Ph.D. in Aeronautics, June 2014. Currently an NRC Postdoctoral Fellow at Wright Patterson Air Force Base
- Neal Bitter, Ph.D. in Aeronautics in progress, anticipated completion June 2015
- Bryan Schmidt, Ph.D. in Aeronautics in progress, anticipated completion June 2016

A.2 M.S.

- Thomas Vezin, MS Aeronautics (Dual degree with Ecole Polytechnique) 2011
- Neal Bitter, MS Aeronautics 2011 - Currently a graduate student at Caltech
- Gregory Smetana, MS Aeronautics 2013 - Currently a graduate student at Caltech
- Neel Nadkarni, MS Aeronautics 2013 - Currently a graduate student at Caltech
- Richard Kennedy, MS Aeronautics 2014 - Currently a graduate student at Ecole Polytechnique
- Jason Schlup, MS Aeronautics 2014 - Currently a graduate student at Caltech

A.3 B.S.

- Stacey Lavine, BS Mechanical Engineering with Aerospace minor 2011
- Srinivasa Bhattaru, California Institute of Technology Summer Student 2014. Currently a senior in Mechanical Engineering at Caltech

A.4 Visitors and Postdoctoral Scholars

- Dirk Heitmann. Postdoctoral scholar in 2014. Currently at TU Braunschweig.
- Patrick Wang. Diploma Student (Universität Stuttgart) in 2013-14. Currently a PhD student at Universität Stuttgart.

B Collaborations

- Dr. Ivett Leyva - Dr. Leyva was a Visiting Associate in Aeronautics at Caltech and Senior Aerospace Engineer at AFRL/RQRE. She participated in the planning and analysis of some experiments carried out in T5. Her participation was sponsored by a separate grant (13RQ14COR) and documented in the separate report AFRL-RQ-ED-TR-2013-0054 published January 2014.
- Prof. Graham Candler, Dr. Ross Wagnild, and Dr. Heath Johnson (University of Minnesota) - Carried out computational analyses of mean flow and boundary layer instability for T5 flows.
- Dr. Dirk Heitmann - Postdoctoral scholar at Caltech from February 2013 to July 2013 supported by DAAD Fellowship from Germany. He carried out research in the Caltech Mach 4 Ludwig tube on transition and stability measurements on capsules. He is continuing to work on supersonic boundary layer stability at Braunschweig.
- Prof. Alexander Fedorov - Visiting Faculty from Moscow Institute of Physics and Technology. Prof. Fedorov visited Caltech in June 2011, April 2012, and June 2013. He presented lectures on boundary layer stability and analysis of T5 injection experiments. Prof. Fedorov and his

colleague Dr. Vitaly Sudakov were separately funded in 2013 by an EOARD grant managed by Dr. Leyva. They carried out stability analyses of boundary layers with mass injection. Dr. Fedorov proposed an alternative injection scheme that was tested at Caltech in 2013-2014.

C Publications

C.1 Archival Journal Articles

- B. E. Schmidt, N. P. Bitter, H. G. Hornung, and J. E. Shepherd. “Gas Injection into Supersonic Boundary Layers.” Submitted to AIAA J., Dec 2014.

C.2 Conferences

- N. J. Parziale, B. E. Schmidt, J. S. Damazo, P. S. Wang, H. G. Hornung, and J. E. Shepherd “Pulsed Laser Diode for use as a Light Source for Short-Exposure, High-Frame-Rate Flow Visualization.” To be presented at the 52nd AIAA Aerospace Sciences Meeting, 13-17 January 2014, National Harbor, MD.
- N. J. Parziale, J. S. Jewell, I. A. Leyva, and J. E. Shepherd “Effects of Shock-Tube Cleanliness on Slender-Body Hypersonic Instability and Transition Studies at High Enthalpy.” To be presented at the 52nd AIAA Aerospace Sciences Meeting, 13-17 January 2014, National Harbor, MD.
- B. E. Schmidt, N. P. Bitter, H. G. Hornung, J. E. Shepherd “Experimental Investigation of Gas Injection into the Boundary Layer on a Slender Body in Supersonic Flow.” 7th AIAA Theoretical Fluid Mechanics Conference, Atlanta, GA, 16-20 June, 2014. Paper AIAA 2014-2496 <http://dx.doi.org/10.2514/6.2014-2496>
- N. P. Bitter and J. E. Shepherd “Transient Growth in Hypervelocity Boundary Layers.” 7th AIAA Theoretical Fluid Mechanics Conference, Atlanta, GA, 16-20 June, 2014. Paper AIAA 2014-2497 <http://dx.doi.org/10.2514/6.2014-2497>
- J. S. Jewell, J. E. Shepherd, and I. A. Leyva. “Shock tunnel operation and correlation of boundary layer transition on a cone in hypervelocity flow.” In Proceedings of the 29th Symposium on Shock Waves, July 14-19, 2013, Madison, WI. Paper No. 300, 2013
- Jewell JS, Wagnild RM, Leyva IA, Candler GV, Shepherd JE. 2013 “Transition within a hypervelocity boundary layer on a 5-degree half-angle cone in air/CO₂ mixtures.” 51st AIAA Aerospace Sciences Meeting, Grapevine, TX. AIAA Paper No. 2013-0523
- Jewell J, Wagnild R, Leyva I, Candler G, Shepherd JE. 2012. “Transition within a hypervelocity boundary layer on a 5-degree half-angle cone in free stream air/CO₂ mixtures.” 64th Annual Meeting of the Division of Fluid Dynamics, Baltimore, Maryland. Bulletin of the American Physical Society, 57(17) Abstract BAPS.2012.DFD.D27.10
- Jewell JS, Parziale NJ, Leyva IA, Shepherd JE. 2012. “Turbulent spot observations within a hypervelocity boundary layer on a thin cone.” 42nd AIAA Fluid Dynamics Conference and Exhibit New Orleans, La. AIAA Paper No. 2012-3036
- Jewell, JS, Leyva, IA, Parziale, NJ, Shepherd, JE. 2011 “Effect of Gas Injection on Transition in Hypervelocity Boundary Layers.” Presented at the 28th International Symposium on Shock Waves. Manchester, UK. July 2011.

C.3 Ph.D. Thesis

- J. S. Jewell “Boundary-Layer Transition on a Slender Cone in Hypervelocity Flow with Real Gas Effects.” Ph.D. thesis. California Institute of Technology, Pasadena, CA. 2014.

C.4 Reports

- B. E. Schmidt, “Compressible Flow Through Porous Media with Application to Injection.” Technical Report, California Institute of Technology, Pasadena, CA, June 2014, GALCIT Report FM2014.001
- Jewell, J. S. and Shepherd, J. E., “T5 Conditions Report: Shots 25262823.” Technical Report, California Institute of Technology, Pasadena, CA, June 2014, GALCIT Report FM2014.002.
- S. A. Bhattarai, J. E. Shepherd, B. E. Schmidt “Design, Construction, and Testing of A Focused Laser Differential Interferometry Setup.” Summer Undergraduate Research Project Report, California Institute of Technology, Oct 2014.
- Alexander V. Fedorov and Vitaly G. Soudakov “Theoretical-Numerical Analysis of Boundary-Layer Stability with Combined Injection and Acoustic Absorptive Coating.” Final Report on EOARD GRANT No. FA8655-12-D-0003, Moscow Institute of Physics and Technology, January 2014. Addendum on Feb 7, 2014.
- P. Wang, “Experimental Analysis of Supersonic Flow on a Concave Surface.” Diplomarbeit, Institut für Aerodynamik und Gasdynamik, Universität Stuttgart, Deutschland, Sept 8, 2013.
- D. Heitmann “Transition and stability measurements in hypervelocity flow around capsule-shaped re-entry bodies.” Final Report on Project DAAD-PKZ: D/12/43796, Sept 15, 2013.
- R. Kennedy and J. Schlup. “New Starting Device for GALCIT Ludwig tube.” California Institute of Technology, Pasadena, CA, Ae104c Project Report, June 5, 2014.
- G. Smetana and N. Nadkarni. “Ultrasonic wave propagation in high temperature gases.” California Institute of Technology, Pasadena, CA, Ae104c Project Report. July 22, 2013.
- T. Vezin, S. Levine, N. Bitter “Optical and Pressure Measurements of Tunnel Noise in the Ludwig Tube.” California Institute of Technology, Pasadena, CA, Ae104c Project Report. June 3, 2011