ULTRASONICALLY ABSORPTIVE COATINGS FOR HYPERSONIC LAMINAR FLOW CONTROL

AFOSR CONTRACT NO. FA9550-06-C-0097

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Abstract
Laminar flow control (LFC) technologies reduce heat-transfer rates as well as the weight and complexity of thermal protection system (TPS). The laminar run can be substantially increased using an ultrasonically absorptive coating (UAC). The project is focused on maturing of the UAC-LFC methodology. Key components of the effort include wind-tunnel experiments, theoretical analysis, direct numerical simulation, fabrication and testing of ceramic materials that integrate UAC and TPS functions. To aid in the design of UAC with regular microstructure to be tested the CUBRC LENS I tunnel, parametric studies of the UAC-LFC performance have been conducted. The UAC parameters providing significant (more than twice) increase of the laminar run were predicted. Our theoretical model dealing with UAC of random microstructure has been refined. Direct numerical simulation of UAC roughness and pore-end effects has been started. A method of ceramic UAC fabrication was formulated and first ceramic UAC samples were made. An apparatus for benchmark measurements of UAC ultrasonic absorption was assembled and its robustness was demonstrated at low ambient pressures relevant to high-altitude flight conditions. The cone model with the felt-metal coating has been prepared for transition experiments in the ITAM AT-303 tunnel at Mach=8. The UAC-LFC technology is now approaching the large-scale demonstration stage in the CUBRC LENS tunnel as well as fabrication of ceramic UAC samples integrated into TPS.

Summary
The project combines experimental, theoretical, direct numerical simulations (DNS) and material development efforts. Together, these four components will produce the enabling technology and design tools as well as provide a basis for design of UAC-TPS test articles that could be manufactured and deployed on an actual flight vehicle. The major objectives of the three-year effort are:

- Demonstrate UAC-LFC robustness on large-scale cone models in hypersonic wind tunnels
- Improve modeling of UAC performance by investigating pore-end and roughness effects
- Optimize UAC for practical ranges of hypersonic flight conditions
- Design and fabricate materials providing integrated UAC and TPS functions
- Develop UAC-TPS design toolbox for technology transfer

The progress that has been made since December 2006 is summarized hereafter.

† PI of this project Dr. Norman Malmuth passed away on July 3, 2007

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14. ABSTRACT

Laminar flow control (LFC) technologies reduce heat-transfer rates as well as the weight and complexity of thermal protection system (TPS). The laminar run can be substantially increased using an ultrasonically absorptive coating (UAC). The project is focused on maturing of the UAC-LFC methodology. Key components of the effort include wind-tunnel experiments, theoretical analysis, direct numerical simulation, fabrication and testing of ceramic materials that integrate UAC and TPS functions. To aid in the design of UAC with regular microstructure to be tested the CUBRC LENS I tunnel, parametric studies of the UAC-LFC performance have been conducted. The UAC parameters providing significant (more than twice) increase of the laminar run were predicted. Our theoretical model dealing with UAC of random microstructure has been refined. Direct numerical simulation of UAC roughness and pore-end effects has been started. A method of ceramic UAC fabrication was formulated and first ceramic UAC samples were made. An apparatus for benchmark measurements of UAC ultrasonic absorption was

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Parametric Studies of UAC Performance To aid in the design of metallic UAC to be tested on a 7-degree half-angle cone in the CUBRC LENS I shock tunnel, parametric studies of the coating laminar-flow-control performance have been conducted for Mach=7 and Mach=10 free-stream conditions [1]. The second-mode amplification factors, N, were calculated using the reduced-order computational package that includes the compressible Blasius mean flow and the local-parallel linear stability solver. It was shown that these N-factors agree very well with those predicted by the STABL solver [2] (Figure 1).

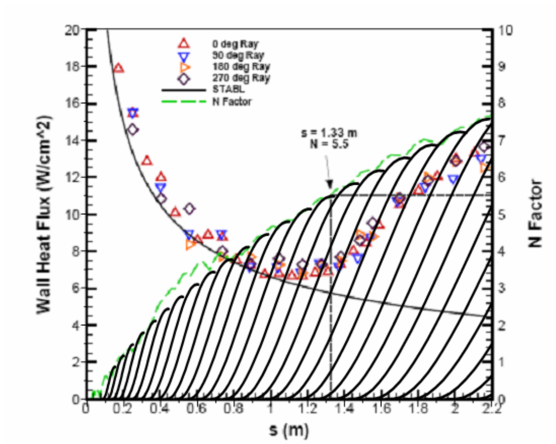

Figure 1: Comparison of N-factors predicted by STABL (dashed green line) with our calculations (family of solid black lines) for Run 22 (sharp cone, Ref. 2); s – longitudinal coordinate measured along the cone surface.

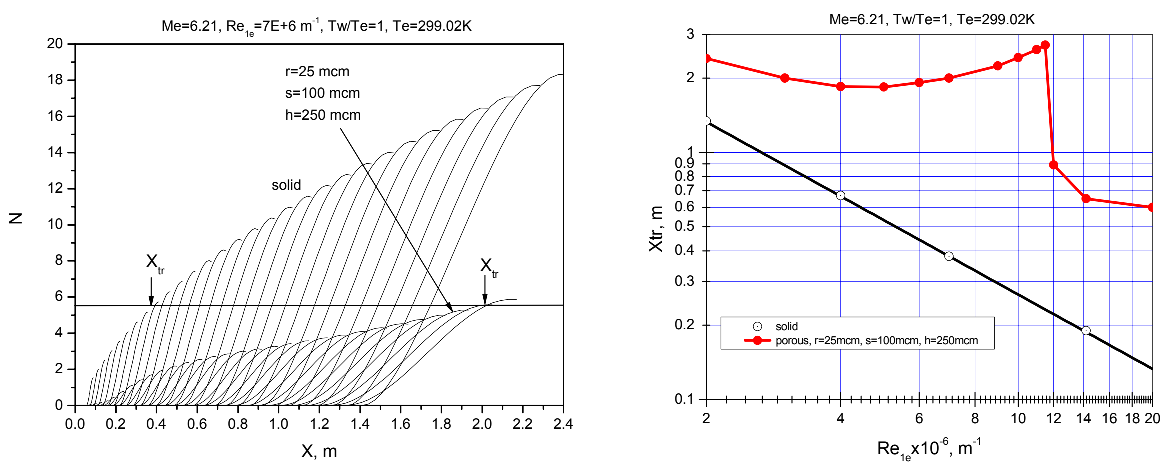

Figure 2: Left panel – second-mode N-factors for solid and porous walls at the local unit Reynolds number $\mathrm{Re}_{1e} = 7 \times 10^6\ \mathrm{m}^{-1}$ and freestream Mach number $M_\infty = 7.14$; right panel – transition onset point X_{tr} as a function of Re_{1e} for solid (black line) and porous (red line) walls at $M_\infty = 7.14$.

This allows us to conduct quick parametric studies and search for optimal UAC parameters. Stability calculations were carried out for the uncoated (solid) and coated (porous) wall. The metallic UAC of regular microstructure, which comprises equally spaced vertical cylindrical blind micro-holes of fixed radius *r*, spacing *s* and depth *h*, has been analyzed. The UAC parameters, at which the coating leads to significant (more than twice) increase of the laminar run, were determined. As an example, Figure 2 shows the second-mode *N*-factors (left panel) and predicted transition onset point (right panel) for solid and porous walls at Mach 7.14. Estimates of the UAC roughness effect indicate that the coating can be treated as aerodynamically smooth in the unit Reynolds number range relevant to the LENS I conditions. These results provide a good launching pad for design and manufacturing of a large-scale cone model for transition loci measurements.

Along with the parametric studies for UAC of *regular* structure, we refine our theoretical model [3] dealing with UAC of *random* microstructure. Using averaging of flow characteristics over the volume of elementary cell we derived from first principles an approximate form of differential conservation laws for porous media. These equations contain the transport coefficients that will be determined using methods of kinetic theory. The acoustic problem, which describes absorption of sound by highly porous fibrous materials, was formulated. Solution of this problem will allow us to obtain more general relationships for the boundary conditions on the UAC surface.

CFD modeling Two-dimensional DNS of the UAC stabilization effect has been carried out for near-wall flows over a flat plate and sharp cone at Mach=6 [4]. The unsteady Navier-Stokes equations were solved using the porous-wall boundary conditions resulted from our theoretical model [5]. Numerical solutions agree satisfactory with the linear stability theory (Figure 3). The coating end effects, which are associated with discontinuity of boundary conditions at the juncture between solid and porous walls, were simulated. It was shown that these effects are localized over 2-3 disturbance wavelength and can be neglected in calculations of the integral UAC performance.

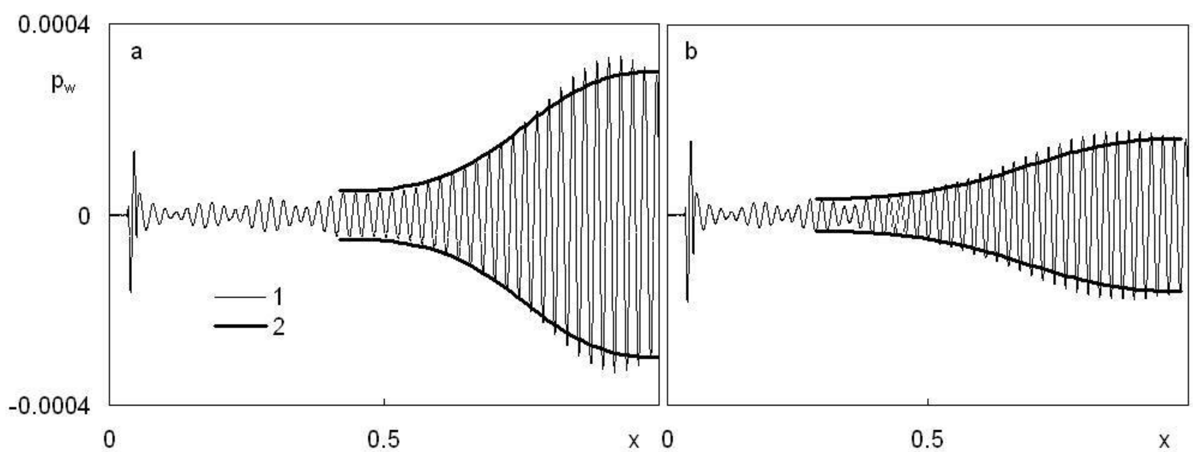

Figure 3: Pressure disturbances on solid (a) and porous (b) wall, flat plate at $M_\infty = 6$, $\mathrm{Re}_\infty = 2\times10^6$; 1 – numerical solution, 2 – stability theory.

The CFD effort also seeks to validate and improve existing porous-wall boundary-condition models. We use DNS to investigate in detail the flow in individual and groups of equally-space micro-holes on the surface under a transitional boundary layer. Comparisons of both 2-D and 3-D simulations with stability theory will allow the boundary-condition models to be validated and, where necessary, improved.

Some tradeoffs are required in order to deduce a set of computationally tractable model problems, since a realistic surface would have as many as 20 pores per wavelength of the most unstable wave. We believe that a simplified configuration that considers a temporally evolving boundary layer on an infinite flat plate with UAC will retain enough of the relevant flow physics. The temporally evolving boundary layer neglects the spatial growth of the boundary layer, and instead diffuses slowly with time. Over short time-scales associated with acoustic energy attenuation in UAC, the laminar boundary layer is essentially frozen, consistent with either a spatial or temporal description of the mean flow field, and consistent with parallel flow approximations that are typically made in instability calculations. The temporal transformation is depicted in Figure 4. Spatial evolution (a) would require that a large number of pores be considered in order to resolve the many wavelengths of instability wave. On the other hand, the detailed physics associated with UAC all occur over a single wavelength of the instability wave (b).

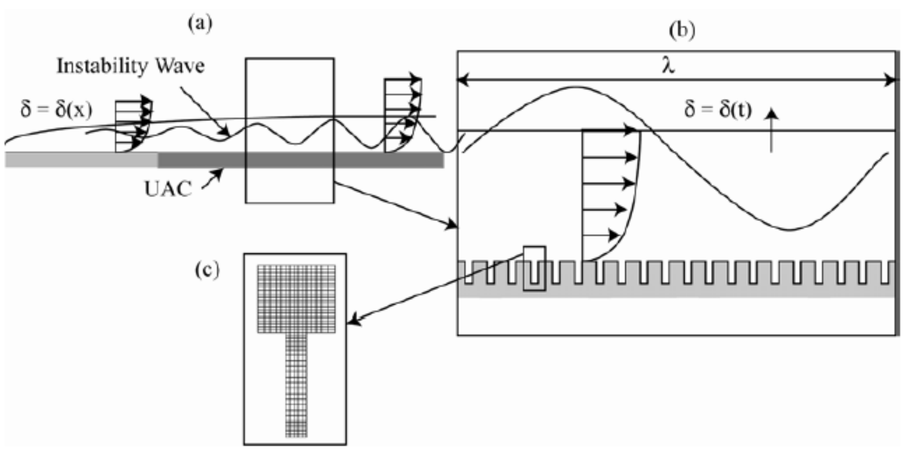

Figure 4: Schematic diagram for DNS of UAC (not to scale). (a) the spatial problem with many wavelengths of the spatially growing instability wave; (b) the temporal problem with a single wavelength of the temporally growing instability wave; (c) a portion of the computational grid around a single pore.

The full compressible Navier-Stokes code [6] has been modified to model the flow in individual and groups of equally-spaced micro-holes in a rigid surface under a transitional boundary layer. We assume shock-free flow and use high-order accurate compact finite difference schemes for streamwise and normal directions, and Fourier-spectral differentiation for homogeneous directions (when present). Two-dimensional DNS of hypersonic boundary layers over a standard no-slip has have been performed to validate the use of the temporally-evolving assumption on both the mean flow profile and instability wave development. A temporal linear stability analysis is conducted for a compressible boundary layer on a flat plate at free-stream Mach number $M_\infty = 6$ and different Reynolds numbers. In the preliminary work presented here, we have used constant viscosity and conductivity. Computations show that instabilities develop under certain conditions, and that the most amplified mode has a streamwise wavelength $\lambda/\delta = 2.5$ (δ – boundary-layer thickness), with frequency parameter $F \equiv \omega\delta^* / U_\infty = 1.35$ (δ^* – displacement thickness) and phase velocity $0.9U_\infty$. These results are consistent with experimental and numerical observations that the most amplified second-mode wavelength is approximately twice the boundary-layer thickness, and that its phase velocity is close the boundary-layer edge velocity of the mean flow. They are in good agreement with the temporal linear stability theory (see Table). However, the spatial growth rates, which are calculated using Gaster transformation of the temporal growth rate, are underestimated by the temporal analysis. In future work, the possible sources of the discrepancies on the instability growth rate between the two methods will be investigated, and the temperature dependence of viscosity and conductivity will be implemented.

Run	Parameters					Linear stability				
	δ^*/δ	M_∞	T_w/T_∞	Re_{δ^*}	Re_δ	λ/δ	$\sigma_T\delta^*/U_\infty$	$\omega\delta^*/U_\infty$	U_{phase}/U_∞	
Case 1	0.600	6	1.4	2380	4000	2.5	5.02e-4	1.34	0.898	DNS
						2.5	4.80e-4	1.34	0.898	ARPACK*
Case 2	0.595	6	1.4	4300	7000	2.5	7.95e-3	1.36	0.900	DNS
						2.5	7.95e-3	1.36	0.900	ARPACK*

*ARPARCK software directly searches for eigenmodes using an Arnoldi method [7]
$\sigma_T\delta^*/U_\infty$ – temporal growth rate

Ceramic UAC development The goal in this program is to develop and demonstrate a suitable fabrication method on test panels of dimension ~ $6'' \times 6''$ as well as to perform benchmark measurements of ultrasonic absorption and other relevant mechanical properties that provide a direct link to the UAC modeling and wind-tunnel testing of metallic UAC. The choice of materials and processing methods is constrained to those that could be reasonably scaled up in a follow-on program to manufacture large panels for wind-tunnel or flight testing.

The effort has been focused on coatings with porosity resembling an ideal geometry of regularly spaced blind holes, formed by adding a layer containing the holes to an existing rigid fibrous TPS tile with a smooth dense surface layer (i.e., reaction-cured glass as in space shuttle tiles). We have procured four shuttle tiles to use as substrates to make test specimens for the program. We investigated heat treatment schedules that will allow us to sinter the coating to the existing tile surface. This is key to our approach as the right conditions must be found to promote enough flow of the glass frit to produce smooth crack-free coatings that adhere well to the existing coating.

A mold master, that allows us to fabricate epoxy molds for stamping the desired patterned on the tile surface, is a laser-drilled stainless steel plate. The $2'' \times 2''$ plates are used for testing the concept of making stamp materials (Figure 4). They are approximately 0.5 mm thick and the holes were tapered through the thickness with a maximum diameter of 200 μm and a minimum diameter of approximately 100 μm. A negative structure is an epoxy sheet with protruding posts as shown in Figure 4. As a next step we use the epoxy master to produce holes in the glass tile coating with the following process: (i) spread RCG slurry in 0.5-1mm thickness on tile surface,

(ii) place epoxy sheet with posts atop the slurry, (iii) place the assembly in a heated platen press to dry the slurry under slight pressure so the epoxy posts rest atop the tile surface, (iv) fire the assembly to burn out the epoxy and leave holes in the coating. The initial trials give the ceramic UAC shown in Figure 4.

To conduct benchmark measurements of UAC ultrasonic absorption, we have assembled an experimental setup shown in Figure 5a. The test plates are a flat solid metal plate of 560 μm thick perforated plate with approximately 100 μm diameter holes. We use a pitch-catch arrangement in which the transmitted ultrasound beam is incident on the plate at ~30° angle. The reflected beam is incident on a symmetrically-located receiving transducer. The setup is covered by the bell jar, and the ambient pressure can be reduced to 1 mBar level using a vacuum pump.

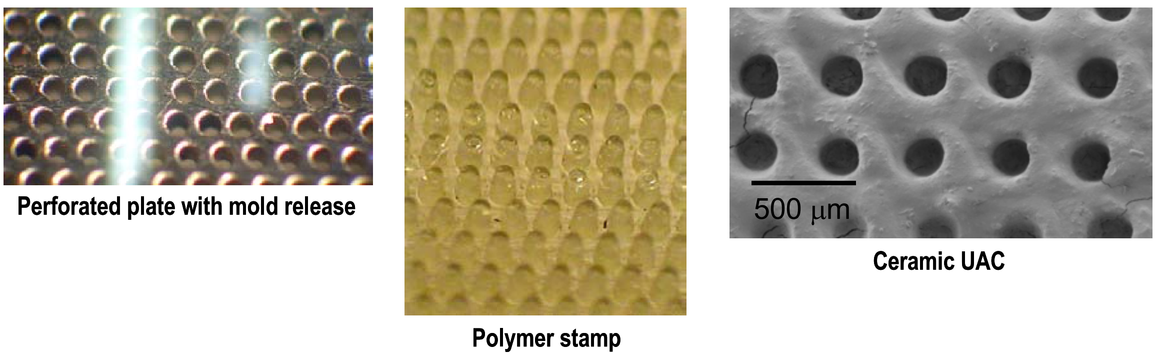

Figure 4: Perforated metallic plate, polymer stamp and ceramic UAC.

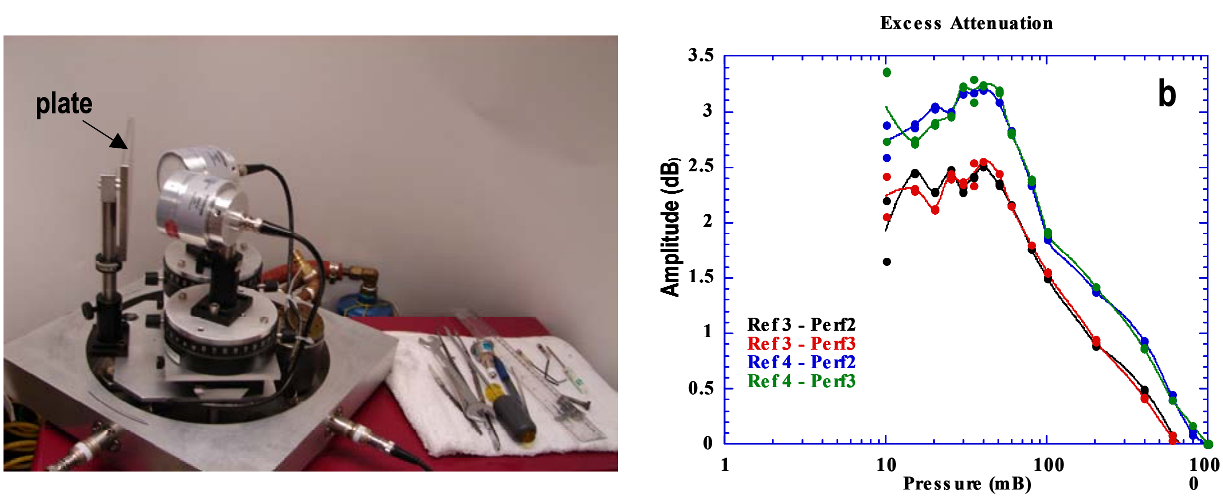

Figure 5: (a) – experimental setup and (b) – preliminary data of benchmark measurements of UAC ultrasonic absorption.

The first set of measurements is acquired on the solid plate. The peak-to-peak amplitude of the received signal is recorded at various ambient pressures. Then the solid plate is replaced with a perforated plate and a second set of data is acquired. The perforated plate data are subtracted from the solid plate data to obtain the excess attenuation versus ambient pressure. Preliminary results (Figure 5b) indicate that it is feasible to conduct measurements at ambient pressures as low as 10 mBar. This allows us to evaluate ultrasonic absorption of UAC-TPS samples at pressures relevant to high-altitude flight conditions.

Wind-tunnel experiments Transition measurements on a 7º half-angle cone will be conducted in the ITAM AT-303 hypersonic wind tunnel in October-November 2007. The cone model, which has one half of its surface solid and the other half covered by the felt-metal coating of random microstructure (Figure 6), has been modified. Namely, the exchangeable noses with the bluntness radii $r_b = 1, 2, 4$ and 8 mm have been designed, and their manufacturing is in progress. The UAC surface was examined and cleaned. The protruded filaments were removed. The system for unsteady calibration of the heat flux gages was assembled and tested. To improve free stream quality, a new heating element was manufactured, installed into the AT-303 and tested at Mach 12. In addition, the new contoured nozzle is designed for Mach 8. This nozzle will be manufactured and tested in the first phase of this project.

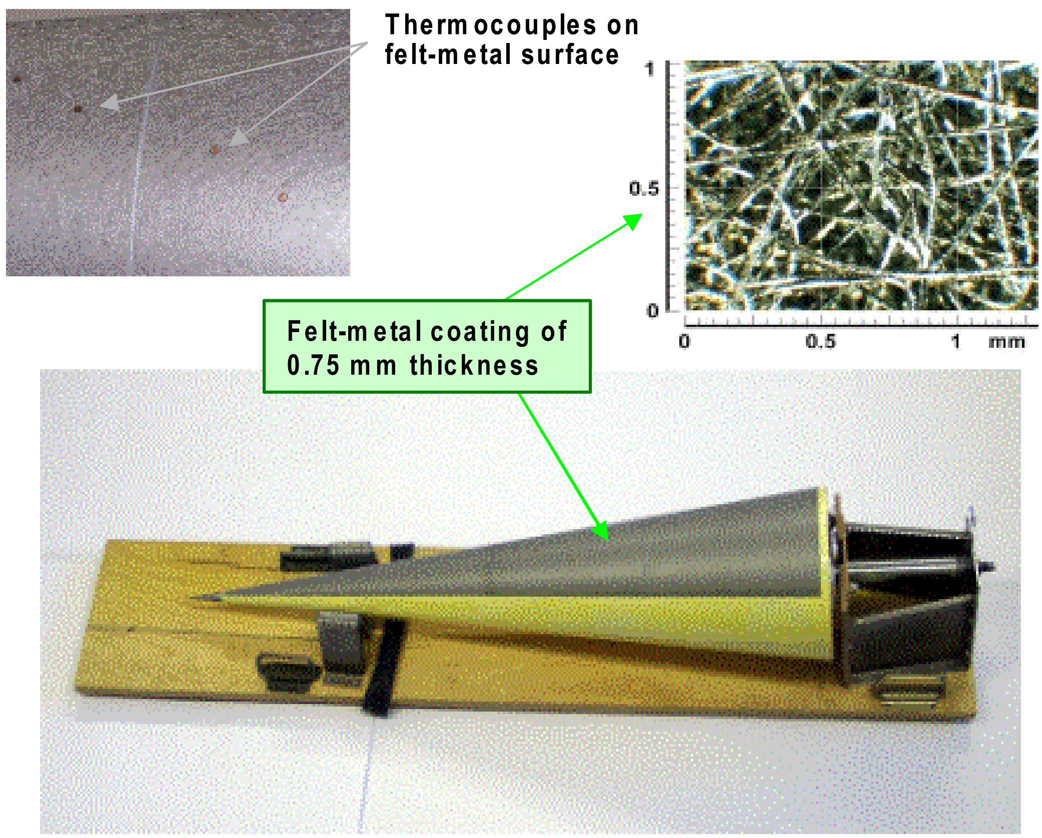

Figure 6: The cone model of 1 m length with the felt-metal coating on one half of its surface will be tested in the ITAM AT-303 wind tunnel.

To design the cone model with UAC for tests in the CUBRC LENS I tunnel, CUBRC shared with the team members data and analysis [2] from the FRESH and Army Inlet Program studies of transition. These data were used for calibration of our stability code. Additional results from the FRESH program will be communicated and discussed with the team members as they become available.

Acknowledgment/Disclaimer

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Publications

"Direct Numerical Simulation of Supersonic Boundary-Layer Stabilization by Porous Coating," Egorov, I.V., Fedorov, A.V., Novikov, A.V., and Soudakov, V.G., AIAA Paper No. 2007-948, Reno, Nevada, 8-11 Jan. 2007.

"Parametric Studies of Hypersonic Laminar Flow Control Using a Porous Coating of Regular Microstructure," A.V. Fedorov and N.D. Malmuth, accepted to 46th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, 7-10 Jan. 2008.

Honors & Awards Received by Dr. Norman D. Malmuth

- Julian Cole Honorary Lecture in Theoretical Fluid Mechanics, AIAA Fluid Dynamics, AIAA 4th Theoretical Fluid Mechanics Meeting, June 6-9, 2005
- Caltech Visiting Associate, 2001-present
- Fellow, American Physical Society, (January 1, 2000)
- Member of AGARD Fluid Dynamics Panel, (1995-1998)
- Fellow, AIAA, (December, 1994)
- AIAA Aerodynamics Award, (September 1991).
- Outstanding Alumnus Award, University of Cincinnati, (October, 1990)

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Transitions

Our transition prediction techniques are being applied to hypersonic vehicles by Don Picetti and others of Boeing and are now being part of Boeing's automated design program (BVIDs)

New Discoveries and Patents

"Absorbing Wall for Hypersonic Boundary Layer Control," 5,884,871, patent issued March 1999