

Characterization of the Flow Field Over an Ablative Surface

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Why do we care?

Of great practical interest and concern in aerospace engineering; coastal engineering (beach erosion, bridge scouring); petroleum transport research (pipe corrosion); and geophysics (deserts, glaciers)

Understanding underlying physical processes of flow-induced erosion is important for:

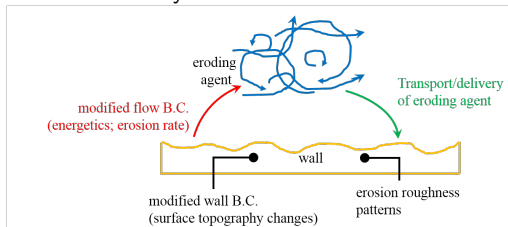
- accurately predicting (using physics based models) the onset of erosion,
- analyzing degradation of an eroding material after onset, and
- designing cost effective erosion preventative measures thereby reducing infrastructure maintenance costs.

Problem

- Most research to date has focused on predictive models for the onset of erosion
- These models are ill-equipped to capture non-equilibrium coupled dynamics between the eroding flow and the erodible material

Complexities of Studying Erosion

Two-way feedback mechanisms



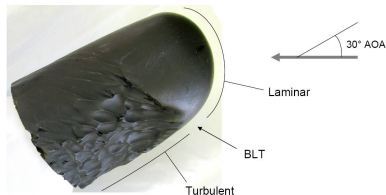
What makes understanding erosion difficult?

- Multi-physics systems (material science, chemistry, fluid mechanics, etc.)
- Driving force for transport of eroding agent (heat, shear, chemical, particles) is turbulent flow
- Non-equilibrium system (dynamic boundary conditions)

It is the feedback loop that current models are neglecting because of a lack of experimental data for model validation.

Observed Growth of Non-Uniform Surface Topography During Turbulent Flow Ablation

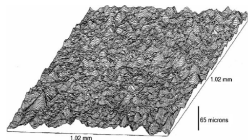
Intermediate Re \rightarrow transition near sonic point



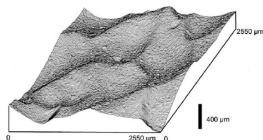
(Plaster cast replica; Charles Povars photo)

Low Temperature Ablator (Camphor) in Naval Ordnance Laboratory (NOL) Hypersonic Wind Tunnel #8, photo from Charles Powers.

Laminar flow



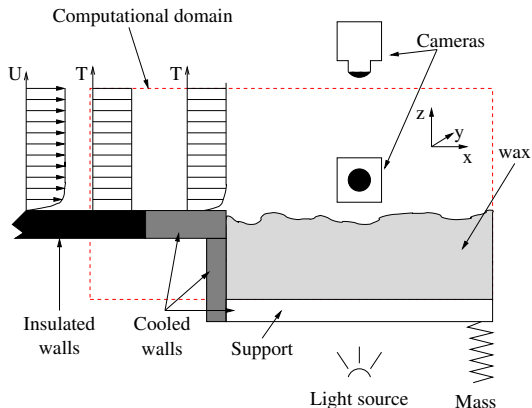
Turbulent flow



Surface topographies of polycrystalline graphite samples ablated under different flow regimes.

Vignoles *et al.*, *Composites Science and Technology*, **69**:1470, 2009

Project Overview



- Spatially heated boundary layer flow.
- Several variations of the inlet conditions, both for flow and temperature.
- Paraffin wax used as ablated material due to its low melt point temperature (other non-melting low temperature ablaters are being considered as well)
- Collaborative numerical (UVM) and experimental (UNH) investigation.

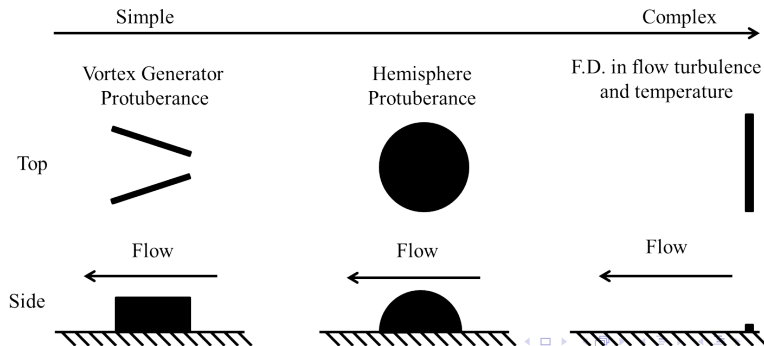
Research Objectives

- Develop and verify experimental techniques to *simultaneously* measure flow dynamics and wall erosion with sufficient spatial and temporal resolution needed to understand underlying physical processes at work
- Synthesize and analyze the experimental datasets to understand the underlying physics
- Develop and verify a reduced model for describing the nonlinear, coupled fluid-surface interactions after onset of erosion to predict the erosion rate based on initial and boundary conditions.

Systematic Approach

Recall that flow-induced roughness patterns develop on an eroding surface. These flow-induced roughness patterns are indicative of coherent structures within the flow (i.e. are their integrated footprints).

So, we will first isolate important flow features such that they are controlled in order to understand their individual effect on erosion.



Experimental Facility

In order to study this phenomena a low-Reynolds number boundary layer open-circuit wind tunnel has been constructed and renovated to include an electric resistive heater bank and seeding manifold for particle image velocimetry (PIV) measurements and flow visualizations.

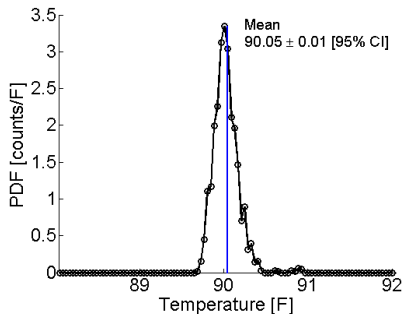
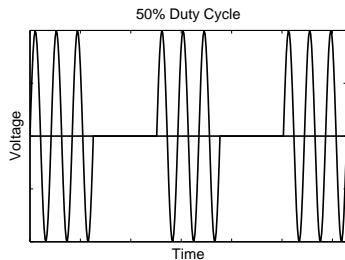


Specifications

- 4:1 contraction section
- Turbulent management section: honeycomb and 4 screens of decreasing mesh size.
- Test section: 305mm \times 140mm cross-section and 2.75m length
- Ducted exhaust section
- $1.7 \times 10^5 \lesssim Re_L \lesssim 1.7 \times 10^6$
- $660 \lesssim Re_{\delta^*} \lesssim 5020$
- $390 \lesssim Re_{\theta} \lesssim 3715$
- $\delta_{99} \mathcal{O}(1 - 5.5\text{cm})$

Heating Section

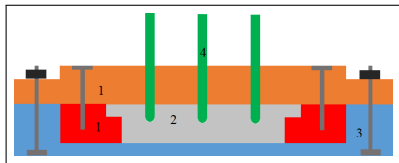
- Heating bank consists of nine sheathed resistive heaters with fins.
- A silicon controlled rectifier (SCR) along with a PID controller with feedback from a thermocouple in the free stream at the measurement location were able to keep the free stream temperature within $\pm 0.01^\circ F$ [95% CI].
- Another benefit of the SCR is it sets a duty cycle for the heaters which prolongs their life cycle.



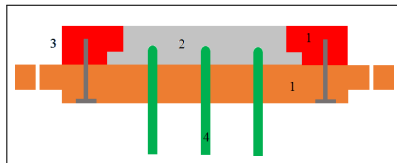
Erodible Material

Currently paraffin wax is used for an ablator because of its low melting temperature, however, will likely switch to naphthalene or camphor because they sublime.

Molding Process:



- 1. Molding Die
- 2. Paraffin Wax



- 3. Molding Cover
- 4. Thermocouple

It will be flush mounted with the floor of the wind tunnel.

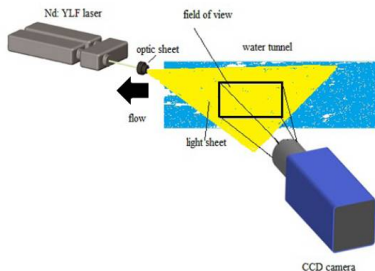
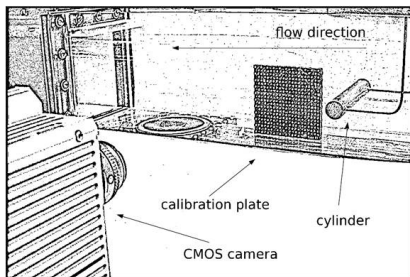
High Speed Particle Image Velocimetry

System Specifications

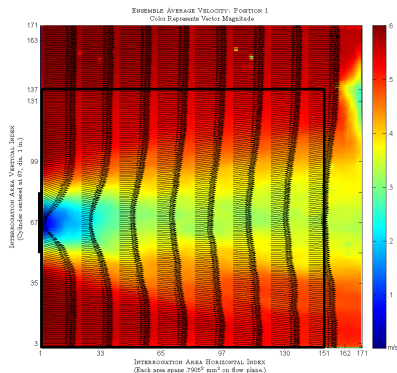
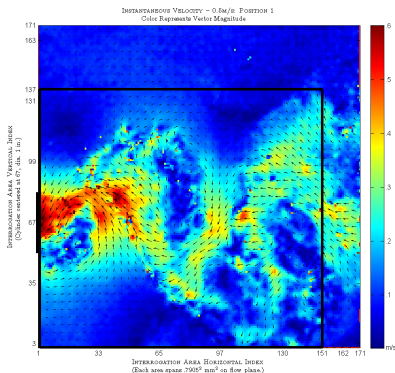
- Twin Photonics Diode-Pumped Nd:YLF lasers
Repetition rates 500Hz to 10KHz
- 2 Photron FastCAM 12-bit 1024×1024 pixel² CMOS cameras.
Repetition rates of 3.6kHz full scale and up to 500KHz at 128×16 pixel².

Example HPIV: Cylinder in cross-flow

$Re_d \approx 7000$, Sampling Frequency 500 Hz, Sampling duration is 1 second.



Example HPIV Results

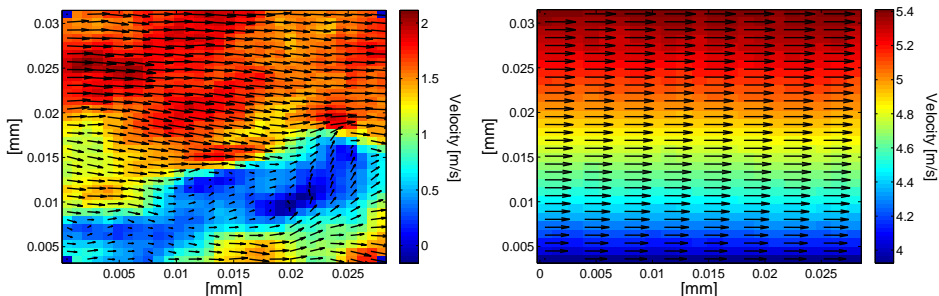


- (left) a representative instantaneous PIV vector plot $u - U_\infty$.
- (right) ensemble average PIV vector plot (data shown every 4th column)

Flow Characterization

Example High Speed Particle Image Velocimetry: Flow over a smooth boundary in rear of tunnel

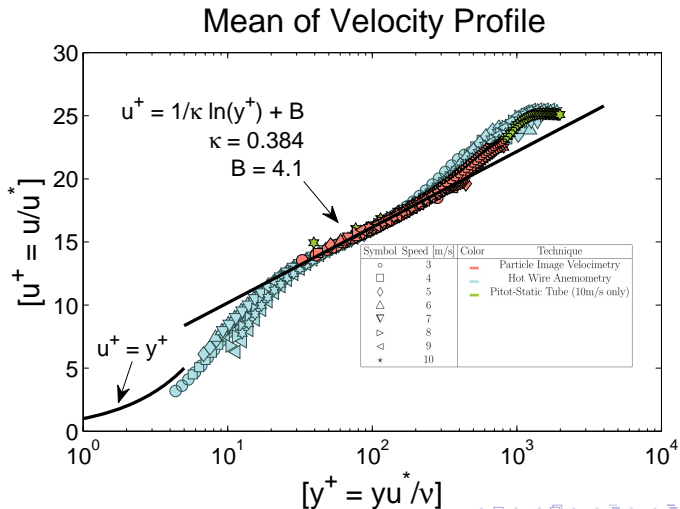
$Re_L \approx 1 \times 10^6$, Sampling Frequency 3600 Hz, Sampling duration ≈ 1.5 s.



- (left) a representative instantaneous PIV vector plot (6m/s) with 4.2m/s convective velocity subtracted from mean $u - U_\infty$.
- (right) ensemble average PIV vector plot (data shown every 4th column)

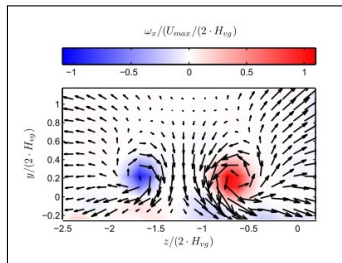
Flow Characterization

The velocity in the rear of the tunnel was characterized using pitot-static tube, hot wire anemometry, and PIV.

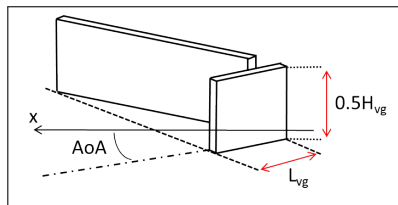


Qualitative Ablation Experiments

- Case 1: Postage stamp mold was placed 46cm from trip/turbulent management system
- Case 2: Rectangular winglet vortex generator was placed 1.25cm upstream at the leading edge of the postage stamp mold
- Case 1 and 2: Free stream temperature was slowly increased from 90°F until visual changes occurred on the surface of the wax



Ensembled Avg. PIV meas.

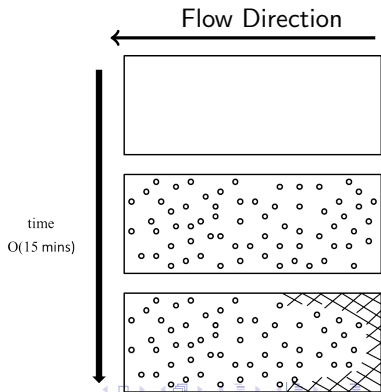
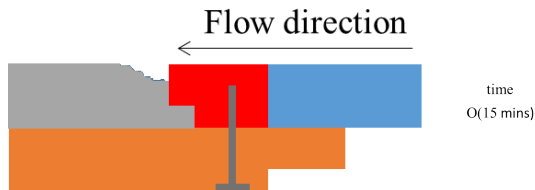


Rectangular winglet vortex gen.
 ($L_{vg} = 4\text{cm}$, $H_{vg} = 2.2\text{cm}$, $\text{AoA} = 20^{\circ}$)

Qualitative Ablation Observations

Transitional flow ($Re_x = 1.5 \times 10^5$) (160°F free stream temperature)

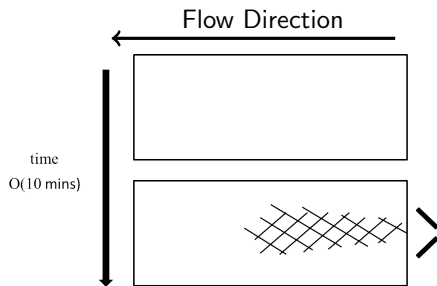
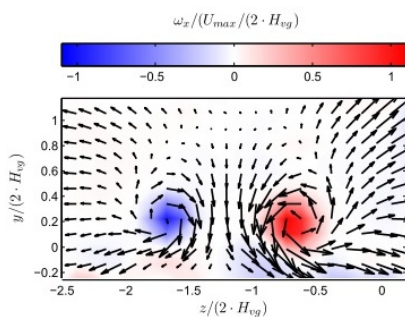
- 1. Postage stamp paraffin wax mold begins to “sweat” over the entire surface
- 2. Leading edge begins to melt and form a liquid layer
- 3. Sidewalls near the corners of the wax mold begin to melt.



Qualitative Ablation Observations

Vortex Generator (140°F free stream temperature)

- 1. Liquid layer vee-groove began melting in the middle of the specimen where the greatest downward flow is impinging the surface.



Insight from observations

- Heating system is able to keep the free stream temperature nearly constant.
- Wax molds were non-homogeneous (air pockets); therefore the molding process will need to be refined.
- Re-design the test mold postage stamp specimens to reduce the effects of a backward facing step when the material at the leading edge begins to ablate.
- Ablation rates were “relatively” slow.
- To increase the ablation rate will increase the heat flux.
- Liquid layer forms when wax melts causing potential measurement complications.
- Switch mold material to naphthalene or camphor, two more commonly used materials to study ablation because they sublime at low temperatures.

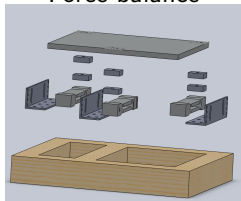
Ablation Measurements

In order to characterize the ablation rate and surface topography evolution of the ablative material, three different measurements methods will be used:

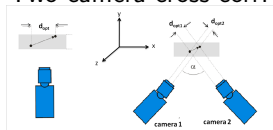
Methods

- 1. Pre vs. Post-experiment surface profilometry
- 2. Experimental force balance (time dependent integral measurement)
- 3. Two-camera cross-correlation or Moiré fringe projection (time dependent local measurement).

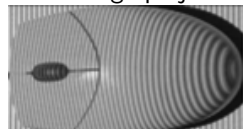
Force balance



Two-camera cross-corr.



Moiré fringe projection



Gorthi, S. S. and Rastogi, Fringe Projection Techniques: Whither we are? P. Optics and Lasers in Engineering, 48(2):133-140, 2010

Future Work

- Address concerns from qualitative ablation experiments.
- Control the thermal conditions of the postage stamp specimens by keeping the bottom surface at a constant temperature.
- Test and validate the three proposed approaches to measure ablation.
- Acquire simultaneous temperature and velocity profiles over the ablative surface as it is eroding.