Development of a Particle Erosion Model for Silicon Microchannel Coolers

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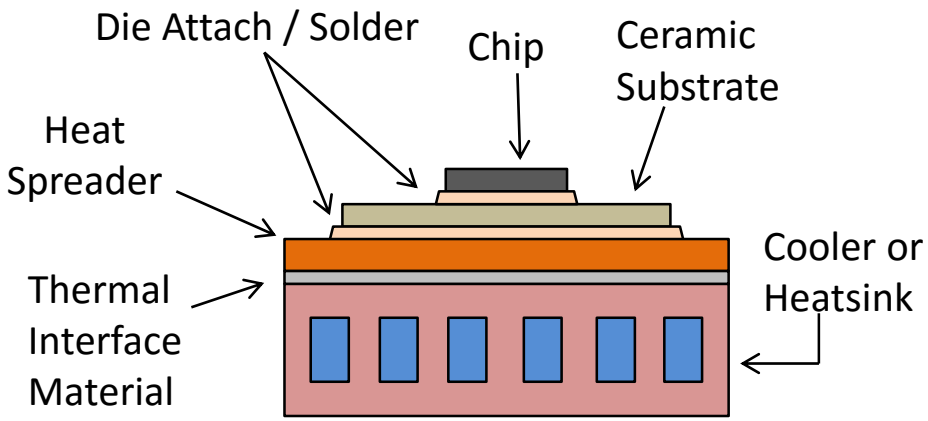
Outline of Presentation

- Introduction to power electronics, reliability and particle erosion.
- CFD simulations (ANSYS FLUENT) to obtain localized particle impact characteristics.
- Test setup, design of experiments and measurement techniques.
- Development and calibration of a particle erosion model.

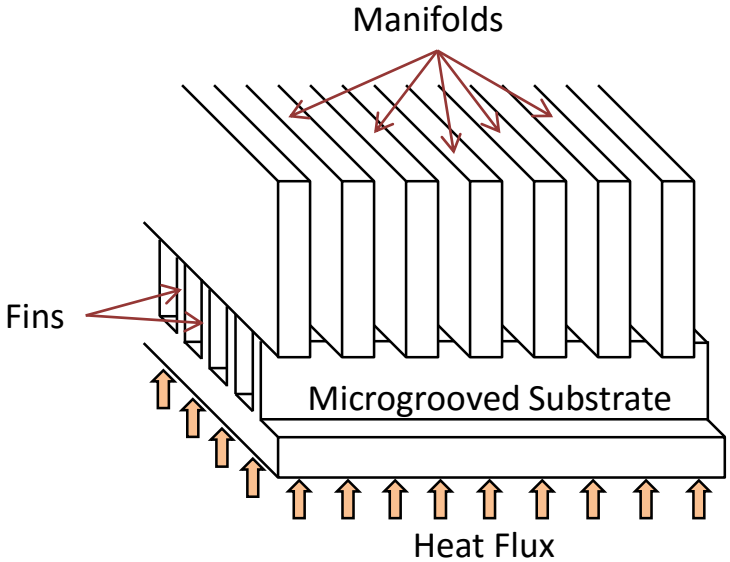
Power Electronics Cooling



- Typically rely on thermal conduction and heat spreading to remove heat.
- Primary limitation of "remote" cooling techniques lie in the complex junction to ambient thermal paths.

Microchannels etched directly into the substrate bring cooling virtually to the source

Other implementations include pin-fin arrays and micro-jet impingement cooling

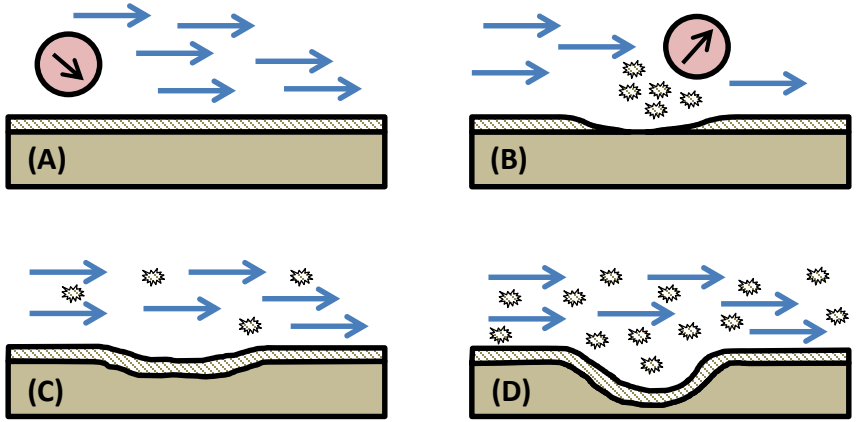


P. McCluskey, T. Podlesak and R. Grzybowski, *High temperature electronics,* CRC press, 1996

M. Ohadi, K. Choo, S. Dessiatoun and E. Cetegen, *Next Generation Microchannel Heat Exchangers,* Springer, 2013

L. Boteler, *Microfabrication and analysis of manifold microchannel coolers for power electronics (Doctoral Dissertation),* UNIVERSITY OF MARYLAND, COLLEGE PARK, 2001.

Particle Erosion/Corrosion Concerns



- Generate more particles and alter microfluidic geometries. Increasing filtering levels increases required pumping.
- Corrosion not likely to be a reliability issue in ceramic / monocrystalline substrates (SiC, AlN, Si, etc.)
- Major concern in jet-impingement cooling (velocities > 20 m/s), potential issue in two-phase flow when fluid accelerates upon evaporation.

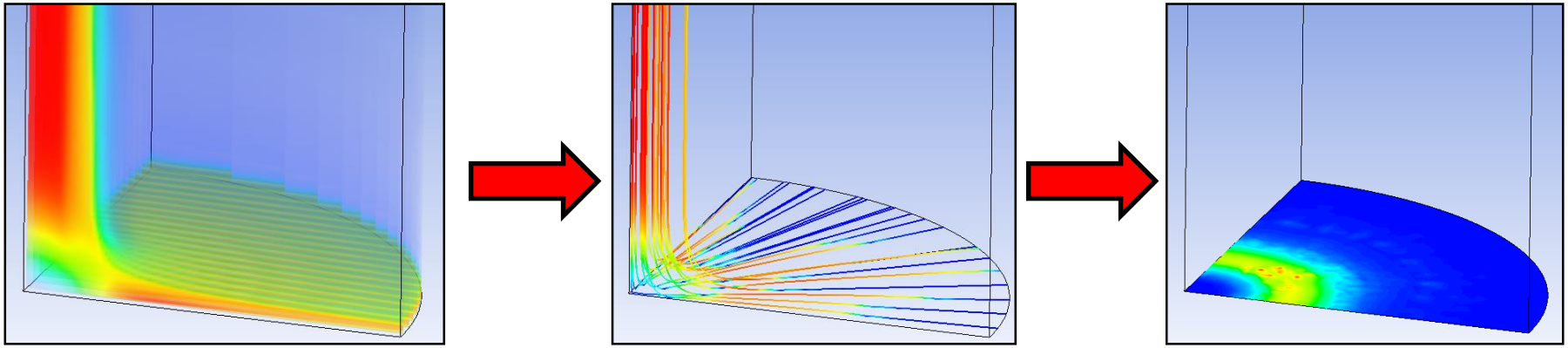
High accuracy erosion predictions must be made to ensure reliable operation throughout the lifetime of the cooler

S. Narumanchi, V. Hassani and D. Bharathan, *Modeling single-phase and boiling liquid jet impingement cooling in power electronics,* National Renewable Energy Laboratory, 2005

Squiller, D., Khanna, S., Dessiatoun, S., Mandel, R., Ohadi, M., & McCluskey, P. Reliable Integration of Microchannel Coolers for Power Electronics. ASME 2015 INTERPACK collocated with ICNMM. July 2015.

CFD-Based Particle Erosion Prediction

- Conducted in three primary steps:
  1. Numerically compute the flow field (FLUENT, CFX, etc.)
  2. Calculate particle trajectories via Lagrangian particle tracking
  3. Employ particle-wall interactions via erosion equation.
- Commercial CFD codes (FLUENT, CFX) have built in erosion models.
- Custom models can be hooked into the CFD software through user defined functions.



Which erosion model accurately captures the mechanisms of erosion present in microchannel coolers?

Overview of Particle Erosion Modeling

Typically given in units [mg/mg], i.e. mass of impacting particles to mass of material removed.

Material/system dependent scaling parameter.

Particle size relation typically follows a power law, D^m, where $0.6 < m < 3.7$ depending on erosion units

$$ER = f(K, V, D, \alpha)$$

Impact velocity follows a power law relation, V^n, where $1.5 < n < 4.4$ depending on the erosion mechanism (brittle vs. ductile).

Impact angle relation depends on erosion mechanism.

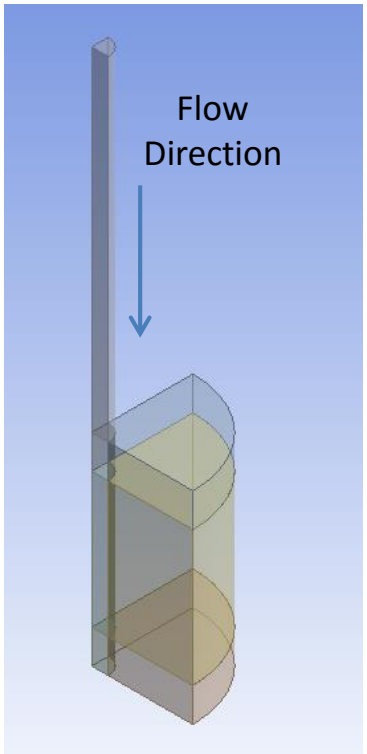
- $ER \propto (V\sin\alpha)^n$ for brittle materials
- $ER \propto (\sin\alpha)^{0.4}(\cos\alpha)^2$ for cutting
- $ER \propto (V\sin\alpha)^x + V^y(\cos\alpha)^2(\sin\alpha)^z$ for combined modes

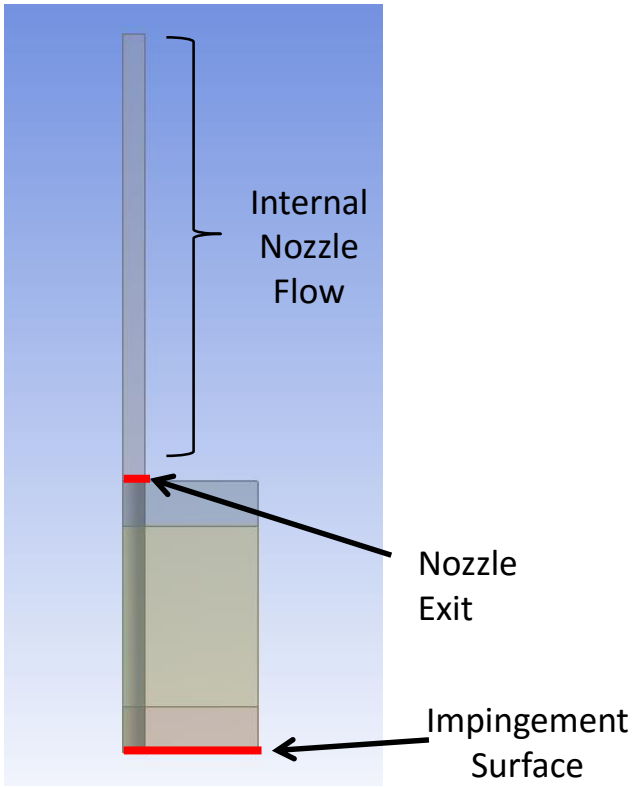
Huang, C., Chiovelli, S., Minev, P., Luo, J., & Nandakumar, K. (2008). A comprehensive phenomenological model for erosion of materials in jet flow. *Powder Technology*, *187*(3), 273-279.

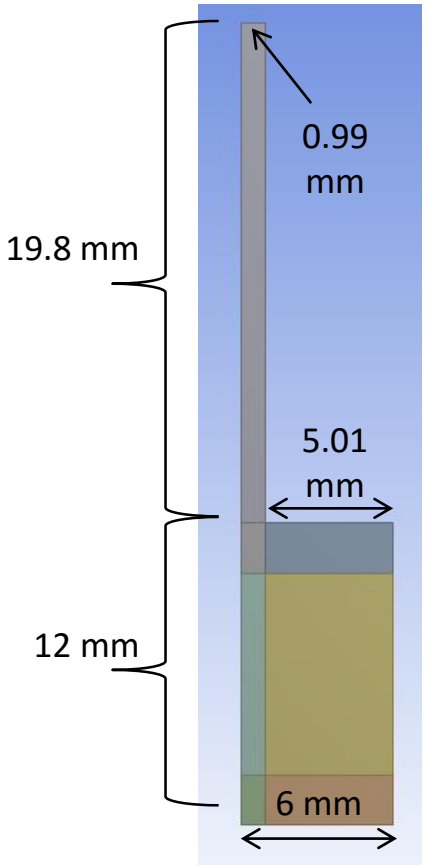
Routbort, J. L., R. O. Scattergood, and E. W. Kay. "Erosion of silicon single crystals." *Journal of the American Ceramic Society* 63.11-12 (1980): 635-640.

Overview of CFD Simulation

- 3D jet-impingement quarter-symmetry model, 1.98mm nozzle.
- Obtain localized particle impact information, e.g. impact velocity, impact angle, percentage of entrained particles that impact the surface.
- ANSYS FLUENT v16.1

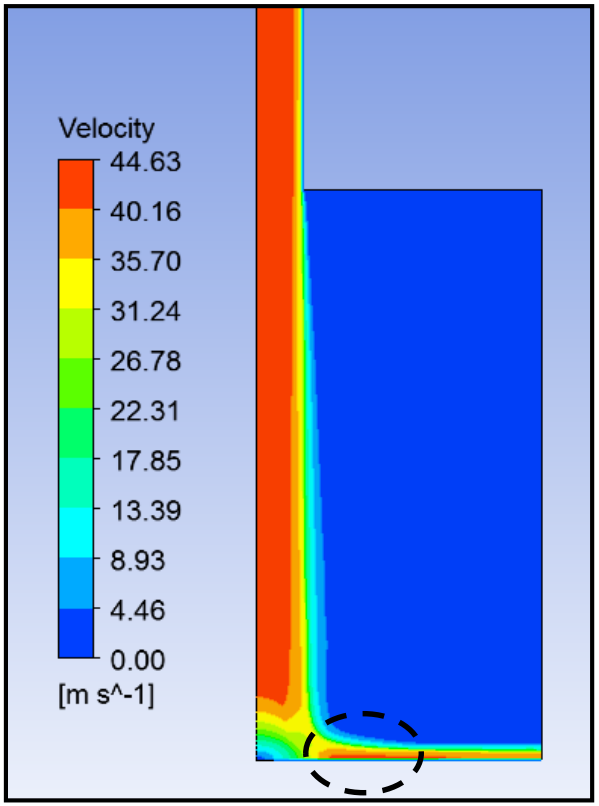




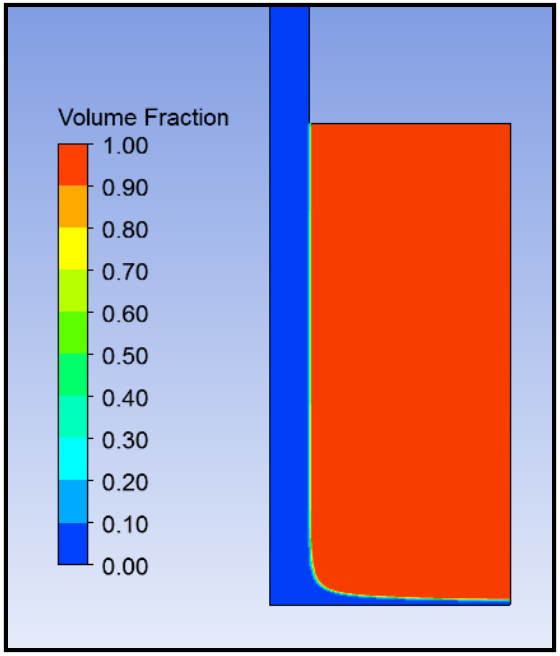


Example Flow Field Solution – 40 m/s Water

2D contour taken from symmetry plane



High fluid velocity region near surface suggests location of maximum erosion



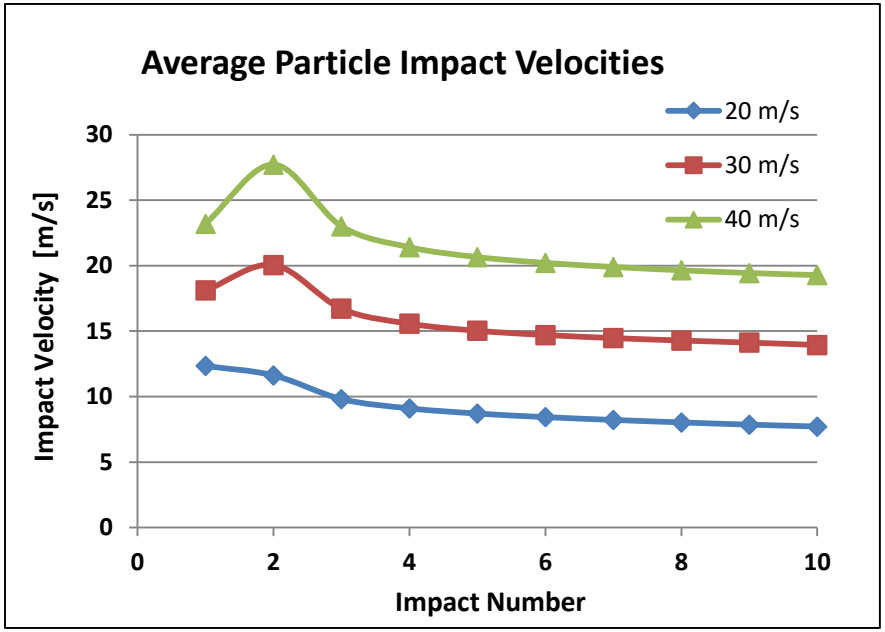
WATER
AIR

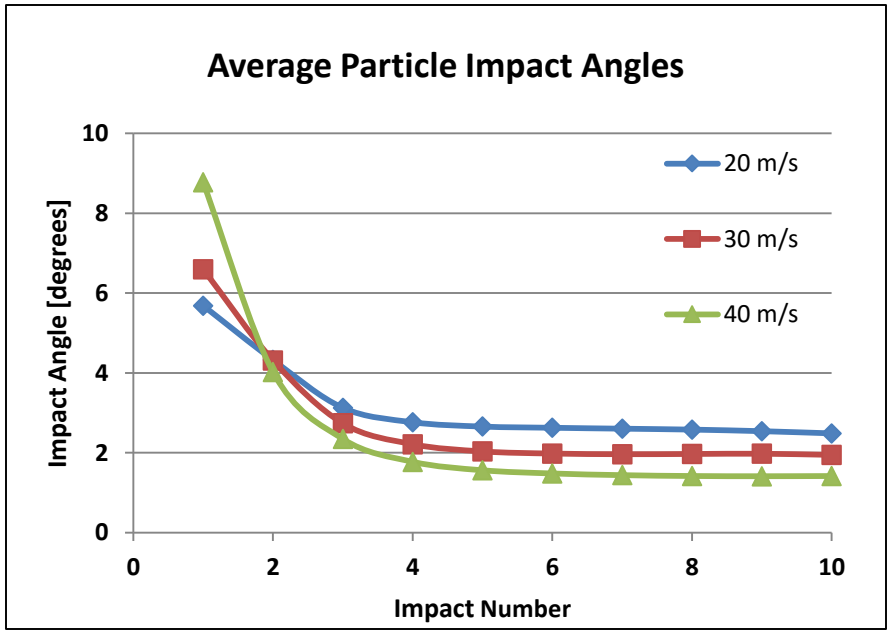
VOF model predicts collimated fluid jet.

- 1.28 million particle tracks released from inlet using the Discrete Phase Model
- UDF written to capture individual particle impact velocities and angles.

Preliminary CFD Results

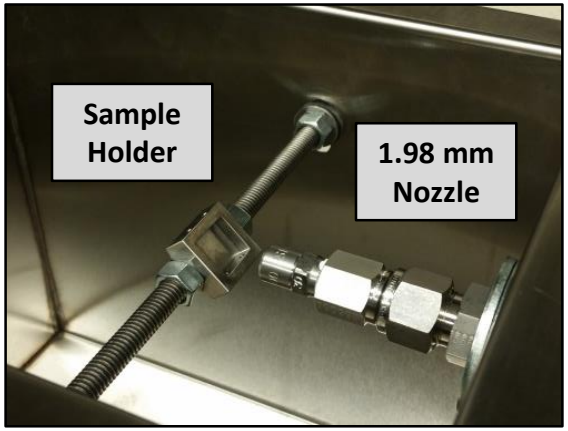
- Up to 10 impacts were captured for each particle track
- 10µm alumina particles were assumed for preliminary CFD simulations
- Average impact characteristics for 1.28 million particle tracks are shown here

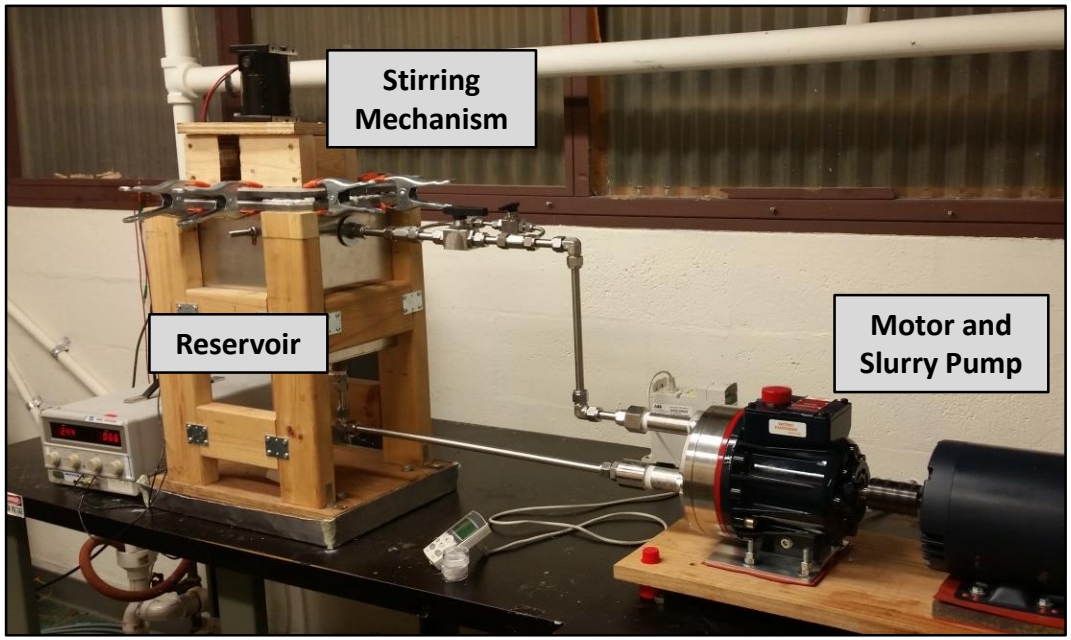


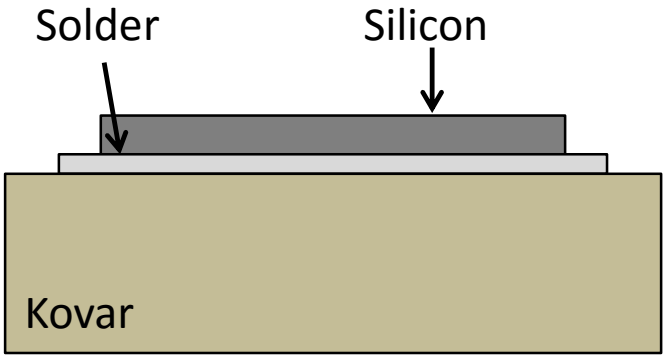


Slurry Erosion Test Apparatus

- Velocity ranges from 5 – 60 m/s for water, slightly less for more viscous fluids.
- Chemically compatible with EG/PG solutions.
- Motor-driven propeller prevents particle settling for a wide range of particle sizes.





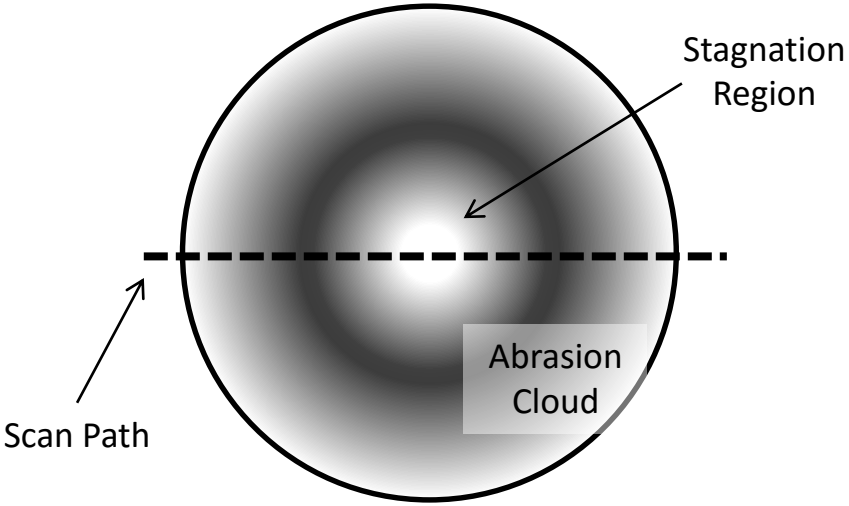


Design of Experiments

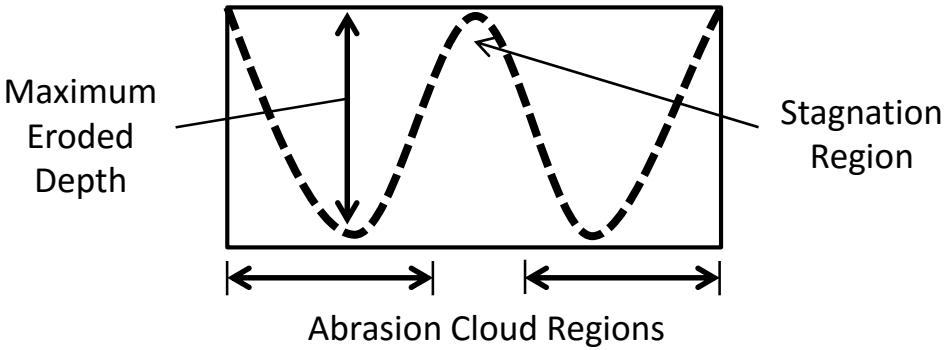
Test #	Particle Size (µm)	Jet Velocity (m/s)	Fluid
1	1	40	Water
2	2.5	40	Water
3	10	40	Water
4	20	40	Water
5	10	20	Water
6	10	25	Water
7	10	30	Water
8	10	40	5% PG
9	10	40	10% PG
10	10	40	25% PG

Tests will investigate major parameters contributing to erosion i.e. particle size, velocity and fluid viscosity.

Stylus profilometer is used to quantify erosion



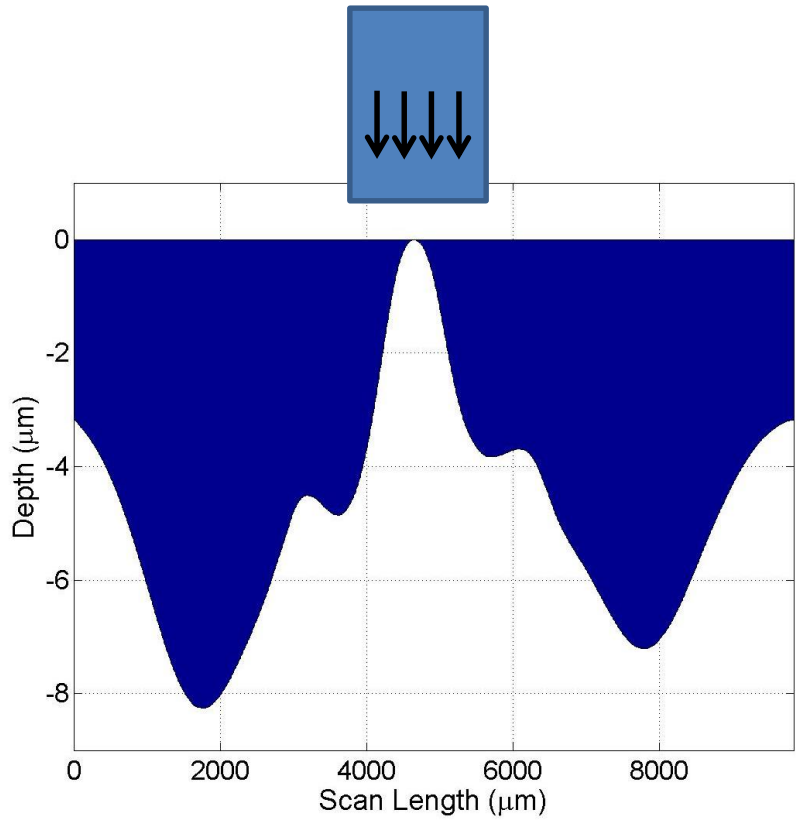
Profile Scan Across Erosion Scar



J. Wang, T. Nguyen and K. Pang, *Mechanisms of microhole formation on glasses by an abrasive slurry jet*, Journal of Applied Physics, 105(4), 044906, 2009.

Analysis of Erosion Scar – ID: 104010D

Sample: 10µm alumina particles, 40 m/s nominal jet velocity, 0.1% particulate concentration, 120hrs.



- Volume loss was approximated using numerical integration techniques in MATLAB.
- Effects of primary and secondary impacts can be seen.
- Mass Loss Rate will serve as the metric through which new erosion model will be calibrated.

Mass Loss Rate	**70 mg/year**
1-D Erosion Rate	**562 µm/year**

Particle Based Erosion Model

$$ER = KD^m \sum_{i=1}^{1.28mil} V^n (sin\alpha)^{0.375} (cos\alpha)^2$$

Modified form of Huang et al. cutting model

ER	Erosion Ratio [mg/mg]
K	Material dependent scaling constant
V	Particle Impact velocity [m/s] (CFD)
D	Particle diameter [µm]
C	Particle concentration [m/m]
n	Impact velocity exponent
m	Particle size exponent
α	Impact angle (CFD)

- Considers particle impact velocity and impingement angle determined from CFD jet-impingement simulations.
- Can be hooked directly into FLUENT to replace built-in models.
- Will enable calibrated erosion predictions in microchannel geometries other than simple jet-impingement scenarios.

Huang, C., Chiovelli, S., Minev, P., Luo, J., & Nandakumar, K. (2008). A comprehensive phenomenological model for erosion of materials in jet flow. *Powder Technology*, *187*(3), 273-279.

Concluding Remarks and Contributions

- First study investigating slurry erosion of single-crystal Si.
- First attempt to study the erosion of brittle materials within the parameter ranges present in microchannel and embedded coolers.
- Methodology can be extended to study the slurry erosion characteristics of other relevant materials: sapphire, tungsten, titanium etc.
- Provide designers with insight surrounding necessary filtering requirements to prevent erosion in jet-impingement cooling systems.
- Particle-based model can be hooked into commercial CFD codes to replace generic erosion models.

Acknowledgements

- DARPA MTO Contract # HR00111320012.
  - Dr. Daniel Green, Program Manager
- Prof. Michael Ohadi
- Prof. Avi Bar-Cohen