Dr. Suresh V. Garimella Research Program
Director of Cooling Technologies Research Center
(https://engineering.purdue.edu/CTRC)

- **Microscale Transport and Microchannels**
  - Two-Phase Transport of Dielectric Fluids through Silicon Microchannel Heat Sinks
  - Enhancement of Boiling in Microchannels
  - Infrared PIV for Non-Intrusive Microfluidic Measurements
  - Micro-scale Temperature Measurement
  - Laser-Induced Fluorescence Thermography Measurements of Flow Boiling Heat Transfer
  - Inlet Manifold Considerations for Microchannel Heat Sinks
  - Effects of Surface Roughness and Wettability on Nucleate Boiling Heat Transfer
  - The Effects of Surface Roughness on Flow Boiling in Microchannels
  - Numerical Simulation of Condensation in Minichannels
  - Rarified Gas Flow in Microtubes
  - Experiments and Models for Two-Phase Transport of Water in Microchannels
  - Non-intrusive Microscale Temperature Measurements
  - Single-Phase Microchannel Heat Sinks
  - System-level Analysis of Microchannel Heat Sinks
  - Microchannel Inlet Manifold Analysis

- **Electrically Actuated Microscale Flows**
  - Microscale Ion-Driven Air Flow
  - Micromechanical Electrohydrodynamic Pump
  - Microscale Ionic Winds for Local Heat Transfer Enhancement
  - Microscale Electromechanical Flow Actuation
  - Modeling of Microscale Electrohydrodynamics

- **Thin-Film Transport, Wicks and Heat Pipes**
  - Fundamental Experimental Investigation of Thin-Film Evaporation
  - Reverse-engineer Microstructures for Optimal Thin-Films
  - Thin Film Evaporation in V-groove Geometry
  - Transport in Wick Structures
  - 3-D Transient Models for Miniature Flat Heat Pipes
  - Characterization of Heat Pipe Wick Fluid Transport and Thermal Performance
  - Heat Transfer During Evaporation of Binary Liquids from Wick Microstructures
  - Numerical Modeling of 3D Vapor Chambers
  - Characterization of Composite Heat Spreaders
  - Theory of Thin-Film Evaporation
  - Modeling of Flow Boiling and Thin Film Evaporation using the Material Point Method

*Purdue University - School of Mechanical Engineering*
Dr. Suresh V. Garimella Research Program
(Continued)

• Novel Air Cooling Approaches
  – Two Phase Liquid Jet Impingement Cooling
  – Fluid-Structure Interaction in Vibrating Cantilevers
  – Thermal-Fluidic Performance of Piezoelectric Fans
  – Miniature Piezoelectric Fans
  – Reduction of Noise Emissions from Small Fans
  – Confined and Submerged Jet Impingement
  – Waste Heat Recovery

• Thermal Materials R&D
  – Transport in Porous Foams
  – Phase Change Energy Storage
  – Analysis of Transport in Porous Microstructures
  – Low-Temperature Synthesis and Bonding of CNT Thermal Interfaces
  – Carbon Nanotube Electrical Interfaces for Thermoelectrics

• Thermal Interfaces
  – Thermal Analog to AFM Force-Displacement Measurements for Interfacial Contact Resistance
  – Low-Temperature Synthesis and Bonding of Carbon Nanotube Thermal Interfaces
  – Thermomechanical Modeling of Thermal Contact Conductance
  – Thermal Contact Conductance Measurements

• Thermal Interfaces (continued)
  – Particulate Thermal Interface Materials
  – Compliant Thermal Interface Adhesives

Small-scale Refrigeration
  – Refrigerant Flow Boiling in Microchannels
  – Miniature Diaphragm Compressors for Electronics Cooling
  – Miniature Linear Compressors for Electronics Cooling
  – Miniature Vapor Compression for Electronics Cooling

Exploratory and Novel Concepts
  – Electrical Actuation of Droplets for Microelectronics Cooling
  – Droplet Actuation and Motion under various Actuation Forces
  – Alternative Heat Rejection Methods for Power Plants
  – Thermal Ratcheting Prevention of a Molten-Salt Thermocline
  – Electroosmotic Pumping through Porous Anodic Alumina Templates
  – Bridgman Growth in a Transparent Material
  – Direct Cooling by Electron Field Emission
  – Microscale Electromechanical Flow Actuation
  – Solar Thermal Energy Storage
Two-Phase Transport of Dielectric Fluids in Silicon Microchannel Heat Sinks

Faculty: S. V. Garimella  
Student: Tannaz Harirchian

**Objective**

Explore, quantify and model boiling heat transfer in silicon microchannel heat sinks using dielectric fluids.

**Approach**

- Investigate boiling phenomenon in micro scale
- Perform high-speed visualizations
- Conduct local measurements of wall temperature & heat flux

**Impact**

- Can achieve extremely high heat transfer rates
- Provides the ability for chip-integration

**Selected Publications**

Objective

To develop techniques for enhancing two-phase heat transfer in microchannel flows.

Approach

Experiments are performed using flat surfaces (pool boiling) and microchannels (flow boiling) with varying surface characteristics.

Impact

- Develop a better understanding of the role of surface effects on boiling in microchannels
- Develop techniques to enhance the boiling process in microchannels

Selected Publications


Experiments are performed using flat surfaces (pool boiling) and microchannels (flow boiling) with varying surface characteristics.
Infrared Micro-Particle Image Velocimetry for Non-Intrusive Microfluidic Measurements

OBJECTIVE

Develop a novel, non-intrusive diagnostic technique for measuring sub-surface fluid flows in silicon microdevices.

APPROACH

The principles of particle image velocimetry are employed using infrared light.

- Silicon is transparent to wavelengths > 1200 nm

IMPACT

- Extends the capabilities of particle image velocimetry, allowing for the measurement of flow fields inside silicon microdevices.
- This technique is ideally suited for measuring flow patterns inside silicon microchannel heat sinks, without optical access.

Velocity Measurements inside Microtube

SELECTED PUBLICATIONS

Measurement of Brownian motion of suspended particles is used to extract temperature information from low-speed, steady flows. A novel technique is being developed to measure temperature at higher velocities.

\[
\Delta s_{o,c} = \sqrt{2d_e^2 / \beta^2}
\]

\[
\Delta \sigma_{o,c} = \sqrt{2(d_e^2 + 8M^2 \beta^2 D \Delta t) / \beta^2}
\]

Shows the effect of Brownian motion in PIV analysis and the equation that relates it to temperature.

Plots shows the measured temperature vs the actual temperature. Uncertainty involved in the method is \(\pm 1\) K.
Explore the heat transfer mechanisms associated with single bubble growth under forced-convection conditions using a laser-induced fluorescence thermography technique.

**Impact**

- Develop a laser-induced fluorescence measurements system for studying temperature fields around a growing vapor bubble
- Conduct measurements and analysis to ascertain the important mechanisms behind nucleate flow boiling heat transfer

**Objective**

Experiments will further elucidate the important heat transfer mechanisms occurring during nucleate flow boiling.

**Approach**

- **LIFT Calibration Cell**
- **LIFT Optical System**
- **Test Section Design**

**Selected Publications**

- B.J. Jones and S.V. Garimella, Measurements of temperature field around a growing vapor bubble using laser-induced fluorescence thermography, *ITherm*, 2010 (abstract accepted).
Inlet Manifold Considerations for Microchannel Heat Sinks
Faculty: S. V. Garimella
Student: B. J. Jones

**Objective**
To study effects of inlet manifold designs on flow maldistribution in microchannel heat sinks.

**Approach**

Comparison of Numerical Results to IR-PIV Experiments

**Impact**
- Develop an understanding of underlying causes of flow maldistribution
- Develop guidelines to avoid flow maldistribution in microchannel heat sinks

Numerical simulations are used to predict the fluid behavior inside a microchannel heat sink, and are validated against experimental (IR-µPIV) measurements.

**Selected Publications**
Effects of Surface Roughness and Wettability on Nucleate Boiling Heat Transfer

Faculty: Suresh V. Garimella  Student: John P. McHale

**OBJECTIVE**

Quantify the effect of random surface roughness on nucleate boiling characteristics for a variety of conditions.

**APPROACH**

- Random surface roughness produced by consistent method
- Wide range of surface roughness
- Working fluids include different wetting characteristics

**IMPACT**

- Quantify bubble nucleation characteristics from realistic surfaces in a statistically meaningful way
- Improve modeling of nucleate boiling heat transfer
- Assist in improved modeling of two-phase flow at the microscale
- Develop high-speed digital measurement techniques for bubble geometry near surfaces

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**Purdue University - School of Mechanical Engineering**

Suresh V. Garimella
The Effects of Surface Roughness on Flow Boiling in Microchannels
Faculty: S. V. Garimella  Student: B. J. Jones

**Objective**
Conduct exploratory experiments on the effect of surface roughness in microchannels.

**Approach**
- Develop method of producing microchannel surfaces of varying roughness
- Conduct experiments to establish the dependence of surface roughness on heat transfer and pressure drop
- Evaluate the suitability of flow boiling correlations over a wide range of roughness

**Impact**
- Surface roughness has a notable impact on flow boiling heat transfer and pressure drop
- Considering the typical uncertainties in flow boiling correlations, the added uncertainties due to surface roughness do not lead to a significant loss in predictive accuracy

Figure 7. Influence of surface roughness on saturated heat transfer coefficients at different mass fluxes.

Numerical Simulation of Condensation in Minichannels
Faculty: S. V. Garimella      Student: E. Da Riva

**Objective**
Study the condensation process inside minichannels with different geometries

**Approach**
Direct tracking of the vapour-liquid interface by means of the VOF method

**Impact**
- Refrigerant charge minimization is one of the most important targets for HVAC applications to cope with the new environmental challenges
- Minichannels appears to be a good opportunity to minimize the charge in HVAC without loss in energy performance

![Axial velocity profile](image)

- Refriment charge minimization is one of the most important targets for HVAC applications to cope with the new environmental challenges.
- Minichannels appears to be a good opportunity to minimize the charge in HVAC without loss in energy performance.

![Vapour-liquid interface in square channel](image)
Rarefied gas flow is important for:

- Gas dynamics in high vacuum environments – orbital science, vacuum pump, etc.
- Compressible gas flow in micro/nano-structures

**Objective**

Develop a model that can predict mass flowrate and streamwise pressure distribution of rarefied gas flows in microtubes

**Approach**

Mass flowrate

\[
Q = \frac{\pi r^4 P}{2\mu RTL}
\]

\[
\frac{P^2 - 1 + 2Kn_x(4 + \alpha(P))(\bar{P} - 1) + 8(b + \alpha(P))Kn_x^2 \ln \left( \frac{P - bKn_x}{1 - bKn_x} \right)}{P^2 - 1 + 2Kn_x(4 + \alpha(P))(P - 1) + 8(b + \alpha(P))Kn_x^2 \ln \left( \frac{P - bKn_x}{1 - bKn_x} \right)}
\]

Pressure distribution

**Results & Comparisons**
Microscale Ion-Driven Air Flow
Faculty: S. V. Garimella, T. S. Fisher; Students: V. Bahadur, W. Zhang, D. Schlitz, M. Peterson

Objective
Utilize travelling wave electrophydrodynamics to develop a novel microscale ion-driven air pump for providing high heat flux air cooling solutions to the microelectronics industry.

Approach
- Unipolar ion generation from atmospheric air using field emission
- Characterization of field emission from nanomaterials
- Monte-Carlo simulation to predict ionization of atmospheric air
- Air pumping by ion drag using a three-phase traveling electric field to move ions
- Multiphysics, multiscale modeling to predict flow and heat transfer

Impact
- Extends limits of air-cooling heat dissipation capacity
- Noiseless, low power consumption
- Provides air cooling-based chip-integrated thermal management solutions

Selected Publications
- Peterson, M.S. Zhang, W., Fisher, T.S. and Garimella, S.V., Plasma Sources Science and Technology 14:654-660
Micromechanical Electrohydrodynamic Pump
Faculty: S. V. Garimella
Student: B. D. Iverson

OBJECTIVE
Design and fabricate a pump that is scalable to the micro-domain for liquid pumping and electronics cooling

IMPACT
Chip-integration of micro-scale pumping can:
- Increase power dissipation while maintaining small form factor
- Significantly reduce packaging thermal resistance
- Provide flexibility in component constraints and layout

Approach

Enhance induction EHD with fluid motion from a vibrating diaphragm.

Selected Publications
- B. D. Iverson and S. V. Garimella, Microfluidics and Nanofluidics, DOI 10.1007/s10404-008-0266-8

Design and fabricate a pump that is scalable to the micro-domain for liquid pumping and electronics cooling.
Microscale Ionic Wind for Local Cooling Enhancement

Faculty: T. S. Fisher, S. V. Garimella
Student: D. B. Go

**Objective**

Design and fabricate a microscale ion wind engine for electrohydrodynamic convection enhancement of microelectronics

**Impact**

Chip-integrated, ionic wind convection enhancement will:

- Increase heat transfer over local, high-heat-flux regions
- Provide additional cooling capacity without impacting volume of overall cooling system
- Provide flexibility in thermal solutions for portable electronics

**Approach**

Modulate a bulk flow using a field emission-generated microscale ionic wind to increase the heat transfer at a surface

- Infrared image of a heated plate with bulk flow cooling
- Demonstration of 25°C drop due to ionic wind

**Selected Publications**

Microscale Electromechanical Flow Actuation
Dr. Dong Liu, Prof. Suresh V. Garimella

**Objective**
Couple electric field to flow field to achieve microscale flow actuation and control

**Impact**
Dielectrophoresis-based microscale flow actuation can:
- Accurately tune forces exerted on fluid via micro/nanoparticles
- Provide flexible flow control by varying signal frequency and non-uniformity in electric field

**Approach**
Generate microscale flow through interaction between dielectrophoretic motion of particle and surrounding liquid

**Applications**
- DEP-based micropumping of nanofluids
- Directed fluidic self-assembly

Lee and Bashir, APL, 2003
Lumsdon et al., Langmuir, 2004
**Objective**

Develop a comprehensive understanding of the transport phenomena occurring at the thin liquid film near the contact line.

**Approach**

Temperature suppression in the thin-film region indicating its high efficiency.

**Impact**

- Thin-film region associated with very high heat transfer rates
- Provide accurate measurements of thin-film evaporation rates and thermocapillary convection which is critical for boiling and heat pipe design
- Develop methods for sustaining and enlarging thin-film area

**Selected Publications**

Reverse-engineer Microstructures for Optimal Thin-Films
Faculty: J. Y. Murthy, S. V. Garimella
Student: Ram Ranjan

Objective

Develop physics-based models to analyze wicking, permeability, thermal conductivity and thin-film evaporation characteristics of microstructures

Approach

Compute liquid meniscus shapes in microstructures
- Horizontal wires (wire mesh)
- Packed bed of spheres (sintered particles)

Impact

- Optimization of the performance of evaporator in a two-phase cooling device
- Capability to remove ultra-high heat flux in electronics by optimizing the microstructure based on developed models

Selected Publications


Model evaporation from liquid meniscus in microstructures

- Superheated solid wall
- Liquid-vapor interface
- Liquid inlet

- 90% of the evaporation occurs from the thin-film region

Purdue University - School of Mechanical Engineering

Suresh V. Garimella
Thin film evaporation in V-grooves will:
- Enhance understanding of the physics of thin film evaporation
- Enable better design of heat pipes

Objective
Investigate heat transfer from evaporating meniscus in V-grooves

Impact

Approach

Experiment and Modeling

Dark region in temperature profile indicates lower temperature near contact line due to thin film evaporation

Modeling efforts will focus on the 3D flow and temperature fields in the V-groove
**Objective**

Experimentally determine the performance of wicks under typical heat pipe operating conditions.

**Impact**

A better understanding of the performance and limits of operation of heat pipe wicks is essential for design improvements and miniaturization efforts.

**Approach**

Two novel setups are developed to evaluate heat pipe wicks in environments typical of operating conditions (partially saturated, evacuated), and measure mass flow rate and wick conductivity.

**Selected Publications**

3D Transient Models for Miniature Flat Heat Pipes

Faculty: S. V. Garimella, J. Y. Murthy
Student: U. Vadakkan

**Objective**

Extend the envelope of current heat pipe technologies by developing predictive capabilities to address the complex phase change processes in the heat pipe system.

**Impact**

The transient, 3D model developed for miniature flat heat pipes allows design, optimization, and analysis of performance limits of heat pipes in constrained spaces and high heat flux applications.

**Approach**

Our stable, convergent numerical scheme for the transient analysis of flat heat pipes at high heat fluxes uses a sequential solution procedure using SIMPLE. The model is in 3D, and handles multiple discrete heat sources. Capillary limits can be explored as well.

**Selected Publications**

Objective

- Determine the capillary fluid transport properties of porous wick materials
- Parametrically characterize the thermal performance of conventional sintered copper powder and screen wick materials
- Investigate the possible thermal performance enhancement due to integration of carbon nanotubes into conventional wick structures
- Optimize heat pipe wick design for minimum thermal resistance

Approach

- Capillary Wicked Boiling and Evaporation Test Facility
- Sintered Copper Powder SEM Image
- Numerical Modeling Optimization of Mass Transport for a Nanostructured Wicking Surface

Thermal Performance Characterization: Boiling Curve

Heat Flux (W/cm²) vs. $T_{\text{substrate}} - T_{\text{ref}}$ (°C)

Heat Pipe Thermal Spreader Capillary Wicking
Condenser Side boiling/evaporation
porous wick material

Fluent Flow Solution
Heat Transfer During Evaporation of Binary Liquids from Wick Microstructures

Faculty: S. V. Garimella and J. Y. Murthy  
Postdoc: Amaresh Dalal

Objective

Development of a numerical model for computing the evaporation of binary liquids from wick microstructures under saturated vapor conditions.

Results

- The addition of 1-propanol is found to increase the overall evaporation rate and hence the overall heat transfer.
- It is found that the water evaporation rate exhibits a maximum at 3.26% mass fraction ($Y$); correspondingly, the heat flux also exhibits a maximum at this value.

Evaporative Model

- User-defined functions have been developed in Fluent to implement the evaporation model.
- The shape of the liquid-vapor interface in the wick structure is obtained using Surface Evolver.
- The binary fluid mixtures contain water-liquid and 1-propanol-liquid as species.
- The wick is made of copper.

Selected Publications


Objective

Develop physics-based numerical models to determine the dry-out of vapor chamber heat spreaders for different wick structures.

Approach

- Coupling Evaporation Micromodel with Vapor Chamber 3D Model
- Compute pressure gradient across interface in the device
- Compute interfacial mass transfer coefficient including thin-film evaporation and Marangoni effects
- Get corresponding contact angle from Surface Evolver model

Impact

- Micro-level effects (thin-film evaporation, Marangoni convection) are captured in the vapor chamber model
- Vapor chamber performance with different wick structures can be predicted using the coupled model

Selected Publications

Combining industrial composite manufacturing with direct growth of CNTs will yield a cost-effective solution to replace copper with high conductivity composite heat spreaders and interfaces.

**Objective**
- Low cost manufacture of diamond-metal composites has become commercially viable
- Leverage group’s expertise and industry partnership for carbon nanotube (CNT) synthesis on composites

**Approach**
- Plasma enhanced chemical vapor deposition of CNTs
- 3-D method for thermal characterization
- Optimization of CNT growth parameters and materials selection for composites

**Method for Conductivity**
- Deposited 3-ω element
- Composite substrate

**Technical Challenges**
- Low temperature growth and optimization of CNT growth parameters on composites
- Establishment of robust thermal characterization strategy for multi layered materials

**Selected Publications**

Purdue University - School of Mechanical Engineering
Objective

Develop a comprehensive evaluation of two-phase liquid jet impingement cooling in confined conditions and provide guidelines for optimal design.

Approach

- Perform experimental measurements
- Compare data to established correlations
- Develop an optimization study with experimental data

Impact

The study will provide:

- Evaluate correlation in the literature with experimental data
- Provide optimal nozzle plate design for a given height for two phase cooling
- Improve details on cross flow affects between nozzle jets

Selected Publications


D. Copeland, “Enhancement of Direct Liquid Cooling of Electronics Doctor of Engineering (DrEng) thesis,” Department of Mechanical and Intelligent Systems Engineering School of Engineering, Tokyo Institute of Technology Adviser: Professor Wataru Nakayama, February 1996


Fluid-Structure Interaction in Vibrating Cantilevers

Faculty: Suresh V. Garimella  Student: Tolga Açıkalın

**Objective**
Develop analytical and numerical models to predict fluid-structure interaction of vibrating cantilevers.

**Approach**
Develop analytical and numerical models to predict fluid-structure interaction of vibrating cantilevers.

**Selected Publications**


**Impact**
This research will help place piezoelectric fans in the thermal management toolkit by providing insight into the fluid flow induced by these devices.

**Experimental flow visualization**

**Numerical CFD models**

Develop analytical and numerical models to predict fluid-structure interaction of vibrating cantilevers.

**Streaming flow models**

2-D streaming model for a baffled piezoelectric fan aggress well experimental flow visualization

Purdue University - School of Mechanical Engineering
Objective

Develop physics-based models to describe and predict performance of piezoelectric fans in single and array configurations.

Impact

This research is helping place piezoelectric fans in the thermal management toolkit by providing insight into underlying physics of vibrating cantilevers, and offering predictive tools for design and optimization.

Selected Publications

Miniature Piezoelectric Fans

Faculty: Suresh V. Garimella
Student: Mark Kimber

Advantages of Piezoelectric Fans
- Low power, 1-10 mW
- Noiseless for frequencies:
  - Less than 100 Hz (infrasonic)
  - Greater than 20 kHz (ultrasonic)
- Lightweight, compact and inexpensive
- No wearing parts, long life, robust and durable
- Versatile – configurable to different applications

Resonant vibration of small piezoelectric elements generates air flow

Flow in an “impingement” mode:

- (a) t = 1/30 sec
- (b) t = 2/30 sec
- (c) t = 3/30 sec
- (d) t = 5/30 sec
Transport in Porous Foams
Faculty: S. V. Garimella, Jayathi Murthy  Student: S. Ravi Annapragada

OBJECTIVE
Study transport through open-celled foam structures for heat transfer enhancement, via experiments and unit-cell models

IMPACT
Use of foams for heat exchange leads to:
• Reduced weight due to low effective density
• Greater heat transfer area due to high surface area/volume
• First-of-its-kind direct numerical representation of foams

Approach

Selected Publications
Phase Change Energy Storage
Faculty: S. V. Garimella  Student: S. Krishnan

**Impact**
Applications include: backup cooling, absorption of thermal transients, quick heating (for startups), defrosting, temperature control, cooling of portable and other devices with low duty cycle,…

**Objective**
Map the capabilities of phase change energy storage for thermal management of transient heat dissipation.

**Approach**
- Develop simple analytical tools and comprehensive numerical models to determine the performance of different PCMs in energy storage systems in different configurations, with and without thermal conductivity enhancers
- Experimentally investigate the performance of PCMs in representative applications

**Selected Publications**
Analysis of Transport in Porous Microstructures
Faculty: J. Y. Murthy, S. V. Garimella, Student: Karthik K. Bodla

**Objective**
Study transport through real random porous media for heat transfer enhancement via direct CFD computations

**Approach**
- Heat Pipe
- Micro CT

**Impact**
- First of its kind analysis of porous media, employing µ-CT
- Development of 1D analytical models based on microstruture
- Correlations for predicting flow and heat transfer

**Selected Publications**
Objective:
Develop a method for measurement of interface resistance through thin-film polymer/Si interfaces using a heated AFM tip.

Approach:
Measure voltage imbalance in and out of contact with a substrate.

Impact:
Use of heated AFM tips for interfacial characterization:
- Enables nanoscale spatial resolution
- Reduces contrast from variance in tip contact
- Provides sub-surface resistance measurement

Identify impact of film thickness on thermal diffusion.

Calibrate voltage change as a function of temperature difference.

Estimate contribution of contact resistance at zero film thickness.
Flow-Temperature Synthesis and Bonding of Carbon Nanotube Thermal Interfaces  
Faculty: T. S. Fisher and S. V. Garimella  
Student: S. V. Aradhya

**Objective**
- Scaling of integrated devices on electronic chips demands improved methods to conduct heat away
- Minimize the thermal contact resistance between CNT tips and opposing surface for better TIMs

Minimizing the thermal contact resistance between free tips of CNTs and their opposing substrate allows for the full utilization of the high conductance of CNTs.

**Technical Challenges**
- Obtaining thin glass layers with requisite composition on metal substrates
- Bonding of CNTs with the glass layer

**Approach**
- CNT synthesis by plasma enhanced chemical vapor deposition
- Spin coating of layers on Si wafers
- In-house bonding setup
- 1-D Reference bar method to measure thermal contact resistance

**Selected Publications**
Thermomechanical Modeling of Thermal Contact Conductance

Faculty: S. V. Garimella
Student: C. T. Merrill, A. F. Black, V. Singhal

**Objective**

Develop a comprehensive model to predict thermal contact conductance at metallic joints with and without a coating.

**Approach**

Heat flow through a rough surface is analyzed using a constriction resistance model for heat flow through each asperity on a surface, and a thermomechanical model to determine actual contact area.

**Impact**

An easy-to-use software tool is developed which accurately predicts contact resistance given only the roughness of the surfaces in contact, material properties and applied load.

**Selected Publications**

Thermal Contact Conductance Measurements
Faculty: S. V. Garimella
Student: C. T. Merrill, P. Litke, A. Black

**Objective**
Experimentally explore factors affecting thermal contact conductance enhancement across bare and coated metallic contacts.

**Impact**
Thermal contact resistance is a ubiquitous problem in electronics cooling. Mitigation of contact resistance has size, weight, manufacturing and cost implications that make this one of the most pressing issues to resolve in packaging design.

**Approach**
Using a CTRC-designed thermal contact resistance measurement apparatus, undertake a design-of-experiments matrix to explore the impact of surface roughness, contact pressure, surface hardness, and effect of metallic coatings.

**Selected Publications**
**Objective**

Experimentally determine the local heat transfer coefficient in refrigerant flow boiling in a cold-plate evaporator with parallel microchannels.

**Approach**

- Perform well defined measurements
- Compare data to established correlations
- Develop new widely applicable correlation

**Impact**

The outcomes of this study will:

- assess existing models against experimental results
- help formulate predictive correlations for flow boiling in microchannels
- optimize design of microchannel cold plate evaporators
- improve simulations of small-scale refrigeration systems

**Selected Publications**

Miniature Diaphragm Compressors for Electronics Cooling
Faculty: Eckhard A. Groll and Suresh V. Garimella
Students: Abhijit A. Sathe

OBJECTIVE
Simulate and test an electrostatically actuated diaphragm compressor as a part of a miniature scale refrigeration system for electronics cooling

IMPACT
• Analytical quasi-static force balance simulation model
• Numerical quasi-static model using FEA
• Analytical dynamic simulation model for fluid damping
• Experimental investigation using custom setup
• Design optimization of diaphragm compressor

WHAT’S NEW
The diaphragm compressor simulation model is
• Among the few to simulate refrigerant compression
• The first model to simulate diaphragm zipping actuation

APPROACH
Diaphragm Chamber

Model Validation with

Selected Publications

What’s new
To prototype, model, and assess the feasibility of a free-piston harmonically oscillating linear vapor compressor for the use in a refrigeration system to cool consumer electronics.

**Approach**

- Design and build a prototype compressor
- Build load stand to test prototype
- Develop a comprehensive compressor model
- Exercise model and develop design recommendations

**Selected Publications**


**Impact**

- An assessment of the scalability of this style of compressor
- A comprehensive compressor model for use in design applications of linear compressors
- A fundamental understanding of linear compressors
Electrical Actuation of Droplets for Microelectronics Cooling

Faculty: S. V. Garimella
Student: Niru Kumari

**Objective**

Develop technologies enabling electrical actuation and control of droplets for providing chip-integrated thermal management solutions

**Approach**

- Electrowetting (electrical control of surface tension) based actuation of electrically conducting droplets
- Electric field-based actuation of dielectric droplets
- Experimental characterization of droplet flow and heat transfer
- Electrically tunable thermal resistance switch through control of droplet states on artificially roughened surfaces

**Impact**

- Significantly enhanced control of flow at the microscale
- High liquid velocities at low voltages
- Noiseless, very low power consumption
- Solutions for chip-level and hot-spot thermal management

**Selected Publications**

- Patent application filed May 2006, #60/747,980
**Objective**

Develop technologies enabling electrical actuation and control of droplets for providing chip-integrated thermal management solutions

**Approach**

- Electrowetting (electrical control of surface tension) based actuation of generic droplets using DC and AC actuation
- Experimental characterization of droplet flow and heat transfer
- Electrically tunable thermal resistance switch through control of droplet states on artificially roughened surfaces

**Electrical Actuation of Droplets for Microelectronics Cooling**

**Faculty**: S. V. Garimella  
**Student**: Niru Kumari, Susmita Dash

**Impact**

- Significantly enhanced control of flow at the microscale
- High liquid velocities at low voltages
- Noiseless, very low power consumption
- Solutions for chip-level and hot-spot thermal management

**Selected Publications**

Objective

Develop experimentally validated numerical models to describe droplet motion under various actuation forces.

Approach

- Perform well defined inclined droplet experiments and measure contact angles
- Develop contact angle correlations for stationary and moving droplets
- Develop VOF based numerical methodologies for predicting droplet actuation and motion
- Compare numerical predictions with data
- Develop new numerical models for the same

Impact

The outcomes of this study will:

- Develop benchmark data for evaluation of numerical models for droplet actuation
- Predictive numerical models for droplet motion under gravitational and electrical actuation

Selected Publications

Alternative Heat Rejection Methods for Power Plants
Faculty: Eckhard Groll and Suresh Garimella
Students: R. Leffler and C. Bradshaw

**Objective**

- Identify and evaluate heat rejection processes that provide power plants with viable alternatives to cooling towers, lakes, and rivers
- Determine feasibility of design in regards to cost requirements, land requirements, and environmental factors.

**Methods**

Solar chimney with a plate fin heat exchanger at the base of the collector.

A spray pond using evaporation and convection to reject heat to the atmosphere.

Low pressure spray nozzles are positioned over the pond in an array.

A shallow, extensive canal system provides the condenser discharge water increased contact with the atmospheric air allowing it to cool before reentry to the condenser.

An open water algae bioreactor is a like a pond with a layer of Thermophyllic algae growing on the surface. The algae is periodically harvested for biodiesel production.

The pond is heated by the condenser discharge water up to a temperature of 75°C.

Wintertime greenhouse heating can be achieved by pumping hot condenser discharge water through pipes in the floor of the greenhouse.

**Impact**

**Direct Impact:**
- Closed loop heat rejection to the atmosphere
- Electricity production from plant waste heat in solar chimney
- Algae bio-fuel production in algae bioreactor pond
- Winter time greenhouse heating by process waste heat
- Lower impact on ecosystem of lakes and rivers
- Less costly than cooling towers

**Broader Impact:**
- Alternative methods of heat rejection not limited to the power generation industry
- Petroleum refineries, Food processing plants, Semi-conductor plants, Chemical plants, etc.
Thermal Ratcheting Prevention of a Molten-Salt Thermocline
Faculty: Z. Yang, S.V. Garimella  Student: S. Flueckiger

**Objective**

- Concentrating Solar Thermal power plants require thermal storage for times of reduced insolation.
- Thermocline tanks store molten salt at both excited (hot) and dead (cold) states in a single tank volume, separated via buoyancy forces.
- A granulated bed of rocks in the tank reduces the required salt volume but can induce thermal ratcheting in the tank wall.

**Approach**

- Detailed CFD investigation of thermocline operation with a multilayer (internal and external insulation, steel shell) tank wall design to determine hoop stress in the steel shell.
- Parametric study of wall dimensions to minimize hoop stress and avoid ratcheting.

**Impact**

- Hoop stresses result from periodic temperature fluctuations in the steel shell in response to internal molten-salt changes.
- Internal insulation dampens influence of molten salt on steel shell temperatures, reducing thermal ratcheting potential.

**Selected Publications**

Flueckiger et al., Integrated thermal and mechanical investigation of molten-salt thermocline energy storage, 2011, DOI: 10.1016/j.apenergy.2010.12.31

![Thermocline temperature and velocity fields during hot molten-salt discharge](image-url)
Electroosmotic Pumping through Porous Anodic Alumina Templates

Objective

Construct a high flow rate, high back pressure pump that is scalable for micro to mesoscale fluid delivery.

Impact

- Porous anodic alumina pumps:
  - Provide multiple nanometer diameter channels in parallel with long-range order
  - Reduces applied voltage while maintaining high electric field
  - Provides the scaffold for an integrated screen electrode
  - Yields high flow rate normalized by applied voltage and cross-sectional area

Approach

- Deposit Pt as an electrode on both sides of the alumina template
- Apply electric field across the alumina channels by probing the deposited Pt film
Bridgman Growth in a Transparent Material
Faculty: S.V. Garimella  
Student: J. E. Simpson

Experimental photographs used to resolve the front locations inside the ampoule during crystal growth.

Selected Publications


Predicted thermal and velocity fields and interface locations for a 40 micrometer growth case.