NSF Graduate Research Fellowship Packet

Submitted for the NSF GRFP competition in December 2012

Student status : Undergraduate at time of submission

Award status : Fellowship awarded

Personal Statement

Introduction: My passion for engineering research and community leadership is what motivates me to work toward becoming a professor in mechanical engineering. I pursued an undergraduate engineering degree because I wanted to apply my critical thinking abilities to address technically complex problems with real-world applications. My desire to earn my graduate degree in mechanical engineering stems from that same passion for advancing scientific knowledge and giving back to my local, national, and global communities. My experiences performing undergraduate research, planning outreach events, and collaborating with diverse groups have further developed my teaching aspirations and prepared me to lead research in new thermal management techniques.

Leadership in the Community: Throughout my life, I have worked to help others achieve their goals. As a junior in high school, I planned and executed my Eagle Scout project at a local food pantry where I volunteered weekly. I saw that the pantry consistently lacked the donations of toiletries and household necessities its customers were requesting, but also noticed that many community members donating perishables were not aware that the center even provided these items. I decided to coordinate a door-to-door donation drive to raise awareness about the pantry's long-term need and to collect napkins, diapers, shampoo, and other essentials. To increase the project's impact, I worked with representatives from a local Sam's Club to create publicity materials, and led a group of scouts that informed shoppers about the project's aims and the items we were asking them to purchase and donate. After two weeks, I had collected over six thousand individual items for the food pantry, and had learned how to plan a major project and communicate my vision to others.

At the beginning of my freshman year of college, I joined The University of Texas chapter of the national service fraternity Alpha Phi Omega (APO). I helped lead weekly meetings at a local Cub Scout pack, and I volunteered to teach First Aid and Fingerprinting courses at the annual Merit Badge University day, or MBU, that APO hosted with the Boy Scouts of America. Preparing compelling examples that showed the scouts biological and scientific concepts made me critically examine how I process information and convey my knowledge to others. As I helped the scouts learn triage methods or print their papillary ridges, my interest in educational advocacy was sparked. I was inspired to see over fifteen hundred scouts from across Texas touring campus and learning about post-secondary educational opportunities, and I decided to run for the position of MBU co-coordinator the next year. After my coalition was elected, I recruited expert volunteer instructors from academia, local organizations, and businesses. For the first time at MBU, we contacted graduate students to teach the Engineering merit badge, and I helped to create lesson plans motivating scouts to apply the concepts they learn in school to form and investigate hypotheses.

I reached out to scout troops from historically disadvantaged areas, and petitioned APO to offer fee waivers that encouraged new participants to attend the event. In response to leader feedback from previous years, I implemented a new online payment system and learned basic HTML coding to make improvements to the event website. I was also interested in adding activities for the adult chaperones, and helped plan CPR training, seminars, and forums on the college preparation and admissions process. My junior year I continued my affiliated service with MBU as a volunteer coordinator while also serving as the APO treasurer.

Volunteering with APO has reinforced my desire to develop educational programming that engages students of all ages. I enrolled in an introductory teacher preparation course to gain more instructional experience, and had the opportunity to design lessons and teach local fourth-grade students about energy conversion. Working with middle school and high school students as an intern in my church's youth ministry department, I helped organize weekly service events, an interfaith dialogue, and tutoring sessions at a nearby summer school. In college, I remain involved in outreach programs with the engineering honors fraternity, Tau Beta Pi, and volunteer at events like 'Introduce a Girl to Engineering Day' and 'Explore UT,' a campus-wide open house that helps students from under-represented communities learn about preparing for post-secondary education.

Broad Impacts of Engineering: During my sophomore year, I participated in Projects for Underserved Communities, an interdisciplinary course that connected college students with Bechtel Corporation engineers to redesign a primary school building and community center in Soyo, Angola. Our group collaborated with Soyo's educational leaders to plan the project aimed at designing a durable recreation area for the children. I learned how to use AutoCAD from an architectural engineering student, and created restroom fixture and classroom installation schematics. We adapted and tuned our plans to meet budgeting and scheduling constraints, and I gained experience working on an inter-disciplinary team to accomplish a common goal.

As I heard about the new energy generation techniques, water treatment mechanisms, and electronic devices that the Soyo community was utilizing, I began to connect how the mechanical engineering concepts that captured my attention at school could improve lives across the globe. In one of our conversations with the primary school principal, he enthused how much easier his leadership role became once he was able to purchase a computer for his office. I kept picturing all the scientists who designed that desktop, and began searching for ways I could apply my engineering abilities to give people tools to succeed like the computer scientists had done. After learning about the vital importance of thermal management in modern electronic devices and energy systems, I began performing thermal-fluid system research and immediately knew that I had discovered the way I would contribute to my community.

Career Goals: As a professor, I want to initiate new energy systems research and identify diverse solutions to scientifically engaging and socially relevant problems in thermal-fluid systems. I will teach challenging courses that help my future students build analytical mindsets, and will use online classes to engage curious minds across the globe. I will work with local teachers and professional organizations to advocate for strong scientific education in primary and secondary schools, and will set aside funding for research positions and summer internships targeted at members of under-represented groups in high school and college.

GRFP Impact: The GRFP will allow me to direct and publicize my research optimizing thermal management devices at the University of Texas at Austin. I will use a portion of the GRFP funds to develop new demonstrations of heat pipe and thermal dissipation technologies for MBU and Explore UT. The fellowship will allow me to conduct my experiments, develop outreach programs that educate children about the role of engineers and scientists in today's society, and prepare myself for my career in academia.

Previous Research

Introduction: My undergraduate research in Dr. Carlos Hidrovo's Multiscale Thermal Fluids Laboratory (MTFL) at UT Austin and my work in a class project studying distributed power generation have given me experience developing analytical models and computational simulations to characterize energy transport systems.

Micropillared Thermal Wicking: In the fall of my junior year, I began working as a research assistant in the MTFL and learned about the applications of heat pipe cooling systems in advanced electronic devices. I collaborated with two undergraduate students to analyze capillary flow through micropillared wicking arrays. The project's research objectives are to develop wicking structures that increase heat pipe cooling capacities and to contribute to the broader scientific understanding of fluid flow in microscale devices.

I began expanding and validating a two-dimensional fluid flow model that a previous graduate student had derived from fundamental principles. I identified simplifications and assumptions in the derivation that could have major effects on the predicted velocities. I wrote a MATLAB program to automate the calculations for different conditions, and compared versions of the model to previous experimental results from our group. I also learned how to develop COMSOL Multiphysics finite element analysis simulations for laminar flow and heat transfer through the wicking structure. Independently leading the modeling and simulations taught me the importance of validating my calculations, performing in-depth background research, and reaching out to other researchers for assistance. My research experience reaffirmed my interest in pursuing the additional training in analytical, computational, and experimental methods I will undertake in graduate school.

The following semester, I collaborated with a new Ph.D. student in the lab as she manufactured wicks and designed an experimental setup to measure the capillary limit. As she discussed the problems she was having with over-etched pillar walls, I began to wonder whether deliberate lateral etching could actually be beneficial for heat pipe wicking structures, a topic that I propose studying in graduate school. I continued to run simulations for the cylindrical pillar design, and authored the modeling section of a paper we recently submitted to the International Journal of Thermal Sciences[1] and the modeling portion of an ASME conference paper[2]. I also helped present our lab's work to first-year UT students in the Equal Opportunity in Engineering Program, sharing my undergraduate research experience and discussing how other students could become involved in research.

Advanced Thermo-adsorptive Battery: For the past year in the MTFL, I have been performing inter-component heat and mass transfer analyses for a novel thermo-adsorptive battery climate control system being developed and tested by researchers at MIT, UT Austin, UC Berkeley, and Ford Motor Company. The team's immediate goal is to increase drive time in electric vehicles by reducing the battery drain to current in-cabin climate control systems. UT Austin's role in the project is to help design, integrate, and test individual heat exchanger components and the total adsorption system. The implemented thermal battery could help the nascent electric vehicle market grow, and the team is exploring how system principles and materials could be used in other high density thermal energy storage applications.

In the spring of 2012, I began working with another undergraduate researcher to lead UT's system design and evaluation. We identified general sizing requirements for vehicular evaporators, and I performed heat transfer analysis to determine the required evaporative surface area. I also examined the mass transport and bulk motion of the evaporated working fluid, and developed COMSOL simulations that coupled heat transfer, laminar flow, and species diffusion within the vapor to assess the effects of changing geometric or material design parameters. Our group has realized that adsorption material advances can lead to powerful, compact energy storage devices only if system-level heat and mass transfer constraints are addressed.

This fall, I am continuing to collaborate on the modeling and evaporator design with a new international post-doctoral fellow and a MS candidate. I have prepared quarterly reports, technical presentations, and non-technical overviews of the project to explain our findings to other researchers and to the general public. I am also helping to design an experimental setup for testing current vehicular evaporator performance at reduced pressures. As this project enters its second year, I will continue to take a leadership role in the modeling and simulation efforts while assisting other members with experimental evaporator characterization.

Distributed Power Generation: In my junior year, I collaborated with three other mechanical engineering students in my Thermal-Fluid Systems course to research and model a distributed power generation system with a microturbine, or a gas turbine with <1 MW power generation. I spearheaded the creation of a thermodynamic model in MATLAB to find state properties in the combined gas turbine and bottoming Rankine cycles, and helped other group members to design a heat recovery steam generator. We validated our results with data from a previously published paper, and performed parametric analyses to gage the impacts of different inlet conditions, fuel types, and component materials on system efficiency and power output.

We created a final report that included a substantial literature review section detailing the benefits and downsides of distributed generation, our parametric design results, and an expanded analysis on emissions savings for microturbines compared with coal or natural-gas centralized power generation. Analyzing the emissions and fuel consumption in large scale power generation strengthened my desire to create improved thermal management systems that can make alternative energy storage and dissipation methods more viable. Performing the thermodynamic analysis and writing technical summaries gave me experience applying my modeling skills in a research environment to identify important system characteristics and communicate my findings.

Preparation for future work: My experiences leading and collaborating on thermal-fluid system research has motivated my desire to create innovative thermal management solutions throughout my career in academia.

1. [redacted] *Direct Thermo-Hydraulic Characterization of the Capillary Limit in Heat Pipe Wicks.* International Journal of Thermal Sciences. Submitted 2012 (In Review).
2. [redacted] *A novel thermo-hydraulic test platform for micropillared array thermal wick optimization.* ASME International Conference on Nanochannels, Microchannels, and Minichannels 2012.

Proposed Research

Introduction and Problem Statement: Capillary heat pipes are thermal management devices utilized in energy storage and integrated circuit cooling mechanisms to passively transfer high heat fluxes with low axial temperature gradients [1]. Inside a thermally conducting encasement, liquid flows through a wicking structure to the heated section and evaporates. Concentration gradients drive the vapor to condense at the heat rejection site. Differing meniscus radii of curvature and surface tension forces at the solid-liquid-vapor phase change interfaces produce an axial driving capillary pressure. Medium-temperature heat pipe cooling capacities are commonly restrained by the capillary limit, where the driving pressure cannot overcome the losses primarily due to viscous effects, and by the thermal resistances in the wicking structure [2].

In the past five years, researchers have fabricated micropillared wicking structures with small thermal resistances using direct deposition or etching of conductive material [3]. Cylindrical pillar array permeabilities were experimentally and numerically established to calculate viscous losses in Darcy's Law relationships [4], and proposed spherical arrays have been numerically analyzed [5]. To keep pace with predicted transistor power density increases, new 3D chip architectures, and advanced thermal storage systems, researchers have nanotextured copper microposts to increase capillarity without decreasing permeability, and have achieved 170 W/cm^2 dissipation at 100 μm pillar heights [6]. Researchers at the Multiscale Thermal Fluids Laboratory (MTFL) at UT Austin have experimentally measured the capillary limit for cylindrical micropillars [7]. In my graduate research at UT Austin in the MTFL, I propose fabricating and testing non-cylindrical micropillars to optimize this thermal capillary flow.

Hypothesis: I predict that inverted conical cylinder micropillar arrays will increase permeability without decreasing capillarity and will achieve 300 W/cm^2 cooling with 100 μm pillar heights.

Methods: In traditional high aspect ratio MEMS microfabrication, deep reactive ion etching (DRIE) and lateral sidewall protection, or passivation, techniques are used to etch vertically into a patterned substrate. An etching or deposition process that produces inverted conical cylinders, with smaller pillar base diameters and larger diameters at the exposed pillar tips, would increase the effective flow area, exponentially decreasing the viscous losses when compared to a circular cylindrical structure of the larger diameter. The meniscus curvature at the solid-fluid-vapor interfaces and the axial capillary pressure differences would not be significantly impacted. Numerical simulations will be developed using COMSOL Multiphysics, a finite element analysis software, and Surface Evolver, a meniscus energy minimization tool, to characterize the thermal conduction, capillarity, and permeability for inverted conical geometries with different diametric tapers, ridges, and scallops resulting from fabrication.

To fabricate these geometries, a pulsed DRIE process will incise grooves in a silicon substrate, initially shaping cylindrical pillars of the nominal mask diameter protected by positive photoresist. Decreasing the passivation cycle duration and increasing the length of the etching cycle when etching out the pillar base will result in increased lateral etch and smaller pillar base diameters. Pillars will be manufactured with different heights, top-to-base diameter ratios, array spacings, and distances from the base at which the diameter becomes constant. SEM imaging will be used to evaluate pillar uniformity. Contingency plans to fabricate variable diameter pillars include isotropic wet etching to undercut pillar bases following DRIE, and using back-etching and via fills to combine two cylindrical layers of different diameters into a single pillar.

The capillary limit for these novel wicks will be directly measured by improving an existing vertical thermal wick setup. The evaporative section of the silicon wick will be mounted on a conductive copper block connected to a series of cartridge heaters. The other end of the wicking surface is submerged in a water reservoir. A load cell will record the reservoir mass change due to the wick's steady-state capillary action. The evaporative heat load will be calculated from input power and heat loss measurements, and will be correlated with evaporation-corrected reservoir mass readings to determine when additional heat flux does not result in larger capillary flow-rates. The ambient humidity and temperature will be controlled in a recently constructed environmental chamber equipped with humidity probes and resistance heaters.

Anticipated Results and Findings: I expect experimental results to show that inverted conical cylinders with top-to-bottom diametric ratios of 2:1 will increase the capillary limit by a factor of three when compared to circular cylindrical micropillars of the same height, spacing, material, and diameter range due to the viscous loss quadratic dependence on pore size. I also predict that lateral etch methods will increase surface roughness and scallops on the pillar walls, increasing the viscous losses but also increasing the heat transfer through the liquid.

Timeline and Resources: In this three-year project's first year, I will fabricate wicking structures, develop simulations, and use my results to identify optimal geometries. The second year will be spent running experiments. For six months I will write and present results, leaving an available six month contingency period. I will receive training on UT's Center for Nano- and Molecular Science (CNM) state-of-the-art microfabrication equipment. Dr. Carlos Hidrovo and senior MTFL researchers have years of experience designing microfluidic systems, and the research lab contains a server computer and DAQ interface system for data collection, COMSOL software, and an environmental chamber designed for thermal wick testing.

Academic Significance: This proposed research offers new insight into capillary heat pipe improvements and passive flow through non-uniform microchannels or wicking structures. Geometric variations can be combined with surface nanotexturing techniques to increase both capillarity and permeability. More generally, the microfabrication processes explored in this project can be used to optimize microcombustion burners, microturbines, or microfluidic separation devices implanted in Lab-On-A-Chip devices. I anticipate that multiple journal papers and conference presentations will result from this research.

Community Impacts: I will design heat pipe demonstrations for Dr. Carlos Hidrovo's 'Not Everything's Bigger in Texas' outreach program to teach underrepresented high school students about microfluidics and the scientific method. I will remain involved in engineering volunteer activities with Tau Beta Pi, and will recruit undergraduate students and high school students as research assistants. I will help these young engineers develop their own hypotheses and testing methods to advance the scientific understanding of microfluidic thermal management.

Citations: (1) Faghri, *Heat Pipe Science and Technology* [1995] (2) Peterson, *An Introduction to Heat Pipes* [1994] (3) Ishino et al., *EPL* [2007] (4) Xiao et al., *Langmuir* [2010] (5) Ranjan et al., *International Journal of Heat and Mass Transfer* [2012] (6) Nam et. al, *Journal of Microelectromechanical Systems* [2010] (7) Hale et al., *International Journal of Thermal Sciences* [Submitted 2012]

Score for [redacted]

Intellectual Merit Criterion

Overall Assessment of Intellectual Merit

Excellent

Explanation to Applicant

This applicant has an outstanding academic record and has the full support of his faculty recommenders. He has been involved in undergraduate research and has published this work. The proposed research plan is well developed.

Broader Impacts Criterion

Overall Assessment of Broader Impacts

Excellent

Explanation to Applicant

The applicant is involved in outreach efforts through Tau Beta Pi and a service fraternity. He exhibits good leadership skills and an eagerness to enhance participation in STEM fields, especially by underrepresented populations.

Score for [redacted]

Intellectual Merit Criterion

Overall Assessment of Intellectual Merit

Excellent

Explanation to Applicant

The student has amassed research experience in which is well aligned with proposed PhD research plan. I am sure this work will ultimately find its way to practice. He interest in becoming a professor. Has made one research presentation and has one paper in review.

Broader Impacts Criterion

Overall Assessment of Broader Impacts

Good

Explanation to Applicant

The student has demonstrated leadership in numerous campus organization. As his research proceed he should address how it may be presented to both lay and technical audience. He should strengthen the proposal in this regard.

Score for [redacted]

Intellectual Merit Criterion

Overall Assessment of Intellectual Merit

Very Good

Explanation to Applicant

Excellent academic background and preparation. The candidate has been involved with on-going research in thermal fluids for two years. There is involvement with a conference paper and one pending journal paper. There is a demonstrated ability with collaborative projects and independent work on computational modeling.

The research proposal and planned activities for the research are articulated very clearly. It would also be useful to include the title of the work with the narrative.

Broader Impacts Criterion

Overall Assessment of Broader Impacts

Very Good

Explanation to Applicant

The candidate has prior involvement with outreach activities and a corporation that was doing a service-learning project. A plan for developing demonstrations based on the research area that would be used in the advisor's outreach program is provided.

The proposed research is beneficial to the development of heat pipe systems, which could possibly be incorporated to create new thermal management technologies.