SLATT UNDERGRADUATE RESEARCH FELLOWSHIP
FINAL REPORT

SCHOLAR NAME:	Brendan Kane
FACULTY ADVISOR:	Hirotaka Sakaue
PROJECT PERIOD:	Spring 2021 – Fall 2021
PROJECT TITLE:	The Development of Luminescent Ice and Novel Thrust Vectoring Techniques for Environmental and Energy Applications
CONNECTION TO ONE OR MORE ENERGY-RELATED RESEARCH AREAS (CHECK ALL THAT APPLY):	**(X) Energy Conversion and Efficiency** **( ) Sustainable and Secure Nuclear** **( ) Smart Storage and Distribution** **( ) Transformation Solar** **( ) Sustainable Bio/Fossil Fuels** **(X) Transformative Wind**

MAJOR GOALS AND ACCOMPLISHMENTS

Summarize your research goals and provide a brief statement of your accomplishments (no more than 1-2 sentences). Indicate whether you were able to accomplish your goals by estimating the percentage completed for each one. Use the next page for your written report.

RESEARCH GOALS	ACTUAL PERFORMANCE AND ACCOMPLISHMENTS	% OF GOAL COMPLETED
Using luminophores characterized in Fall 2020 and early Spring 2021, develop (and improve current samples of) a novel ice sensor capable of resolving temporal and spatial temperature information.	Many luminophore-additive mixture were evaluated as candidates for luminescent ice sample creation. Two very promising mixtures were identified for further study (experimentation with addition of another luminophore); the promising mixtures were 0.1 mmol of Pyrenesulfonic Acid with 15 mmol of salt and 0.1 mmol Pyrenesulfonic Acid with 5 mmol of salt.	65%
Validate the use of Pressure Sensitive Paint (PSP) as a tool for analyzing the dual-jet impingement fountain-flow phenomenon and develop an PSP-based experimental technique for general analysis of fountain flow.	Contributed to the conceptual development of a PSP based technique for the analysis of the fountain flow phenomenon and aided in conducting the first test of this experimental technique. Conducted a literature study to gather information about the current understanding of fountain flow in the scientific community.	10%
Formulate a novel thrust-vectoring technique that combines the environmentally-friendly nature of fluidic thrust vectoring techniques with the effectiveness of traditional mechanical thrust-vectoring techniques.	A literature review of fluidic thrust vectoring techniques was conducted; the shock vector control, fluidic throat skewing, counterflow, co-flow, and dual throat methods. The counterflow method was selected for further study, and initial plans are in place to use the counterflow method to develop a novel, environmentally conscious thrust vectoring method.	25%

RESEARCH OUTPUT

Please provide any output that may have resulted from your research project. You may leave any and all categories blank or check with your faculty advisor if you are unsure how to respond.

CATEGORY	INFORMATION
EXTERNAL PROPOSALS SUBMITTED	(Sponsor, Project Title, PIs, Submission Date, Proposal Amount)
EXTERNAL AWARDS RECEIVED	(Sponsor, Project Title, PIs, Award Date, Award Amount)
JOURNAL ARTICLES IN PROCESS OR PUBLISHED	(Journal Name, Title, Authors, Submission Date, Publication Date, Volume #, Page #s)
BOOKS AND CHAPTERS RELATED TO YOUR RESEARCH	(Book Title, Chapter Title, Authors, Submission Date, Publication Date, Volume #, Page #s)

PUBLIC PRESENTATIONS YOU MADE ABOUT YOUR RESEARCH	(Event, Presentation Title, Presentation Date, Location)
AWARDS OR RECOGNITIONS YOU RECEIVED FOR YOUR RESEARCH PROJECT	(Purpose, Title, Date Received)
INTERNAL COLLABORATIONS FOSTERED	(Name, Organization, Purpose of Affiliation, and Frequency of Interactions)
EXTERNAL COLLABORATIONS FOSTERED	(Name, Organization, Purpose of Affiliation, and Frequency of Interactions)
WEBSITE(S) FEATURING RESEARCH PROJECT	(URL)
OTHER PRODUCTS AND SERVICES (e.g., media reports, databases, software, models, curricula, instruments, education programs, outreach for ND Energy and other groups)	(Please describe each item in detail)

RESEARCH EXPERIENCE

Please let us know what you thought of your research experience: Did this experience meet your expectations? Were lab personnel helpful and responsive to your needs? What else could have been done to improve your experience or achieve additional results?

My research experience was great! I very much enjoyed working with the members of Sakaue Lab – everybody there was encouraging and helpful. I also very much enjoyed my time conducting independent research during the Summer and Fall. Professor Sakaue provided insightful guidance during our regular meetings, and the information I learned during my literature studies of fountain flow and fluidic thrust vectoring furthered my knowledge of not only those particular phenomena/technologies, but also of flow mechanics and aerospace engineering in general.

FINAL WRITTEN REPORT

(Please use the space below to describe your research project and objectives, any findings and results you can share, and graphs, charts, and other visuals to help us understand what you achieved as a result of this research experience.)

In Spring 2021, the luminescent ice research continued with the testing of the emission spectrums of more luminophore-based mixtures. There was, however, a shift in the focus of these tests. During the prior winter break it was discovered that combinations of luminophores with non-luminescent additives (such as sugar, salt, etc.) yielded increased emission intensity in the ice phase. The Spring 2021 research was then focused on identifying the optimal luminophore-additive mixture for luminescent ice production. A favorable mixture would satisfy the following criteria: high emission intensity in the ice phase, high temperature sensitivity, low luminophore and additive concentration (it was desired that the mixture behave as much like water as possible), and two emission peaks in the ice phase. The effect of cooling on the emission spectrum (temperature sensitivity) of the luminophore-additive mixtures was analyzed through the use of a Peltier cooler.

A series of “quick tests” were completed to rapidly determine the affect of various additives on the ice and liquid phase emission spectrums of a 0.1 mmol Pyrenesulfonic (PSA), 10 mL H_2O mixture. The tested additives were sulfuric acid, sugar, salt, copper oxide, aluminum oxide, and a single control mixture (no additive). Additives were added to the PSA mixture in 20 mmol quantities. The Peltier cooler was used to bring mixture samples to 20^o C (liquid phase), and a spectrometer was used to excite the samples at a wavelength of 365 µm (with emissions recorded in wavelengths ranging from 390 µm to 550 µm). Similarly, the Peltier cooler was used to bring mixture samples to -15^o C and excited at the same wavelength (with emissions recorded over the same range) to measure the ice emission spectrum. Consistent with the winter results, the emission behavior of all additive-included mixtures was of a markedly higher intensity in both the liquid and ice phases than the emission behavior of the control mixture.

To eliminate the affect of minor variances in experimental setup and environment that result from multiple-day mixture testing, the “blue-to-green” signal ratios of the mixture emission spectrums were calculated. This was done by numerically integrating the counts-per-second (CPS) vs. emission wavelength plots (the emission spectrums) taken of the mixtures over a range of wavelengths representing “blue” and “green” coloration (465 µm wavelengths and below were considered blue, 465 µm wavelengths and above were considered green). The resulting blue integral value was then divided by the resulting green integral value to find the blue-to-green signal ratio. A mixture’s temperature dependence could be ascertained by observing the change in its blue-to-green ratio with respect to temperature. In the liquid phase, all mixtures tested emitted blue coloration. In the liquid phase, the amount of blue and green coloration emitted by the mixtures became very similar in magnitude (leading to low blue-to-green ratios). The mixtures with the lowest ratio in the ice phase (and correspondingly high ratio in the liquid phase) were those that changed color the most with temperature drop – i.e. the most temperature sensitive. By this measure, the PSA-aluminum oxide mixture was the most promising with a ratio value of approximately 7.5 in the liquid phase and 0.75 in the ice phase.

It was then decided that a parametric study of the PSA-aluminum oxide mixture would be conducted, with the intensity of the emission spectrum analyzed at a number of different aluminum oxide concentrations (and with the PSA concentration kept constant at 0.1 mmol). During preparation of this parametric study, it was found that mixtures with concentrations of aluminum oxide of 15 mmol and greater emitted as a sea-green coloration in the liquid phase (rather than the usual purple). This was unexpected, and so prompted further study. A high-resolution camera was used to record the emission coloration behavior of a 20 mmol aluminum oxide with PSA mixture over a period of 1 hour. It was found that the blue and red color signals remained relatively constant over the 1 hour period. The green signal, however, quickly decreased in intensity over a period of approximately 30 minutes. These results prompted a brief literature study, leading to the revelation that the porous structure of the aluminum oxide particulate was likely causing localized increases in the concentration of PSA through absorption of the luminophore into these particulates. This made sense, as the emission behavior of PSA is concentration dependent. Such spatially dependent effects were undesirable considering the intended purpose of luminescent ice, and so further analysis of the PSA-aluminum oxide mixture was discontinued.

The PSA-salt mixture was, based on the blue-to-green signal ratio metric, the second-best performing mixture, and so it was selected for the next parametric study. Mixtures were tested with 1, 5, 10, 15, and 20 mmol concentrations of salt additive at temperatures of 20^o C and -6^o C. Data analysis was conducted on the resulting emission spectrums to extract the blue-to-green ratio signal information. Figures 1 and 2 below display these blue-to-green ratios for the liquid and ice phase respectively. As discussed above, the magnitude of the ice phase blue-to-green ratio indicated the degree of temperature sensitivity. This metric was further refined through analysis of the difference in the liquid and ice phase blue-to-green ratios. The magnitude of the difference between these ratios indicates more exactly the extent of color variation during freezing (temperature and phase change sensitivity). It can be seen in Figure 3 that the highest blue-to-green ratio difference is found in the 15 mmol salt mixture, indicating that this is the most temperature sensitive of the mixtures. The 15 mmol mixture has the second highest average emission intensity (CPS value) in both the liquid and ice phase of the mixtures tested (the highest being the 20 mmol mixture). The 15 mmol mixture satisfies, then, two of the specified criteria: high emission intensity and high temperature sensitivity. It does not, however, satisfy the third criteria of low luminophore and additive concentration (relative to the other mixtures tested). Because it was found that the ice phase emission intensity of the 15 mmol mixture is close to that of the 5 mmol mixture, and because the disparity between the blue-to-green ratios of the 15 mmol and 5 mmol mixtures is not exceedingly large, the 5 mmol mixture may be said to satisfy (in some part) all the luminescent ice sample criteria save the last (two emission peaks). The next steps in the luminescent ice project involve experimenting with adding an additional luminophore to the promising 15 mmol and 5 mmol salt and PSA mixtures.

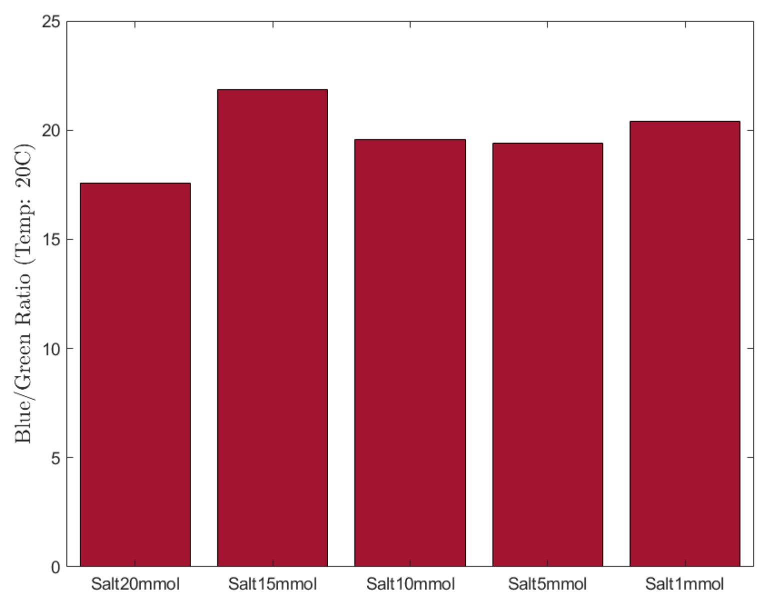

Fig 1. Blue/Green ratios for mixtures of 0.1 mmol of Pyrenesulfonic Acid, 10 mL of H_2O, and varying concentrations of salt additive in the liquid phase. Blue signals are defined as emissions at wavelengths between 390 and 465 µm, and green signals are defined as emissions at wavelengths between 465 µm and 550 µm.

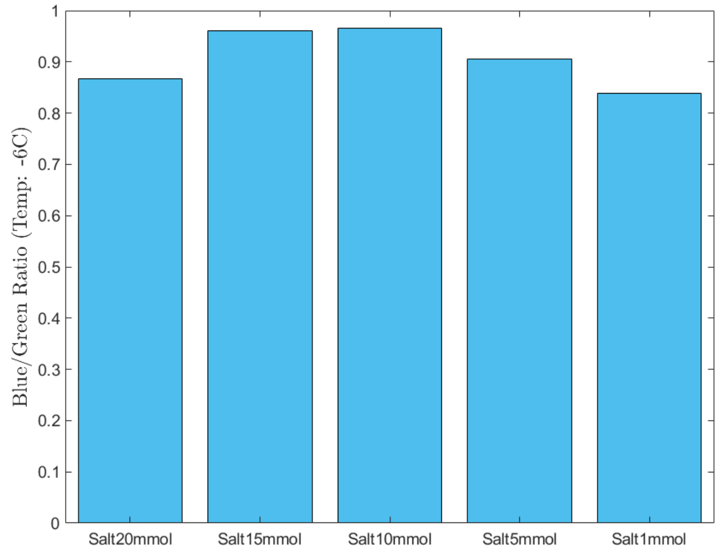

Fig 2. Blue/Green ratios for mixtures of 0.1 mmol of Pyrenesulfonic Acid, 10 mL of H_2O, and varying concentrations of salt additive in the ice phase. Blue signals are defined as emissions at wavelengths between 390 and 465 µm, and green signals are defined as emissions at wavelengths between 465 µm and 550 µm.

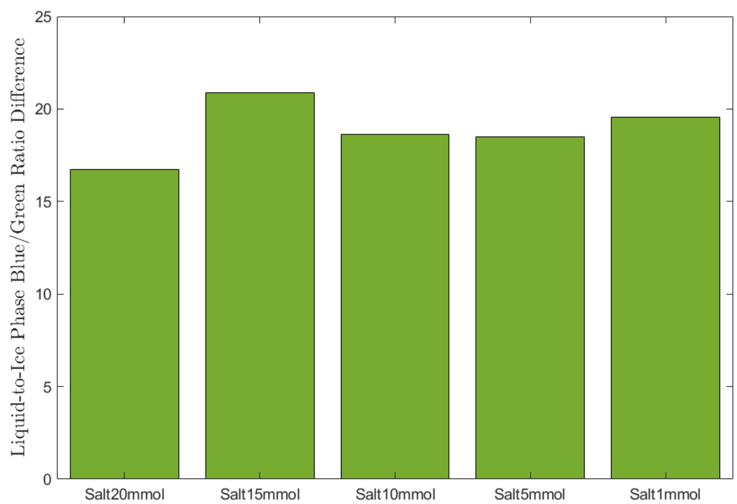

Fig 3. Blue/Green ratio differences between the liquid and ice phase emission spectrums of 0.1 mmol of Pyrenesulfonic Acid, 10 mL of H_2O, and varying concentrations of salt additive.

Towards the end of Spring 2021, my personal focus shifted to analysis of fluid flow problems. The first of these was the dual-jet impingement, or fountain flow, phenomenon. Fountain flow occurs when two closely spaced jets of air impinge on some surface. The flow from each jet deflects radially on the surface. The radial deflection of flow from each jet contacts each other in a space on the surface that is the projected midpoint between the two jets, and the flow washes up at the contact point much like water spewing from an upward facing fountain nozzle (hence the name "fountain-flow"). Fountain flow is an important flow phenomenon to consider when designing Vertical Takeoff and Landing Aircraft (VTOL), as the unique forces created by the flow upwash between dual-impinging jets can cause instability and loss of control if not properly understood. The study of fountain flow is of particular interest because of its role in enabling environmentally conscious urban air travel. Many aerospace companies are developing "eVTOL" (electric-powered VTOL) vehicles that they hope will spurn the creation of an urban air mobility market. Essentially, these vehicles are intended to replicate the function of the "flying car" as seen in science fiction – they will be personal use aircraft for navigating urban and suburban spaces rapidly. eVTOL aircraft are much more environmentally friendly and energy efficient because they draw power from onboard batteries rather than liquid fuel. Many problems must be addressed by those companies currently developing eVTOL aircraft. Chief among these is the low specific power density of batteries relative to liquid fuel, but also of concern is the aerodynamic stability of larger quadcopter takeoff and landing behavior. Better understanding of the fountain flow phenomenon that takes place beneath quadcopters during takeoff and landing is crucial to ensuring that eVTOL aircraft dominate the burgeoning urban air mobility market (thus ensuring that this industry will be an environmentally conscious one from the beginning).

The goal of this fountain flow research was to validate a Pressure Sensitive Paint (PSP) based experimental technique for the analysis of fountain flow behavior. In this technique, a clear, square piece of acrylic was coated on one side with PSP. This plate was screwed to a base-mechanism so that the PSP covered face of the plate was kept rigidly vertical. Two small nozzles were also attached to the base mechanism and spaced approximately 5 mm horizontally from the acrylic plate. The nozzles were oriented so that their jets were perpendicular to the PSP coated surface. A high-powered excitation laser was placed behind the acrylic and apart from the base mechanism itself, with the laser pointing at an angle so that it illuminated the PSP covered face through the clear acrylic. A camera was set up behind the plate with its viewport pointed directly at the plate. To conduct the experiment, the lights in the room were shut off and the excitation laser was turned on. In tandem, airflow was allowed to pass through the nozzles, creating a dual-jet impingement zone on the PSP coated acrylic surface. The camera was used to record the coloration of the PSP as it reacted to the fountain flow. By analyzing this coloration during data post-processing, the pressure distribution on the surface could be determined. This pressure distribution could, in turn, be analyzed to extract useful information about the particular fountain flow conditions tested.

After conceptual development of this experiment, it was tested in the same way as described above. The base mechanism was fixed to a test table, the camera was oriented approximately a foot behind the acrylic plate on a tripod, and a blue excitation laser was placed approximately an inch behind the acrylic plate and significantly to the right so as to not obstruct the camera viewport (the camera lens was fitted with a filtering lens to eliminate the blue illumination source). Air was passed through the nozzles. The camera failed to detect any significant change in illumination in the PSP. Two small dark dots appeared in the camera footage at the areas corresponding to each nozzle jet stagnation point on the acrylic. It was theorized that these dots were areas in which the PSP had been “blown away” by the force of the jets, or that the stagnation point conditions caused oxygen quenching in the PSP. Later examination of the plate showed that no PSP had been stripped from the acrylic. The Spring 2021 semester ended before further data analysis could be conducted, but the examination of fountain flow remains a topic of interest in the Sakaue lab.

During Summer 2021 and Fall 2021, my research was focused on conducting a literature review of both the fountain flow phenomenon and fluidic thrust vectoring techniques. Valuable information about fountain flow was learned – this information will be used by members of the Sakaue lab in the future to refine the PSP-based experimental technique. Certain papers of note included *A review on multiple liquid jet impingement onto flat plate* (S. Nawani, M. Subhash, 2021), *Simulation of Single and Twin Impinging Jets in Cross-flow of VTOL Aircrafts* (Review) (C.A. Cardenas, C.A. Collazos Morales, J.C. Amaya, Y.P. Caviativa Castro, and E. De-la-Hoz-Franco, 2020), and *Aerodynamic Design of Long-Range VTOL UAV* (P. Footohi, A. Bouskela, and S. Shkarayev, 2019). In the paper by Nawani and Subhash, it was concluded that the heat transfer effects at a surface undergoing multiple jet impingement are well understood, but that the hydrodynamic characteristics are not fully known/exploited. In the paper by Cardenas et al., it was determined that the high speed jet flow impinging on the surface beneath dual jets can entrain the ambient flow, thus causing a low pressure region under the jets. A “suckdown” effect then results, which could destabilize a VTOL aircraft during takeoff. In the paper by Footohi et al., it was found that a quad-jet configuration was the most optimal for supporting a theoretical UAV aircraft.

Research into the fountain flow phenomenon and VTOL aircraft naturally led to an exposure to discussions of thrust vectoring in the literature. Thrust vectoring became a focus, as it was yet another regime of aerospace technology that could be made more environmentally conscious through the use of proper technique. The technique of interest was, in this case, *fluidic* thrust vectoring. Traditional thrust vectoring (that found in aircraft such as the Harrier Jump Jet and F-22 Raptor) is conducted via mechanical deflection of the flow at the nozzle exit. The mechanisms in place to enable this deflection of the flow add a tremendous amount of weight to the engine and aircraft. In *Summary of Fluidic Thrust Vectoring Research Conducted at NASA Langley Research Center*, it was estimated that a 43-80% weight reduction in the thrust vectoring mechanism could be expected by switching from mechanical to fluidic methods, and that an overall 7-12% improvement in engine thrust-to-weight ratio could be achieved. Considering that increasing an aircraft’s weight directly correlates to a greater impact on its environmental friendliness (significantly higher weight often necessitates a redesign that includes a more powerful engine or carrying more fuel to reach a desired range), fluidic thrust vectoring techniques could significantly reduce the harmful impact that fighter aircraft have on the environment. Fluidic thrust vectoring techniques such as shock vector control, fluidic throat skewing, counterflow, co-flow, and dual throat were studied during the literature review. Towards the end of Fall 2021, the counterflow method was selected for more focused study because of its promising deflection angle and deflected thrust coefficient performance. This literature study will continue in Spring 2022 with the goal of eventually developing a novel thrust vectoring method that combines the environmentally conscious nature of the counterflow thrust vectoring method with the efficacy of mechanical thrust vectoring.