Airbreathing Cold Engine Start

Alex Bertman, Tristan Isaacs, Alex Johnson, Matthew McKernan,
T.R. Mitchell, Nicholas Moore, James Nguyen,
Matthew Robak, Lucas Sorensen, and Nicholas Taylor

AIAA Student Members, University of Colorado, Boulder, Colorado, 80305

The Airbreathing Cold Engine Start (ACES) system is designed to facilitate starting a JetCat P90-RXi miniature jet engine at -50°F. This will be accomplished by controlling the temperature of the fuel to a specified value between 60°F and 115°F ± 3.6°, controlling the mass flow rate of fuel into the engine between 0.8 and 4.8 g/s (± 0.13 g/s), and ensuring that the engine electronics remain at a specified temperature (± 3.6°F) within their operating temperature range of 60°F and 122°F. This is a proof-of-concept project sponsored by the Air Force Research Laboratory (AFRL) demonstrating high-altitude (cold-temperature) engine ignition capabilities for a jet-powered, unmanned aerial system (UAS). This paper focuses on the problem posed by controlling the temperature and mass flow rate of fuel into the jet engine. In order to overcome the freezing of Jet-A fuel, resistive heating elements and Cryogel insulation are implemented alongside a custom electronic controller to achieve the aforementioned temperature and mass flow goals. With this solution, models indicate that the fuel will reach the desired temperature before entering the engine. Furthermore, tests have demonstrated that the fuel will enter the engine at the desired flow rate. As a result, the temperature and mass flow goals have been achieved such that this project could be used as a test bed for future researchers.

Nomenclature

$AFRL$	Air Force Research Laboratory
CPE	Critical Project Elements
CU	University of Colorado Boulder
ECU	Engine Control Unit
ESB	Engine Sensor Board
FDS	Fuel Delivery System
HCU	Heating Control Unit
UAS	Unmanned Aerial Vehicle
$B - Field$	Magnetic Field Strength

I. Introduction

The Airbreathing Cold Engine Start (ACES) project is an undergraduate senior capstone project for a team from the University of Colorado at Boulder (CU) consisting of 11 undergraduate aerospace engineering students. The ACES team was tasked with designing a system intended to start a JetCat P90-RXi miniature jet engine, pictured in Figure 1, at -50°F.

Figure 1. JetCat P90-RXi Miniature Jet Engine

This was a proof-of-concept project sponsored by the Air Force Research Laboratory (AFRL) to demonstrate the capability of high-altitude, cold-temperature jet engine ignition for a small, jet-powered unmanned aerial system (UAS). Being a proof of concept, the design will not fly aboard a UAS, but rather focuses on the challenges associated with starting the engine at the required temperature conditions while on the ground. The -50°F starting temperature was chosen because this is the ambient temperature at 30,000 ft where the UAS would be released from. This temperature is also notable as it is below the freezing point of the engine's fuel, Jet-A. Since the kerosene that composes Jet-A is a distilled substance, it consists of several discrete elements that have different freezing temperatures. At temperatures below -40°F, some of these substances freeze more quickly than others, increasing the viscosity of the fuel and thus making it more difficult to pump. To mitigate the difficulty caused by the increased viscosity the team's design will control the temperature of the fuel to a specified value between 60°F and 115°F ± 3.6°F. This temperature tolerance was chosen based on the accuracy of the TMP-36 temperature sensors the team will be using. It will also control the mass flow rate of fuel into the engine to a specified value between 0.8 g/s for idle and 4.8 g/s for full throttle, with a tolerance of ± 0.13 g/s, based on how accurately the system can control the fuel pump. In addition, the team seeks to ensure that the engine electronics, including the engine battery, Engine Control Unit (ECU), and Engine Sensor Board (ESB), remain at a specified temperature within their operational ranges. The temperature of the engine battery must be between 60°F and 122°F ± 3.6°F, while the temperatures of the ECU and ESB must remain above 60°F and below 150°F ± 3.6°F. The lower temperature bounds were chosen because they are on the lower end of room temperature, and the higher bounds were chosen because these are the maximum temperatures that the components can attain before experiencing damage.

Figure 2 shows the components and layout of the ACES system, not including the ESB, which is located in the cowling of the engine. The system functions as follows: first, the low temperature batteries provide power to the Heating Control Unit (HCU). The HCU allows current to flow from the main heater battery, located inside the battery compartment, to resistive heating wire wrapped around the ECU, fuel hopper, fuel lines, and the engine battery, also located inside the battery compartment. The HCU also provides current to ceramic power resistors located inside the fuel hopper and the engine cowling. Once the desired temperature has been reached, the HCU initiates fuel flow through the fuel lines by providing current to the fuel pump. The HCU continually monitors the temperatures and mass flow rate and ensures that they remain at their commanded values by adjusting the current to the heating wire and fuel pump. The following sections will discuss the methodology used to achieve the desired heating and mass flow rate control.

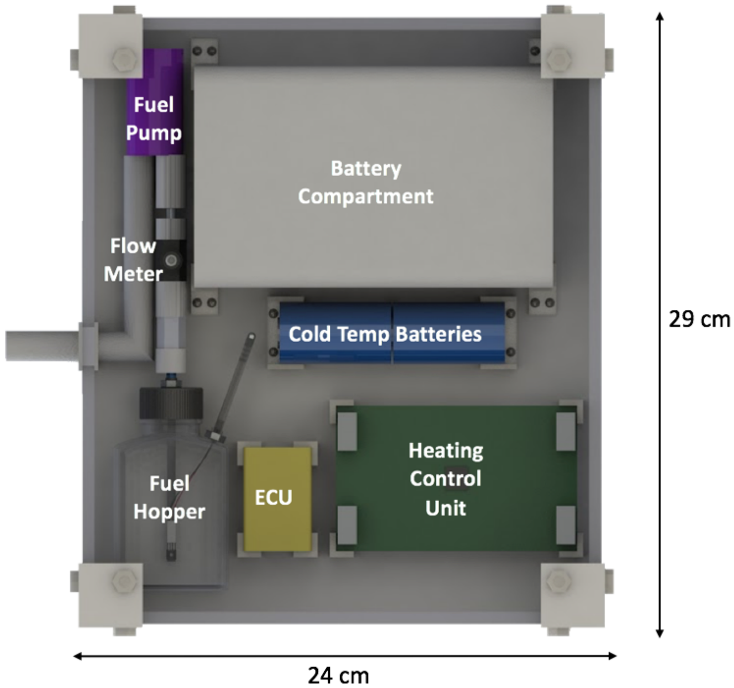

Figure 2. Electronics Box Layout

II. Control Laws

II.A. Temperature Control

One of the most important aspects of controlling the temperature and mass flow rate of the fuel is creating an effective control law. For this project, a conditional control law was chosen to regulate the warming of the various components. This type of control law was chosen in part because of the relatively long timescales at which the thermodynamic processes involved in conductive warming occur. The warming period was designated to be 8 minutes, which accounts for the UAS falling from 30,000 ft. Since the starting temperature for all components can be assumed to be -50°F, and the final temperature is at most 122°F due to electronic component limitations, the greatest temperature change experienced will be 172°F. The average temperature change for any component in the project will be at most 0.4°F per second. It is important to point out that the Heating Control Unit (HCU) must perform the temperature conversion calculations for all temperature sensors every 0.25 sec and thus would be able to observe the transient warming of the project to well within the $\pm\ 3.6°F$ requirement.

Figure 3 illustrates the performance of the aforementioned temperature control scheme. This figure highlights that with the repeated on/off nature of a conditional control law with an operational frequency of 4Hz, the temperature of any of the regulated components can be maintained at its desired temperature to $\pm\ 3.6°F$.

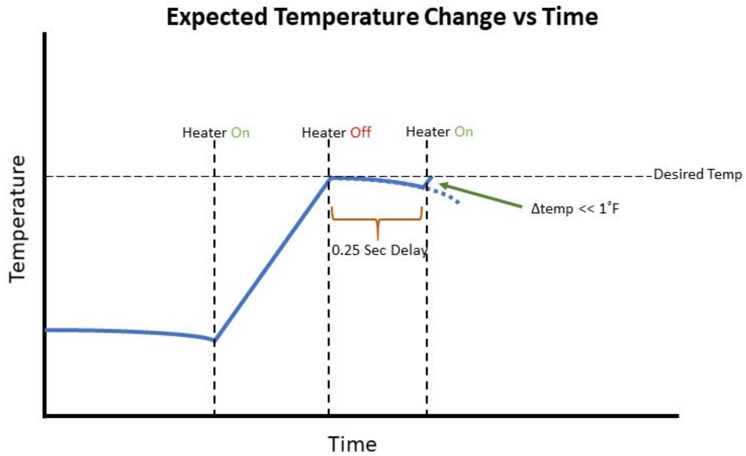

Figure 3. Validity for the Temperature Control Scheme

II.B. Flow Rate Control

The next type of control law which will be introduced for this project is the control law which governs the fuel pump and, by extension, the mass flow rate of fuel. This control law is built upon the assumption of a linear relationship between the input voltage to the pump and the output fuel mass flow rate. This assumption is adequately confirmed by a test, whose data is displayed in Figure 4. The error on the linear regression for the region up to 4.5 volts has been calculated to be 0.13 g/s. The control law leverages this linear relationship to translate from voltage to mass flow rate and *vice verse* in order calculate a duty cycle by which to regulate the voltage coming from the main heater battery. The first step is to use the linear relationship to select an initial estimate for the voltage to send to the fuel pump. The pump is then allowed to run for 0.26 seconds while the flow meter samples the flow rate of fuel passing through it. This flow rate is then compared against the desired flow rate and then the voltage is then altered using the slope of the line in Figure 4, rather than using the line itself. Using the slope of the line ensures that the voltage for the fuel pump will always decrease if the flow meter records a flow rate which is larger than desired and will always increase the voltage if less mass flow was recorded than expected. This process will then continue until a mass flow rate of zero is recorded, thus signifying that all of the fuel has been exhausted from the hopper.

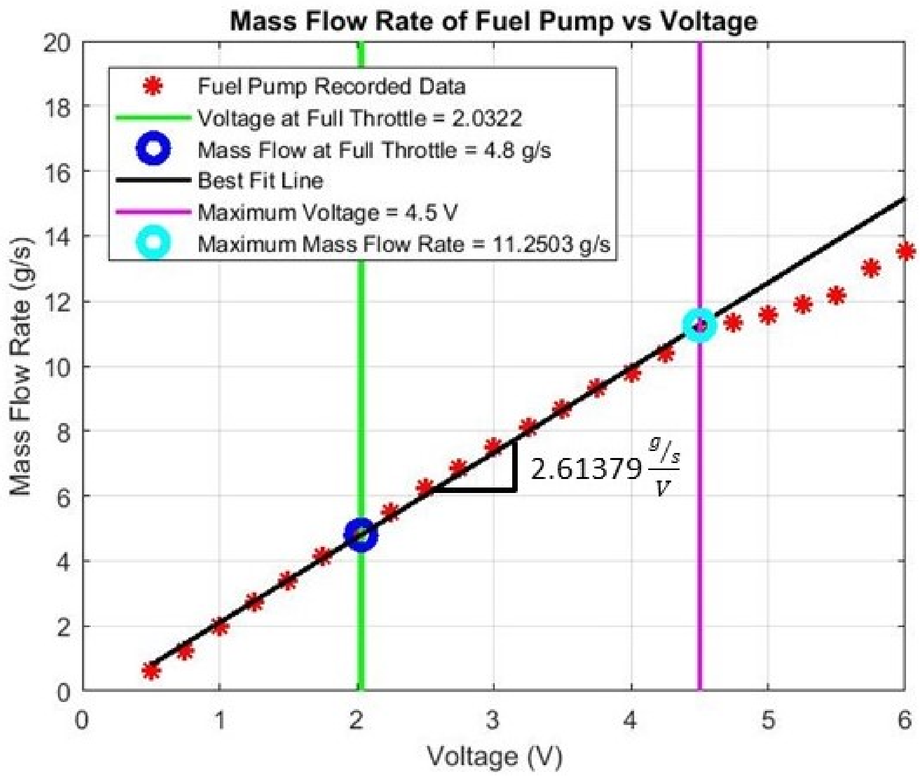

Figure 4. Relationship Between Mass Flow and Input Voltage

III. Insulation

For this project, one of the major concerns was providing initial energy to power the electronic control unit and the resistive heating elements. The team discovered an Aerogel brand insulation called Cryogel, designed specifically for low-temperature applications. The Cryogel insulation has a thermal conductivity of 15 mW/m*K at -100°F, making it ideal for the ACES application. Given the cold soak conditions, the design demands insulation on the heating battery, the engine battery, and the fuel lines. However, there are several concerns with this particular insulation. The primary concern is how to secure the insulation around the components. Adhesives can't be used directly on the insulation, since Cryogel is extremely dusty and any adhesive will simply pull dust off the insulation sheet. The team was originally going to use a needle and thread to seal the insulation, but discovered that the insulation compressed significantly when punctured by the needle, potentially decreasing its thermal resistance. To mitigate this, the team sealed the insulation by surrounding the components with layers of Cryogel and bound them with nylon thread. The insulation-covered batteries are then wrapped with thin polyvinylidene chloride (PVDC) sheeting, and sealed with adhesive wrap. This solution is shown in Figure 5.

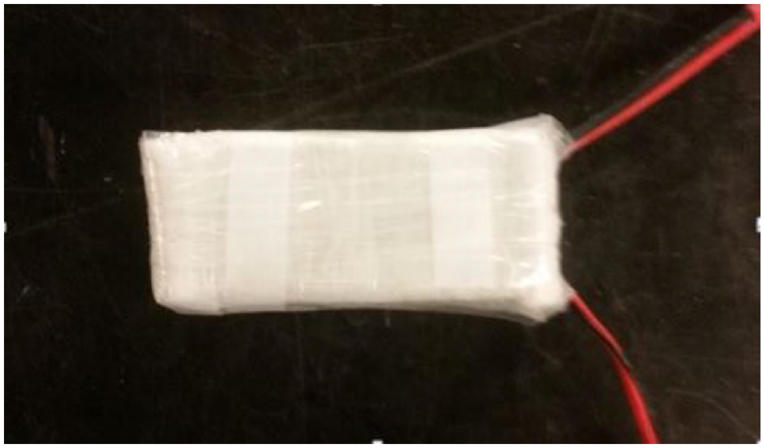

Figure 5. Insulation Configuration around a Battery

This configuration seals the insulation, and avoids compromising its effectiveness as an insulation.

IV. Resistive Heating Patterns

IV.A. Resistive Wire & Power Resistor Placement

Using the insulation, the effects of the cold soak environment will be reduced. Using Solidworks[1] thermal simulations, a basis for the temperatures after cold soaking could be analyzed. Figure 6 shows the results of these thermal simulations for the proposed heating box.

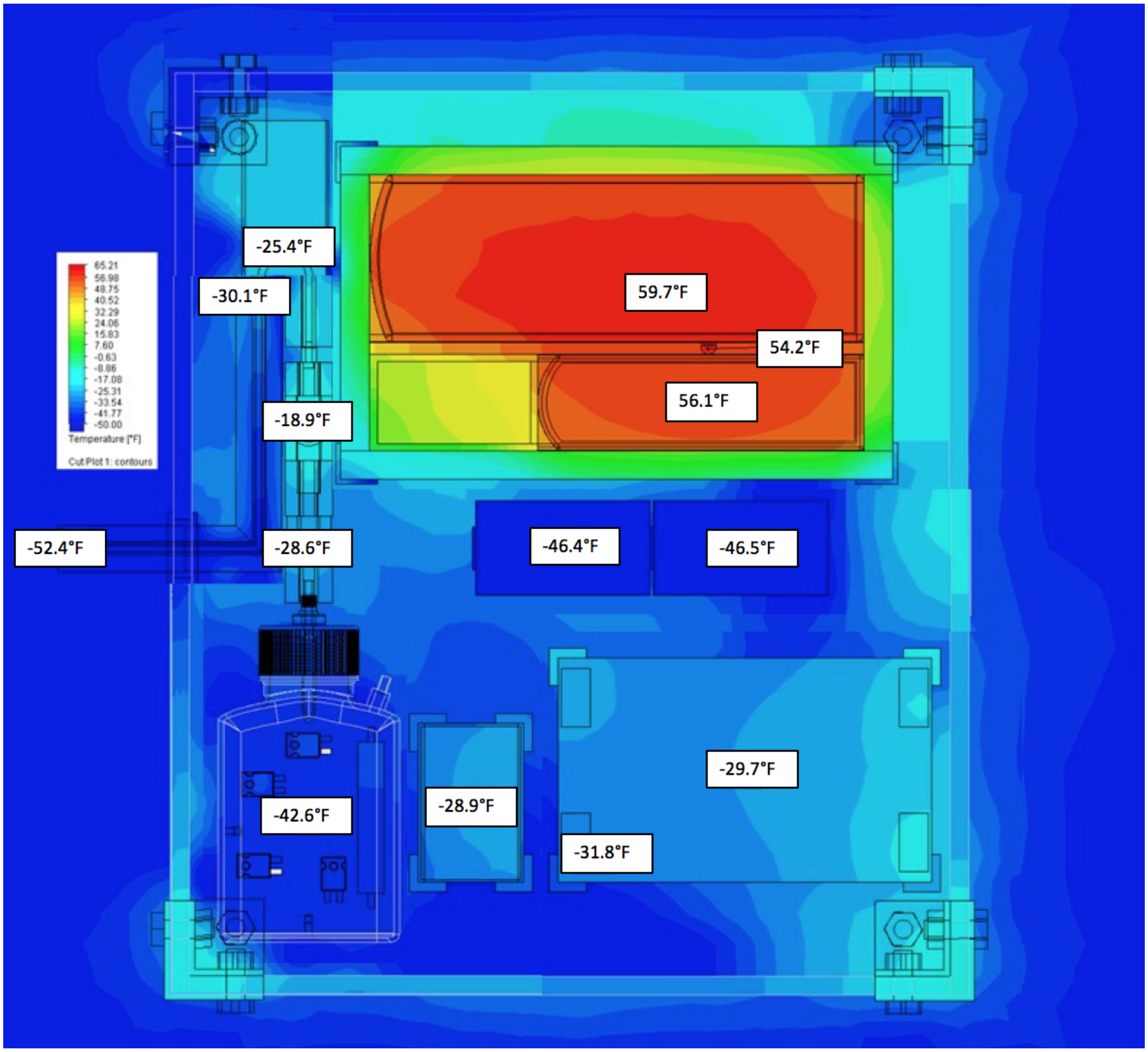

Figure 6. Solidworks Flow Simulation for the Cold Soaking of the Electronics Box Over One Hour at -50°F

These results demonstrate that although the batteries stay operable due to their insulation, other components will reach temperatures that are below the temperature range defined by the critical project elements. In order for the components to reach the desired temperatures, resistive heating elements were implemented in order to heat the components to their desired temperatures. The resistive heating elements chosen for this purpose are two different values of resistive wires, 3.1 Ω/ft and 0.88 Ω/ft. Ceramic power resistors will used within the fuel hopper and engine cowling. These wires and resistors were chosen due to their high reliability, manufacturablility, and versatility. The heat produced by the resistive wire wrapped about the components will be controlled by varying the voltage provided to the wires. The two LiPo batteries, fuel hopper, fuel lines, and the ECU were determined to need additional heating and have been surrounded with resistive wire. Specifically, the 3.1 Ω/ft wire is wrapped around the fuel line that goes from the fuel pump to the engine, outside of the fuel hopper, and the engine control unit. The 0.88 Ω/ft wire is wrapped around the smaller sections of the fuel lines and both batteries. Power resistors will also be located within the fuel hopper, since the external heating didn't provide enough heat to raise the temperature of the fuel within the hopper to its desired operating temperature. For the purpose of this design, all of the fuel will be heated to an operating temperature of at least 60°F by these resistive elements. Figure 8 shows the results of the cold soak thermal simulations for the engine cowling, showing that the ESB also needs active heating. For this reason, power resistors will be placed underneath the engine sensor board. The location of the resistors within the engine cowling can be seen in Figure 7.

Furthermore, while Figure 6 indicates that the LiPo batteries nearly satisfy their temperature requirement without the need for additional warming, it is important to remember that a user might want the LiPo batteries warmer so they operate with better performance.

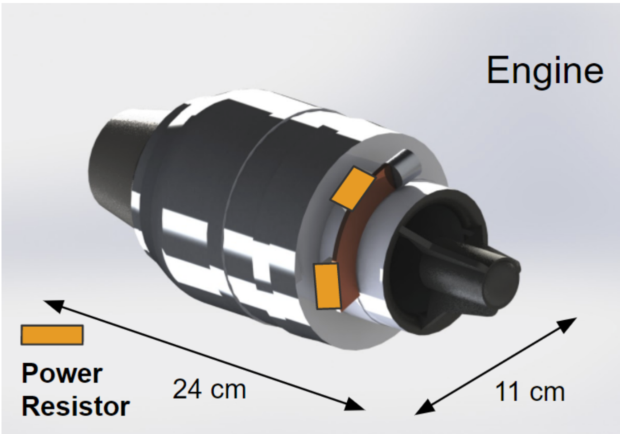

Figure 7. JetCat P90-SXi Engine Showing Power Resistors

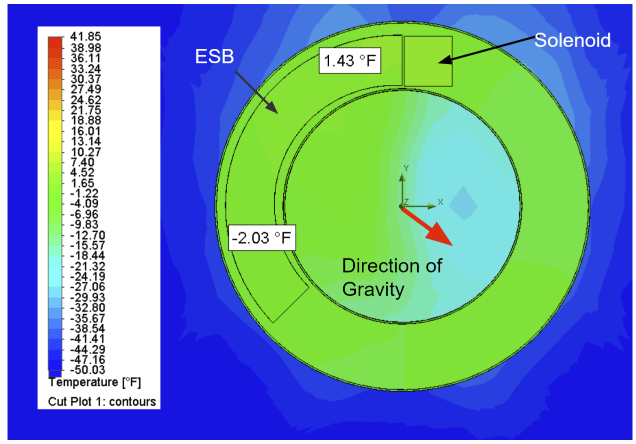

Figure 8. Solidworks Flow Simulation for the Cold Soaking of the Engine Cowling Over One Hour

Once resistor location and wire placement were determined, another thermal simulation was conducted to find the exact power values needed to heat each component to an operating range. The results of the heating thermal simulation for the box are shown in Figure 9, and the results of the simulation for the engine cowling are shown in Figure 10.

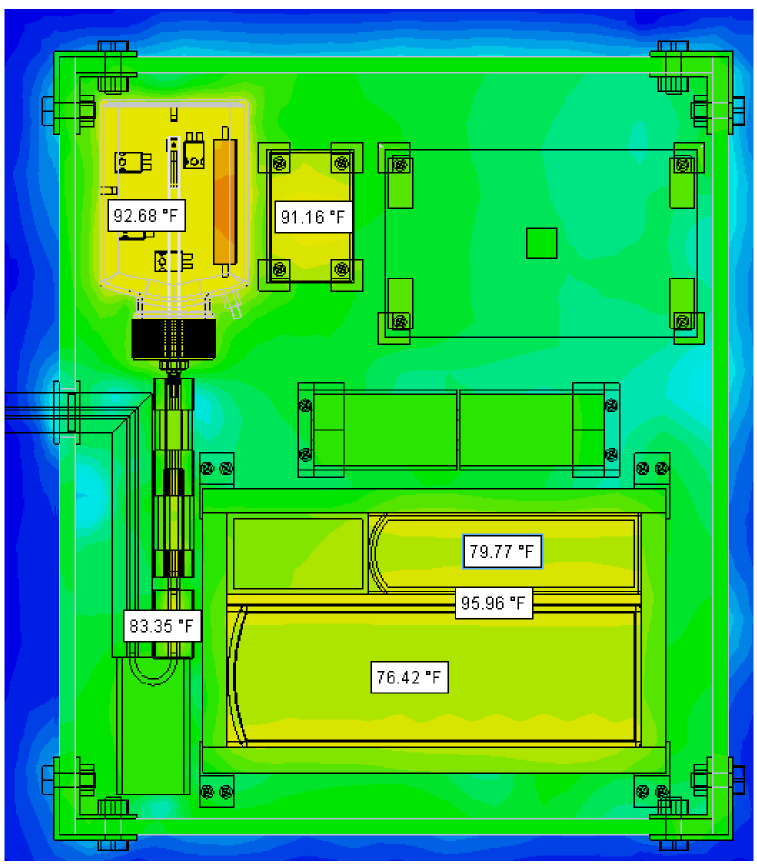

Figure 9. Solidworks[1] Flow Simulation for Heating the Box

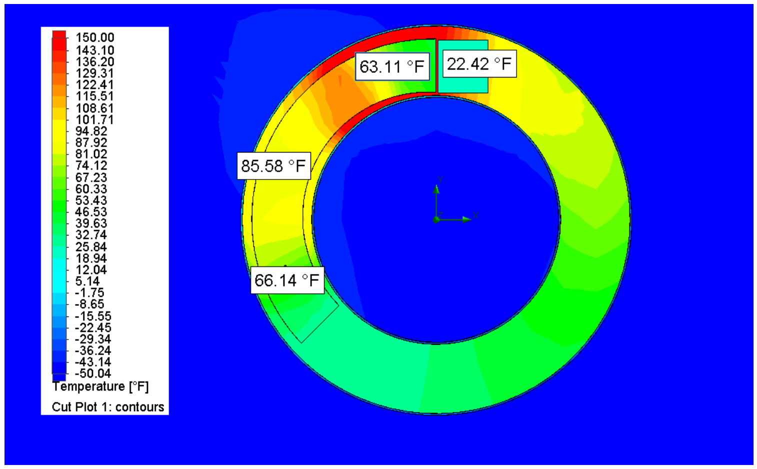

Figure 10. Solidworks[1] Flow Simulation for Heating the Engine Cowling

The heating simulation showed that the fuel hopper will require a total of 53 W to go from -50°F to 60°F within 8 minutes. This power is being supplied through the use of four 2Ω resistors that will provide 11.39 W each and 1, 1.3 Ω resistor that will provide the 7.49 W. Two resistors are required within the cowling and will provide 10 W per resistor to heat the engine sensor board to an operating temperature. The batteries require 18 W, the ECU requires 11.9 W, outside the hopper requires 12 W, and the fuel lines require 1.5 W. With the power value determined, the exact length of wires were measured and wrapped around each component.

IV.B. Magnetic Field Mitigation

Initially, the plan was to wrap the various heated components in a circular pattern, seen in Figure 11, showing the proposed pattern on the main heater battery of the design. This pattern was changed once the team realized an induced B-field would be produced as running a high current through a coil of wire generates a magnetic field through the center of the coil. The team was concerned that the multi-cell Lithium Polymer composition of the main heater battery would be adversely affected by the induced B-field. Specifically, the B-field would tamper with the charge equalizer circuits within the battery, meaning one cell in the battery could be overused. The purpose of the charge equalizers is to ensure the cells are drawn from at a uniform rate. With the tenuous energy situation created by the cold soak conditions of this design, any unnecessary tampering with the battery was deemed unwise and the circular wrapping pattern of the batteries was exchanged for one in which a B-field would not be induced.

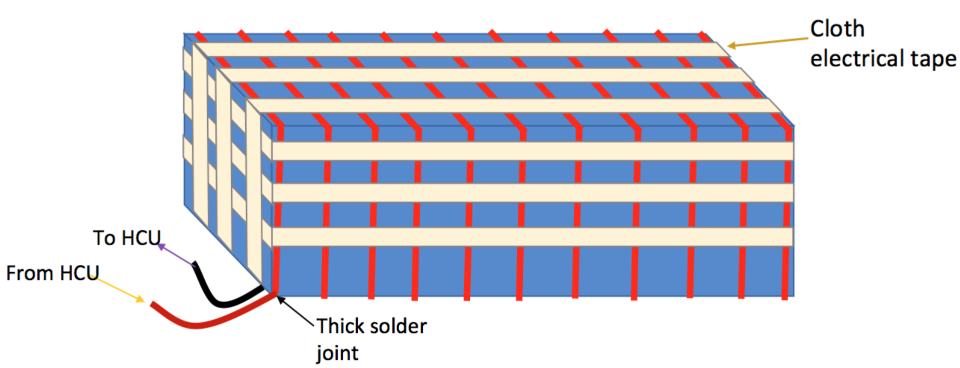

Figure 11. Circular Resistive Wire Pattern on Main Heater Battery

The team then decided to wrap the resistive heating wire in the pattern shown in Figure 12, in which the lines were folded back upon themselves in order to eliminate the coiled nature of the wire from the previous pattern. This design was replicated on all other electronic components, as they also could have been adversely affected by a magnetic field.

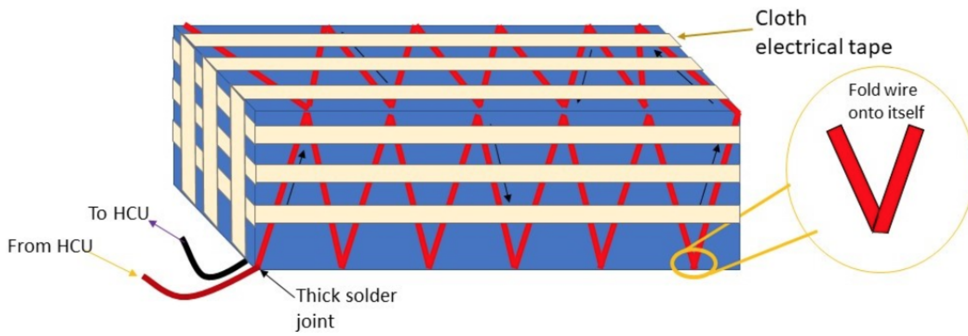

Figure 12. Current Wire Wrapping Pattern for Main Heater Battery

V. Project Application

This project is intended to be utilized as a testbed for researchers interested in starting a JetCat P90 or similar engine at cold temperatures. The goal is for researchers to be able to specify a desired temperature and mass flow rate of fuel, which the system will then provide, while ensuring that the ECU, ESB, and engine battery remain within their operating temperature ranges. Thus, researchers would be able to manipulate these variables as they desire, within a tolerance designated by the capabilities of the system. This would allow the researcher to investigate the effect of changing temperature and mass flow rate on fuel spray and ignition characteristics inside the engine. Additionally, the Air Force Research Laboratory desires to carry a drone, powered by the P90 engine, on the exterior of a parent aircraft flying at 30,000 ft. At this altitude, the ambient air temperature is -50°F, and the drone would be released from the parent aircraft and must start its engine in cold-soaked conditions before reaching the ground. In this way, the drone can be deployed to remote locations without drawing attention to itself, as the heat signature of its engine will not be visible until it is close to the ground. The work that the team has performed will assist in the development of this drone by providing a platform that will facilitate future research regarding starting the P90 at -50°F.

VI. Conclusion

With the motivation being driven by the Air Force Research Laboratory's conference held in May of 2018, a group of 11 aerospace engineering students from the University of Colorado Boulder have derived a list of requirements, goals, and tests in order to conduct a successful senior capstone project. The overarching goal of the conference is to compare the design solutions of eight different universities with the intention of using the more successful ones for practical application. The Air Force wants to deploy a UAS from a mother-ship at an altitude of 30,000 feet, which has a typical temperature of -50°F. Therefore, the goal is for these universities to design possible solutions for being able to start the JetCat P90-SXi miniature jet engine after being cold soaked to this temperature.

For a senior capstone project, the ACES team has developed a solution that focuses on the heating of the essential fuel delivery and electronics components associated with this particular miniature jet engine. As this paper is being written, the team has been able to accomplish various tasks as well as verify their functionality in order to accomplish the aforementioned goals explained in higher detail in both the abstract and introduction. At the date of submission of this paper, necessary control laws have been implemented to the heating control unit in order to provide power to heat the components of focus not only above operational range, but to also keep them below temperatures that would cause them to get damaged. The control for the fuel pump has also been implemented to the HCU, with the desire to keep the fuel flow rate within its nominal operational range. The method of securing the robust Aerogel insulation to certain components has also been verified in order to determine its manufacturing feasibility, however, the ACES team still needs to test its effectiveness in the coming weeks. This will be achieved by utilizing the team's designed cold temperature chamber, which uses dry ice and control fans in order to keep the ambient air temperature at a uniform -50°F. While some of the components were able to be simply coiled with resistive heating wire, electronic components have been wrapped in a specific diamond pattern in order to cancel the magnetic fields generated by the flowing current. ACES is on schedule to complete essential sub-systems tests prior to conducting a final full integration test of the system as a whole on April 6th. In order to ensure the final integration test runs as the team has designed for, ACES must first finish wrapping all of the components in the Aerogel insulation, individually test these components to compare to the corresponding thermal models, and test the heating control unit's ability to control the fuel delivery and electronics subsystems individually.

Acknowledgments

We would like to thank Dr. Donna Gerren as well as the rest of the Professional Advisory Board of CU Aerospace Engineering Sciences Senior Projects for their assistance with this project.

References

[1] *SolidWorks 2015*. Dassault Systemes SolidWorks Corporation., 2015.