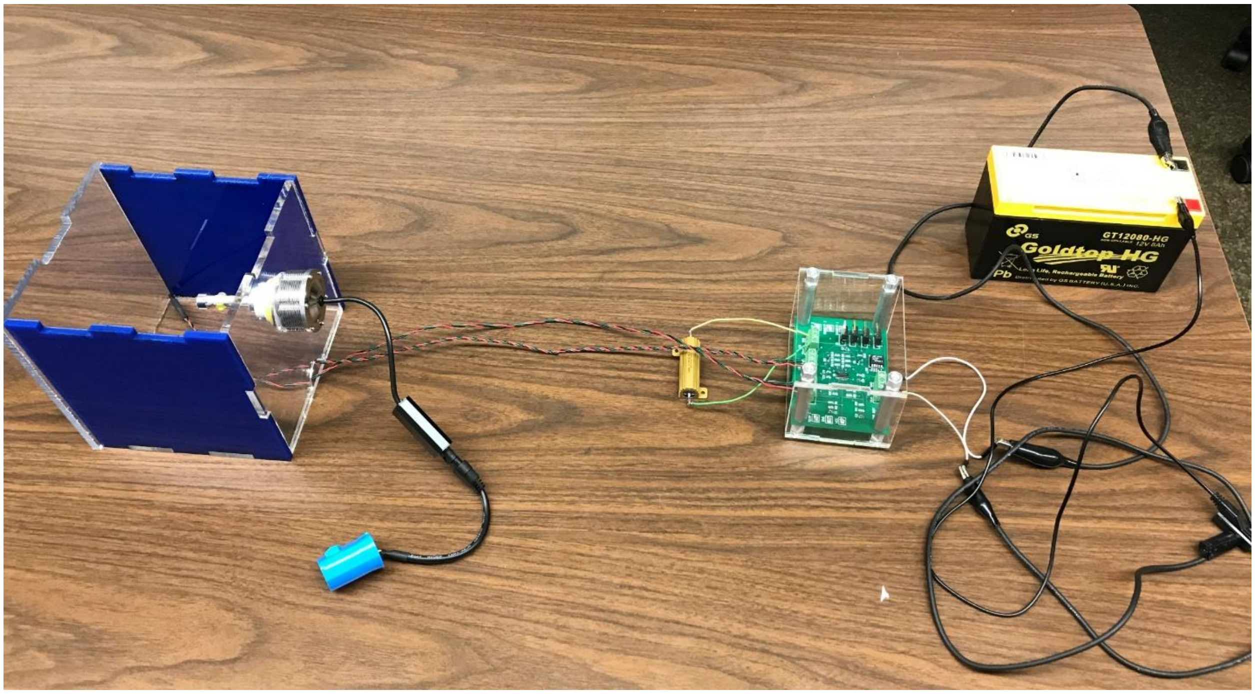
Efficient LED Headlight Heating System



A Major Qualifying Project
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Abstract

Light-emitting diode (LED) headlights are becoming more popular on automobiles due to their increased efficiency. This increased efficiency causes a problem: ice and snow accumulation on the headlight lenses. This project explores the feasibility and implementation of an LED headlight heating system in order to prevent dangerous snow and ice accumulation. Several different methods are simulated and prototyped. The ultimate method decided upon utilizes a temperature sensing circuit to control a transparent heater. A printed circuit board (PCB) is constructed and used in a mock headlight enclosure. There are several future recommendations for this project which are designing an alternative headlight enclosure, implementing additional sensors, using pulse-width modulation for the heat film, exploring the interface to the car, running additional temperature simulations for air flow models, and performing additional research into configuration of the temperature sensors.

Executive Summary

Traditionally, automotive headlights have used halogen bulbs as their primary lighting source. Halogen bulbs provide light while simultaneously outputting large amounts of heat, rendering them fairly inefficient. A newer trend in automotive lighting, LED bulbs offer increased efficiency and design options. Unlike their halogen counterparts however, LED bulbs do not output excessive amounts of heat. This leads to an unfortunate consequence: the build-up of ice and snow on the headlight lenses. This is dangerous for the driver, other drivers, and pedestrians as it reduces visibility.

Several solutions for this problem are explored in this paper. To test each solution, a headlight was modeled using a 6” cube. Five of the sides are constructed out of acrylic and the lens is polycarbonate to replicate the material of a standard car’s lens. The back side of the enclosure has two holes in it; one hole is for the headlight, while the other is for wires. To produce an air tight seal, the sides are fit together using tabs and glued using an acrylic solvent.

In order to maximize efficiency, the first solution explored the use of the small amount of heat the LED produces. This heat is directed at the interior of the lens with the goal to conduct through to the front of the lens in a timely manner. This method utilizes fans to push the heat towards the interior of the enclosure. A control circuit uses two temperature sensors to determine if the lens is below a threshold temperature and uses that information to control a switch to the fans’ power. Heat flow simulations show that simply using the heat from the bulb does not produce sufficient heat to melt the snow and ice in the desired time of 10 minutes.

As a revision, the heat sink of the bulb was then included in the enclosure. Using the same control system, the expectation was that the additional heat from the heat sink would be enough to heat up the front lens. Again, running heat flow simulations show that this still does not provide a timely response.

The final revision to produce a timely response removes the fans and adds an Indium Tin Oxide (ITO) transparent heater to the interior of the lens. Ideally, applying heat directly to the lenses would melt the snow and ice quicker and more effectively. Heat flow simulations prove that this solution is feasible for the desired response time.

A printed circuit board (PCB) is constructed and used in a mock headlight enclosure to test the functionality of the control system. Four sets of terminal blocks are on the PCB in order to connect the car battery, the two temperature sensors, and the heating film. The system works by processing the analog output voltage from two temperature sensors and determining whether the heating film needs to be on to melt snow and ice. Two Schmitt triggers create individual hysteresis loops that determine the on and off cutoff temperatures. In order to neatly display the PCB, an acrylic display case was designed.

To test the cutoff temperatures of the control system, the necessary outputs from the temperature sensors are simulated in the lab. To test the system as a whole, the temperature sensors and the heat film are connected and tested using a 12V battery. To test the physical response of the system, the mock headlight is placed in a freezer and allowed to reach the ambient temperature of 0°F. The time required to heat the front lens to the desired temperature is measured while applying 12V to the heating film. Based on the testing performed, the heating film can heat the front lens from approximately 0°F to 65°F in a 10 minute window. This proves that the application of an ITO heating film can be used to defrost an LED headlight in the time that it takes to warm up a car.

There are several future recommendations for this project that could increase its durability and marketability. Using an alternative headlight enclosure where the heat film is positioned between two panes of polycarbonate would reduce the time needed to melt the snow and ice off of the headlight. Additionally, it would protect the LED headlight from excess heat produced by the heating film. In order to reduce the power consumption of the system, pulse-width modulation (PWM) could be used to power the heating film. By setting the duty cycle of the PWM, significant power can be saved which will increase gas mileage. Furthermore, adding a photosensor to determine how much light is being reflected back from the front of the headlight can ensure a more accurate system. Currently, the system will be on when the temperature is below 35°F, however, there is not always snow and ice accumulations when it is cold. A photosensor can determine if the headlight is blocked and the heating film needs to be on. Moreover, a human interface in the car needs to be added so the driver can control when the system is being used. At this time, the system runs off the battery regardless of whether the car is running. Based on the current power consumption, this system will drain a fully charged car battery in approximately 14 hours. In order to avoid this, the system should only run when the car is running. Also, additional temperature simulations should be run to account for air flow on the outside of the headlight. This would account for the wind blowing against the headlight as the car is moving. This simulation is likely to show that it will take longer for the headlight to reach optimal temperatures as the wind will cool off the outside of the lens and the heating film is running. Lastly, during testing it was proven that the temperature sensors do not pick up the changes in temperature of the lens in the current configuration. Further research is required to find a configuration that can accurately measure the temperature of the headlight and shut off the heating film when the threshold temperature is reached.

1 Introduction

Technology in household and automotive lighting is rapidly advancing as more efficient means of illumination are becoming prevalent. Light Emitting Diodes (LEDs) have emerged as the most energy efficient type of bulb. The automotive headlight industry is slowly evolving as manufacturers push to make vehicles more energy efficient. Incandescent halogen bulbs have been the traditional lighting technique since the early 1960s, but are slowly being pushed out by this newer technology. The increased efficiency of LEDs allows much less heat dissipation than traditional halogen bulbs. As a result, in cool climates, snow accumulation on LED headlights raises a safety concern. When headlights are covered in snow and ice, drivers are put at risk due to decreased visibility, especially in snowstorms.

As it stands now, not all vehicles which incorporate LED headlight technology also incorporate mechanisms to prevent snow accumulation. Currently, only a few car manufacturers build solutions to this problem into their headlights. For example, Audi uses a fan system to heat their headlights so that they do not frost over [1]. This project explores a similar fan system to heat the headlight.

In order to solve the problem of snow and ice accumulation on the headlights various heating techniques are explored. These techniques are simulated and tested to explore their feasibility. Once determined that a technique is feasible from simulations, it is tested in the field to ensure functionality.

2 Background

This section explores the current automotive headlight technology and problems that it faces. It also explores the research behind possible solutions to these problems.

2.1 LED Market Trends

As the drive for a more sustainable world increases, more electrically efficient solutions are becoming available. One such solution to current electrical demand problems is the LED bulb. The lighting market is a $1.4 billion revenue industry, accounting for approximately 10% of all electricity consumed in the United States [2], [3]. LEDs are directly competing with the traditional lighting industry, as in recent they "have grown as a share of the global lighting market from an estimated 1.5% in 2011 to more than 27.2% in 2016" [3]. This overall infiltration of LEDs into the market extends into many specific industries. The automotive industry is one market which is seeing many technological improvements with the addition of LED technology.

Lighting accounts for approximately 18.9% of the automotive electronics industry which can be seen in Figure 1 below [3].

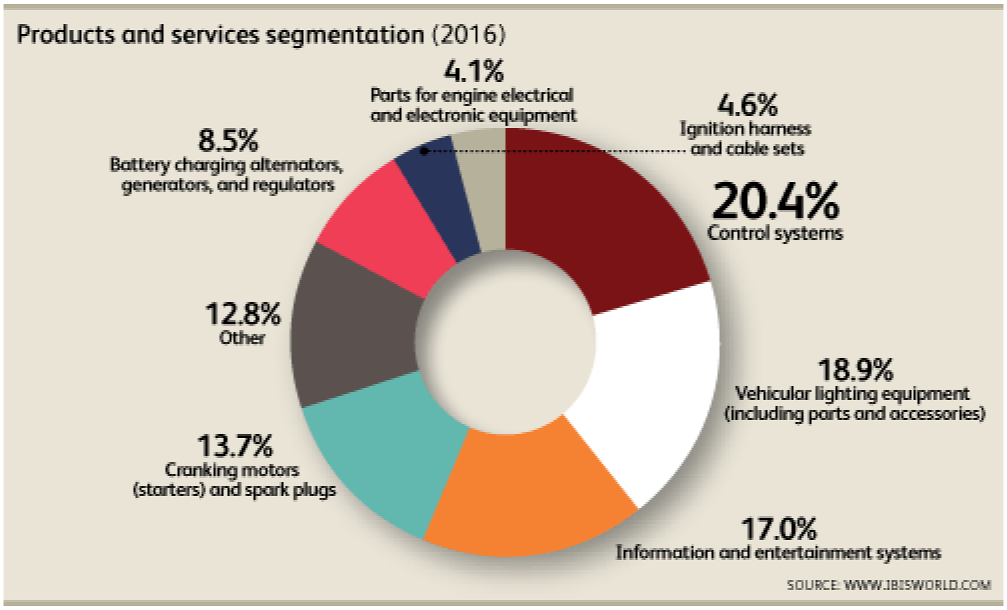


Figure 1 – Products and Services Segmentation of the Automotive Industry [2]

Due to the increased efficiency of LEDs, they are becoming a popular choice for car manufacturers to use and will likely be slowly transitioned into as the main automotive lighting type. Within four years, it is predicted that 20% of cars will use LEDs [4].

In terms of the available LED headlight technology, there are two current approaches: built-in models and retrofits. Many luxury car dealers such as Audi [1] are already participating in the LED headlight trend. Other more economical cars such as the Ford Explorer and Toyota Corolla now come standard with LED low beams [4]. For cars that do not come with LED headlights, there are many aftermarket bulbs available for purchase. Both General Electric and Phillips create their own retrofit LED headlight bulbs. These bulbs are not available or compatible for all types of cars, however [5], [6].

2.2 Automotive Headlight Technology - Existing types of headlights

Different types of automotive headlights that are available today are halogen bulbs, HID bulbs, and LED bulbs. Luxury car manufacturers are exploring the use of lasers as the future of headlight technology.

2.2.1 Halogen

Incandescent tungsten-halogen headlamps are the most popular automotive headlamp in the world, consisting of over 80% of the cars on the road [7]. These lights have been around since the early 1960s, therefore making them readily available, easy to replace, and cost effective. They work by heating up a tungsten filament with electricity from the car's battery. The filament heats up to approximately 2,500°C, emitting about 800-1000 lumens (lm). This high temperature reached by halogen headlamps is the grounds behind the headlight industry evolution. The excessive wasted energy being dissipated as heat ultimately shortens the lifespan of the battery and decreases the gas efficiency of the car [8].

2.2.2 HID

Xenon headlamps, known as high-intensity discharge headlamps (HIDs), are one solution to the efficiency problem. These headlamps were introduced in the mid-1990s and provide a more efficient way to create more light, which generates better visibility on the road than conventional halogen bulbs. They work through gas discharge principles, sending a current between two tungsten electrodes through a gas like xenon and medal salt. This forces a chemical reaction which intensifies light and increases efficiency over its halogen counterpart. Since there is no filament, these bulbs are more durable than halogen bulbs, allowing them to have a longer lifespan. With this advanced technology, HID bulbs tend to be more expensive. Furthermore, the blinding bright white color that these headlights emit causes complaints from oncoming traffic [8].

2.2.3 LED

LED headlamps are on the upward trend as car manufacturers are stressing efficiency. Their small size allows them to be easily maneuvered into tight size constraints and LED matrices, allowing for optimal light emission. Furthermore, the light emitted by the LEDs is a warmer color light than that of the HIDs, and therefore does not distract oncoming traffic. LEDs are composed of p-n junctions. When a suitable voltage is applied, the free electrons move across the p-n junction and fill in “holes” which releases energy in the form of photons. This process is called electroluminescence. This light is proven to be brighter than the standard halogen headlight by emitting between 2,000 and 3,500 lumens. A disadvantage of LEDs is that they are more expensive than even the HID headlamps. Additionally, the LED driver circuit produces heat, which needs to be drawn away from the bulb to maintain optimal efficiency. This typically requires a large heat sink. Although the driving circuit produces a lot of heat, the bulb itself does not; this has become a problem in colder climates. Halogen headlights melt snow and ice that have accumulated on headlights, while LEDs do not reach necessary temperatures to do so [8].

2.2.4 Lasers

Laser headlights could be a possible solution in the future. Engineers working for companies such as BMW and Audi are developing laser headlights. They would be the most efficient bulb on the market, exhibit small packing, and be 1,000 times brighter than any other modern headlight. In order to implement this, manufacturers are proposing that they use lasers pointed to the back of the headlight assembly which will then reflect off a matrix of mirrors in order to deliver light at the desired orientation. Future disadvantages to this type of headlight are that they will be extremely expensive and therefore will only be found in top end cars. Additionally, laser headlights will require a large heat sink for cooling because the driving circuit will create more heat than the LED driving circuit [8].

2.3 Power Comparison of Bulb Types

The three main types of bulbs for headlights vary greatly in power usage, light output, and lifetime. As a baseline, halogen headlights consume about 55 watts and produce only about 1400 lumens. This gives them a 25.45 lumens/watts ratio [8]. Additionally, halogen headlights have about a 1,000-hour lifetime under normal driving conditions. Next, HID headlights consume about 35 watts and produce about 3000 lumens giving them an 85.71 lumens/watt ratio. HIDs are one step above halogens as their average lifetime is about 2,500 hours. HID headlights have been reported to be too bright and thus are dangerous for oncoming traffic [8]. Though halogen and HID headlights have very standard electricity consumption and light output, LEDs can vary greatly in power usage, light output, and lifetime. A standard set of low beam LED headlights can produce as low as 1,900 lumens and up to 3,500 lumens. However, the power consumption scales almost linearly with the light output. The lumens/watt ratio varies between about 90-100 lumens/watt for all LED headlights. Additionally, the lifetime of the headlights varies between 30,000 and 50,000 hours under normal conditions. However, LEDs are vulnerable to non-ideal conditions which can drastically reduce the lifetime of the headlight. While LEDs can produce more lumens than HIDs, which have been described as too bright, LEDs can produce a warmer color that is not as blinding while still producing more light [9]. This information can be summarized in Table 1.

Table 1 – Comparison of Headlight Bulbs [8], [9] Problems with LED Headlights

Type of Bulb	Lifespan (hours)	Lumens	Watts	Lumens/Watt
Halogen	1,000	1,400	55	25.45
HID	2,500	3,000	35	85.71
LED	30,000-50,000	1,900-3,500	20-35	~90-100

2.4 Current Problems with LED Headlights

As with any new technology, there are a myriad of technological problems which must be solved. One of the largest problems with LED headlights is how to deal with the heat produced in the driving circuit. Currently, large heat sinks are placed at the drivers of LEDs in order to diffuse the heat produced. Although LEDs do not produce as much heat as their halogen counterparts, there is still some heat production. In experiments, the heat sink of a fully lit LED bulb was found to be 60°C - 100°C [10]. While this seems like a lot of heat, it is minimal compared to a Halogen bulb, which can reach up to 181°C. This difference in heat production leads to the development of a prominent problem in LED headlight technology: the accumulation of snow and ice on headlight lenses. Since LED lights naturally do not produce an abundance of heat, ice accumulates on headlights and becomes a safety hazard for drivers. Figure 2 exhibits this problem. In this figure, on the left is a halogen bulb with no ice accumulation and on right is a LED covered in snow.

This problem is a real safety issue. Newer luxury cars that come standard with LED headlights come with a built-in solution for this safety issue. Audi states that “Fans blow the heat of the LEDs towards the headlight cover to keep it free of fogging and snow as much as possible” [11]. This built-in functionality prevents the buildup of snow and ice accumulation.

Figure 2 – Snow accumulation on LED Headlight [12]

The real problem lies in retrofit bulbs, like the ones shown in Figure 3. Since these bulbs exist as drop in replacements for current headlights, there is no pre-existing infrastructure within the headlamp casing to ensure no snow accumulation.

Figure 3 – GE Nighthawk [5] and Philips X-treme Vision [6] LED Headlight Retrofits

This problem is especially evident in Jeep Wranglers. Many individual complaints of ice and snow accumulation on jeep’s headlights have been reported [13]. This is likely due to the lack of encasing around Jeep’s headlights, shown in Figure 4. The shape of Jeep headlights seems to lend itself more to snow accumulation than other types of headlights. However, this is not to say that ice accumulation is not a problem for other headlight shapes, as it certainly is. The problem with creating a de-icing system for Jeeps and similar vehicles is the lack of headlamp lenses at which to direct heat. The bulb itself would have to come prepared with a heating or de-icing system, as opposed to installing a system in the headlamp assembly. The aforementioned Figure 2 is a good example of typical snow and ice buildup on the lenses of headlights.

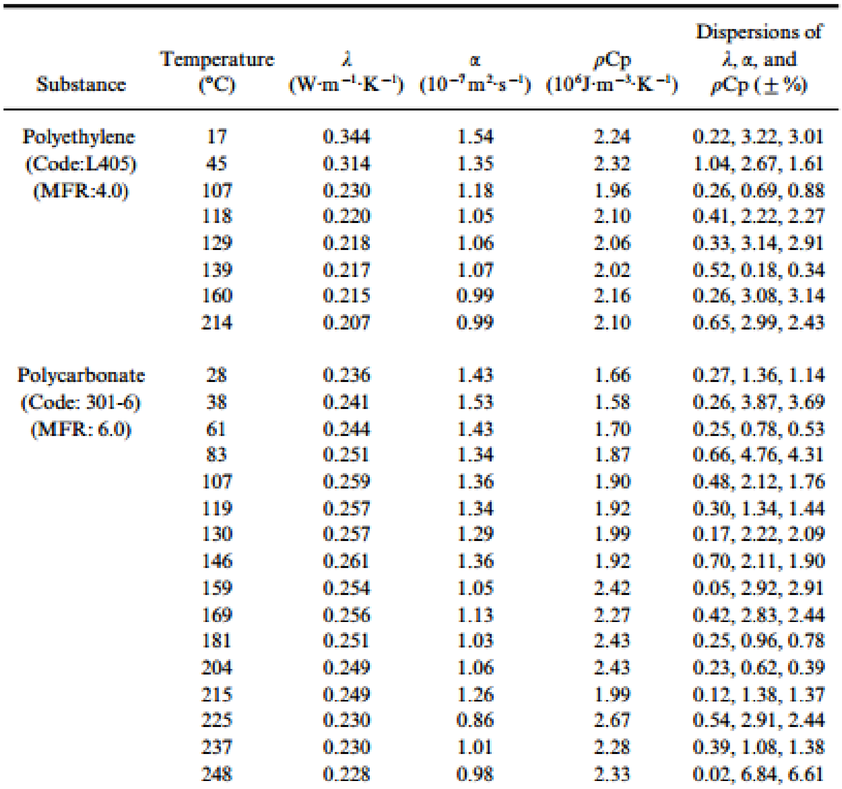
Figure 4 – Snow Accumulation on Jeep Headlight [14]

2.5 Thermal Properties of Headlight Enclosure

Headlight enclosures have become more and more standardized as time has passed. While the lens or cover for a headlight enclosure used to be made of glass some 30 years ago, nearly all headlight enclosures are now constructed of polycarbonate material. Polycarbonate is now used because it is transparent, relatively shatterproof, lightweight, and easily formable. These qualities make it excellent for use as headlight covers. Not only is polycarbonate used for the headlight lenses, but it also is becoming more commonplace for use as the actual bulb [15].

In applications concerning the movement of heat, it is important to understand the thermal properties of the material through which heat is to be moved. Repeated experimental analyses shows different thermal properties of polycarbonate in [16]. Summation of these results is shown in Table 2. In this table, thermal conductivity is the intrinsic property of a material to conduct heat. It is defined as the quantity of heat transmitted through a unit thickness in a direction normal to a surface area due to a certain unit temperature gradient with all other conditions as a control [17], and is denoted below by λ. This quantity can be used to determine the rate of heat transfer through the polycarbonate material.

Table 2 – Thermal Conductivity and Thermal Diffusivity of Polymer Melts [16]



Substance	Temperature (°C)	λ ($W \cdot m^{-1} \cdot K^{-1}$)	α ($10^{-7} m^2 \cdot s^{-1}$)	ρCp ($10^6 J \cdot m^{-3} \cdot K^{-1}$)	Dispersions of λ, α, and ρCp ($\pm$%)
Polyethylene	17	0.344	1.54	2.24	0.22, 3.22, 3.01
(Code:L405)	45	0.314	1.35	2.32	1.04, 2.67, 1.61
(MFR:4.0)	107	0.230	1.18	1.96	0.26, 0.69, 0.88
	118	0.220	1.05	2.10	0.41, 2.22, 2.27
	129	0.218	1.06	2.06	0.33, 3.14, 2.91
	139	0.217	1.07	2.02	0.52, 0.18, 0.34
	160	0.215	0.99	2.16	0.26, 3.08, 3.14
	214	0.207	0.99	2.10	0.65, 2.99, 2.43
Polycarbonate	28	0.236	1.43	1.66	0.27, 1.36, 1.14
(Code: 301-6)	38	0.241	1.53	1.58	0.26, 3.87, 3.69
(MFR: 6.0)	61	0.244	1.43	1.70	0.25, 0.78, 0.53
	83	0.251	1.34	1.87	0.66, 4.76, 4.31
	107	0.259	1.36	1.90	0.48, 2.12, 1.76
	119	0.257	1.34	1.92	0.30, 1.34, 1.44
	130	0.257	1.29	1.99	0.17, 2.22, 2.09
	146	0.261	1.36	1.92	0.70, 2.11, 1.90
	159	0.254	1.05	2.42	0.05, 2.92, 2.91
	169	0.256	1.13	2.27	0.42, 2.83, 2.44
	181	0.251	1.03	2.43	0.25, 0.96, 0.78
	204	0.249	1.06	2.43	0.23, 0.62, 0.39
	215	0.249	1.26	1.99	0.12, 1.38, 1.37
	225	0.230	0.86	2.67	0.54, 2.91, 2.44
	237	0.230	1.01	2.28	0.39, 1.08, 1.38
	248	0.228	0.98	2.33	0.02, 6.84, 6.61

The conductivity of the polycarbonate material can be calculated by using Fourier's Law, which states

$$q = \lambda A \frac{\Delta T}{s}$$

Equation 1 – Fourier's Law

Where

q = the amount of heat transferred in Watts

A = heat transfer surface area in meters squared

λ = thermal conductivity of the material in W/(∘K * m)

ΔT = temperature gradient, which is the difference in the temperature of the material in ∘K

s = the material's thickness in meters.

This is analyzed further in the Methodology Section.

Existing experiments have been conducted to see how the heat moves around in an enclosed headlamp space with LED headlights, a large heat sink, and an axial fan [18]. This study examined the large amount of heat produced by LED drivers and different cooling methods to mitigate the problem. The objective of the experiment was to examine the factors which influence the cooling performance of the air cooled heat sink model used in an automobile LED headlamp system. This was performed by measuring the temperature and thermal resistance of the enclosure at different significant locations. The enclosure used for this experiment is shown below as both a diagram and in actuality in Figure 5.

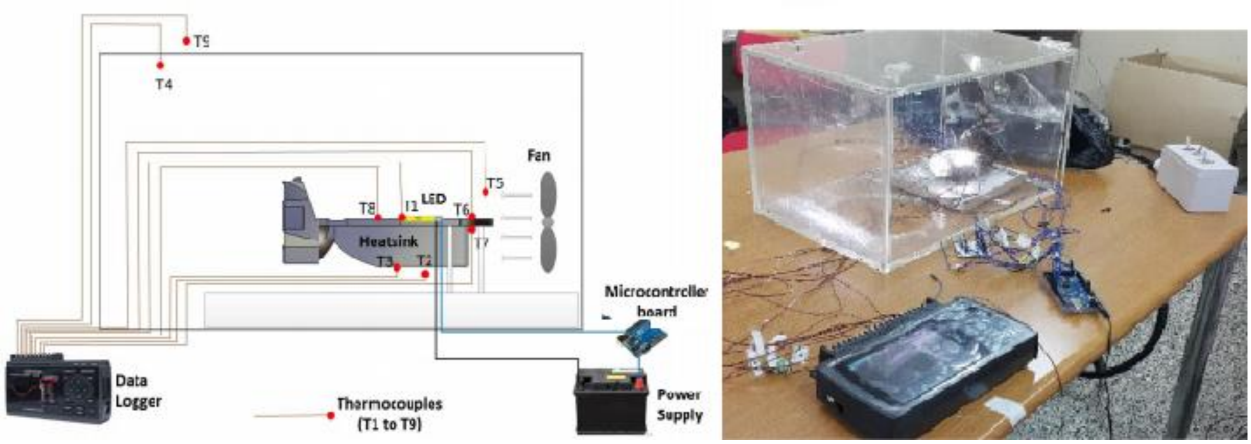


Figure 5 – Set up for LED Cooling System Heat Analysis [18]

This experiment, which was published in the International Journal of Control and Automation, yielded a few conclusions of evidence. The first is that “This thermal management protects LED from overheating as well as supports defogging of outer lens in cold conditions. This is achieved by moving hot air over the lens which gets heated up” [18]. The second important result as it relates to this project is the conclusion that the speed of the fan plays a very minimal role in the amount of heat moved around. Simply the addition of a fan seems to be enough, and increasing the speed of the fan only minimally increases the movement of the heat. The third important result is the plot of the temperature gradient in the enclosure. The relevant plot is shown in Figure 6. Here, the temperature at different points in the enclosure with the application of a fan is shown. Naturally, the junction temperature of the heat sink is highest. It is important to note the increase in the temperature of the air in the glass enclosure increases as time with the fan goes on from approximately 23°C to 25°C over a time period of only 1 hour. As the heat sink is significantly hotter than the ambient air, the laws of thermodynamics dictate that the temperature of the air is bound to increase over time [18].

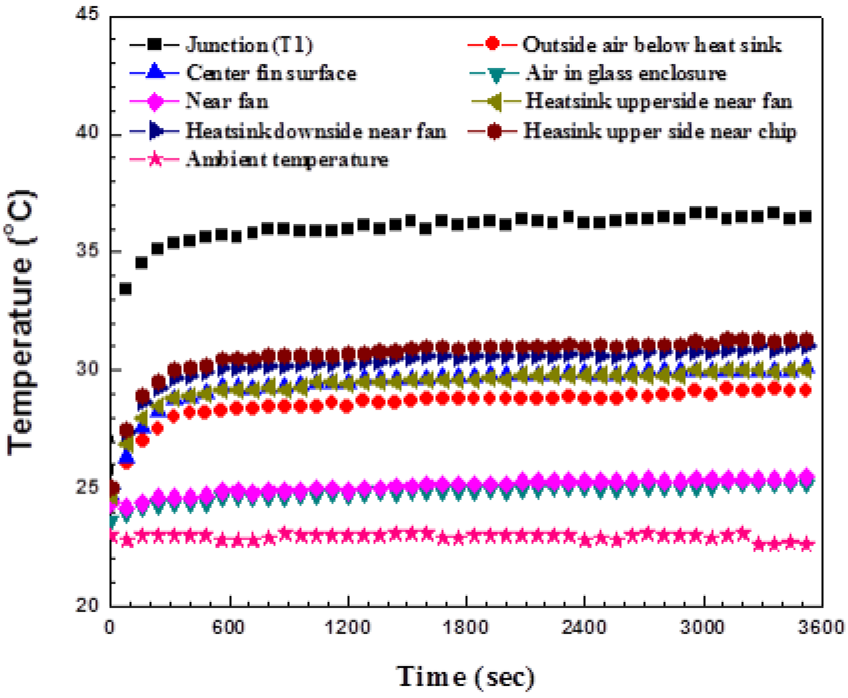


Figure 6 – Temperature Distribution at Different Locations within Enclosure [18]

2.6 Fan Research

In electronics, it is often vital to have small fans that can move heat away from heat sensitive components or to move heat to an area in need. There are many different types of fans that are used to circulate air. These fans are generally built to fit within a small size constraint, but powerful nonetheless. CPU cooler fans are the most common use of this application to keep the components in the CPU from overheating. A problem with these fans is that although they come in many small sizes, they cannot maneuver air around any obstacles. One type of fan that is better apt to maneuver air around obstacles is a bladeless air multiplier. A well-known example of a bladeless air multiplier is the Dyson fan, shown in Figure 7.

Figure 7 – Dyson Air Multiplier [19]

The Dyson Air Multiplier is a fan without any visible blades which gives effective air flow without needing much hardware. There is a typical axial fan hidden inside the pedestal, which pulls air into the device. The air flows through a hollow channel in the pedestal and hits the interior tube, acting like a ramp. The air flows along the ramp and then goes through slits in the back of the fan, and once again goes around an additional inner tube ramp before exiting the device. The Dyson fan does not just redirect the air being blown from the fan, it actually multiplies the air flow by a factor of fifteen [19]. The physics behind the Dyson Air Multiplier is due to the phenomena called inducement, which draws the air behind the outer tube to the front, multiplying the amount of air flowing through to the front of the fan. Additionally, the process called entrainment collects the air surrounding the edges of the fan to flow in the same direction of the breeze. Figure 8 shows how these properties work together to multiply airflow.

Figure 8 – Dyson Fan Airflow Diagram [20]

2.6.1 Power Consumption of Fans

Along with power consumption of the headlights, the power consumption of the fans used to move the air throughout the headlight needs to be examined as well. There are fans available from Sunon as small as 10mm x 10mm x 3mm, which only use 0.29 watts. They also make 15mm x 15mm x 3mm fans, which only use 0.1 watt. As the size of the fan grows, it will use more power, but will also move more air. The smallest fan available from Sunon moves 3.43 liters/min of air while the 15mm fan moves 8.75 liters/min [21]. Once it is determined how much air is needed for this application, the fan can be selected based on power usage and air flow.

2.7 Heat Film Research

Indium Tin Oxide (ITO) is the latest development in transparent heating film technology. It is a composition defined as either a ceramic or an alloy, depending on the concentration of oxygen. Oxygen-saturated composition is most common, creating a colorless and almost completely transparent ceramic when built in thin layers. ITO's are electrically conductive, making them functional for flat-panel displays, smart windows, polymer-based electronics, and heating applications. The conductivity of the material depends on its thickness. Thicker concentrations of ITO increases the concentration of charge carriers making the material more conductive, however, less transparent. Moisture does not affect ITO material, making it durable even in harsh conditions.

The electrical properties of Indium Tin Oxide make it diverse for many applications. ITO is an n-type semiconductor (electrons are the majority carriers) with a direct band gap of 3.5-4.3 eV [22]. ITO fabrication is executed through many applications such as DC and RF magnetron sputtering, electron beam evaporation, and thermal evaporation. Magnetron sputtering is the most common in industry, allowing for optimal control of the electrical and optical properties of the film. The sputtering of oxygen creates an oxygen concentration that is responsible for lowering resistivity and increasing optical transmittance in the ITO films [22].

Typical applications for ITO displays include transparent conductive coating for flat panel displays, organic light-emitting diodes, solar cells, antistatic coatings, and EMI shielding. Additionally, ITO films are applicable for defrosting surfaces or devices in cold settings. ITO heating films are widely used in extreme weather conditions such as defrosting aircraft windshields [23]. Camera lenses are another area where ITO heating films are applied, allowing photographers to be in frigid climates without their lenses fogging up or freezing.

One of the leaders in ITO technology is Thin Film Devices (TFD). Since thin film heat applications are a unique product, most orders from TFD and others in the industry are custom. Custom orders allow for flexibility in terms of the electrical and physical properties of the ITO heater. Tradeoffs between transparency and power ratings determine the physical thickness and construction of the material. The resistivity of the material determines the heat and power properties with lower resistance causing higher power consumption. TFD allows for resistances from 2 to 350 Ohms/Sq. Inch and power ratings for 0.1 – 5 Watt/Sq. Inch [24]. The greater the power per square inch, the faster the material will heat up as shown in the following figure.

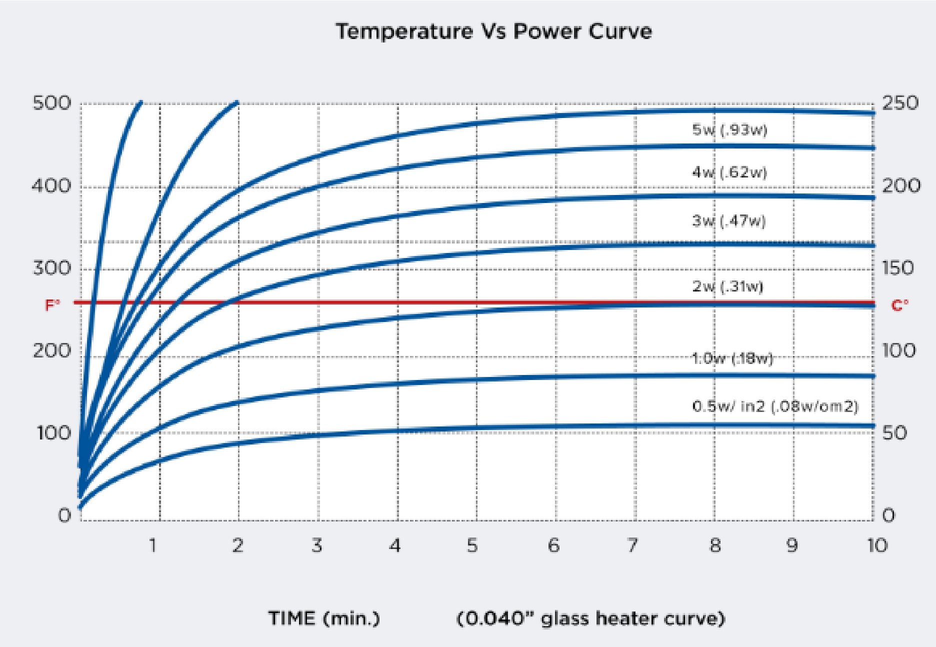


Figure 9 – Temperature vs. Power Curve [24]

2.8 Headlight Regulations

Any improvements to headlights in the US must comply with the rules and regulations set forth by the United States Department of Transportation National Highway Traffic Safety Administration (NHTSA) and the Society of Automotive Engineers (SAE). The rules and regulations for the NHTSA are published in the Federal Motor Vehicle Safety Standard 108 (FMVSS 108) and the SAEJ1383 for the SAE. These two publications regulate headlight specifications such as brightness, angle of the light, color, and when headlights must be turned on [25], [26].

Although the two publications set specific regulations, there are some areas where the manufacturers can customize their headlights to make them have a different visual appearance. For example, car manufacturers can change the location of the turn signals to be next to the headlight or it could surround the headlight. This allows car companies to have a distinct look to their cars that can distinguish them from other manufacturers. Car manufacturers can also use different types of lights, and the DOT has different regulations for each type of legal headlight. For upper beams, the DOT NHTSA sets the regulations, which are shown in Table 3. For lower beams, the SAE sets the regulations, which are shown in Table 4. Additionally, there are regulations set forth by the SAE, which states that upper beams must be symmetrical around the y-axis. Lower beams are not quite symmetrical, but are close. The SAEJ1383 includes a graph showing where the upper beam and lower beam light must be concentrated and the angles at which the light must be projected from the headlights. This graph can be seen in Figure 10.

Table 3 – Upper Beam Headlight Bulb Specifications [25]

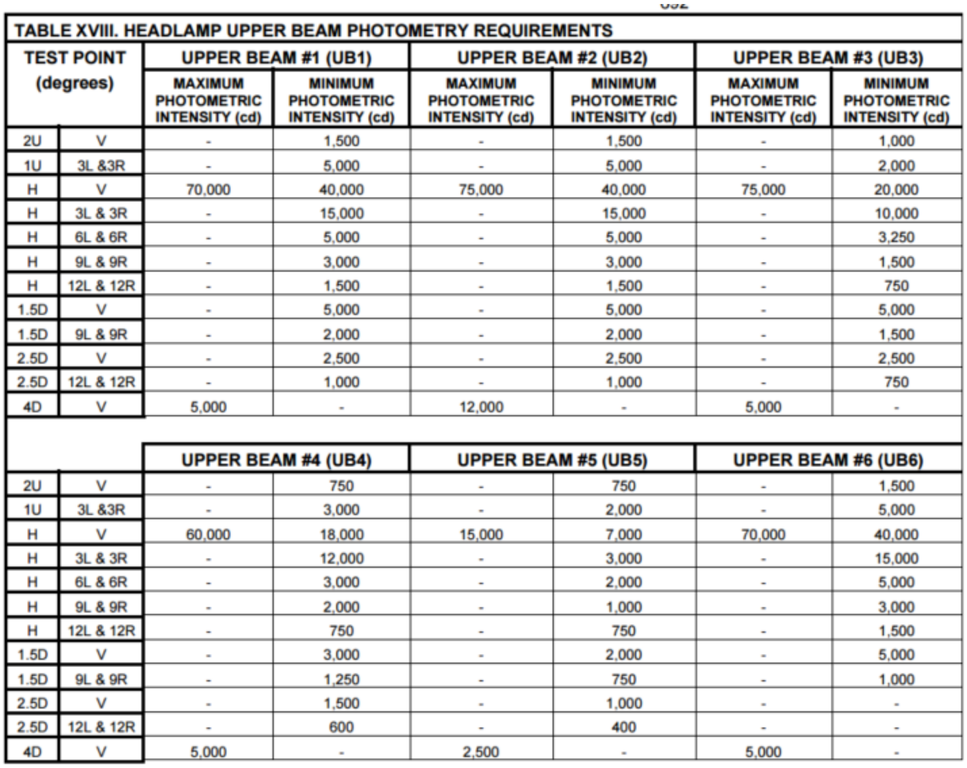


TABLE XVIII. HEADLAMP UPPER BEAM PHOTOMETRY REQUIREMENTS

TEST POINT (degrees)		UPPER BEAM #1 (UB1)		UPPER BEAM #2 (UB2)		UPPER BEAM #3 (UB3)	
		MAXIMUM PHOTOMETRIC INTENSITY (cd)	MINIMUM PHOTOMETRIC INTENSITY (cd)	MAXIMUM PHOTOMETRIC INTENSITY (cd)	MINIMUM PHOTOMETRIC INTENSITY (cd)	MAXIMUM PHOTOMETRIC INTENSITY (cd)	MINIMUM PHOTOMETRIC INTENSITY (cd)
2U	V	-	1,500	-	1,500	-	1,000
1U	3L &3R	-	5,000	-	5,000	-	2,000
H	V	70,000	40,000	75,000	40,000	75,000	20,000
H	3L & 3R	-	15,000	-	15,000	-	10,000
H	6L & 6R	-	5,000	-	5,000	-	3,250
H	9L & 9R	-	3,000	-	3,000	-	1,500
H	12L & 12R	-	1,500	-	1,500	-	750
1.5D	V	-	5,000	-	5,000	-	5,000
1.5D	9L & 9R	-	2,000	-	2,000	-	1,500
2.5D	V	-	2,500	-	2,500	-	2,500
2.5D	12L & 12R	-	1,000	-	1,000	-	750
4D	V	5,000	-	12,000	-	5,000	-
		UPPER BEAM #4 (UB4)		UPPER BEAM #5 (UB5)		UPPER BEAM #6 (UB6)	
2U	V	-	750	-	750	-	1,500
1U	3L &3R	-	3,000	-	2,000	-	5,000
H	V	60,000	18,000	15,000	7,000	70,000	40,000
H	3L & 3R	-	12,000	-	3,000	-	15,000
H	6L & 6R	-	3,000	-	2,000	-	5,000
H	9L & 9R	-	2,000	-	1,000	-	3,000
H	12L & 12R	-	750	-	750	-	1,500
1.5D	V	-	3,000	-	2,000	-	5,000
1.5D	9L & 9R	-	1,250	-	750	-	1,000
2.5D	V	-	1,500	-	1,000	-	-
2.5D	12L & 12R	-	600	-	400	-	-
4D	V	5,000	-	2,500	-	5,000	-

Table 4 – Lower Beam Headlight Bulb Specifications [26]

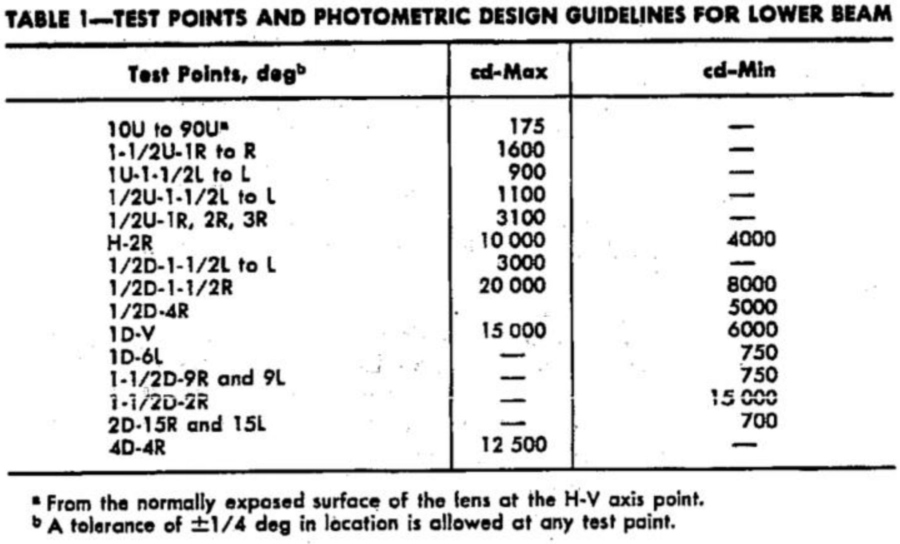


TABLE 1—TEST POINTS AND PHOTOMETRIC DESIGN GUIDELINES FOR LOWER BEAM

Test Points, deg[b]	cd-Max	cd-Min
10U to 90U[a]	175	—
1-1/2U-1R to R	1600	—
1U-1-1/2L to L	900	—
1/2U-1-1/2L to L	1100	—
1/2U-1R, 2R, 3R	3100	—
H-2R	10 000	4000
1/2D-1-1/2L to L	3000	—
1/2D-1-1/2R	20 000	8000
1/2D-4R		5000
1D-V	15 000	6000
1D-6L	—	750
1-1/2D-9R and 9L	—	750
1-1/2D-2R	—	15 000
2D-15R and 15L	—	700
4D-4R	12 500	—

[a] From the normally exposed surface of the lens at the H-V axis point.
[b] A tolerance of ±1/4 deg in location is allowed at any test point.

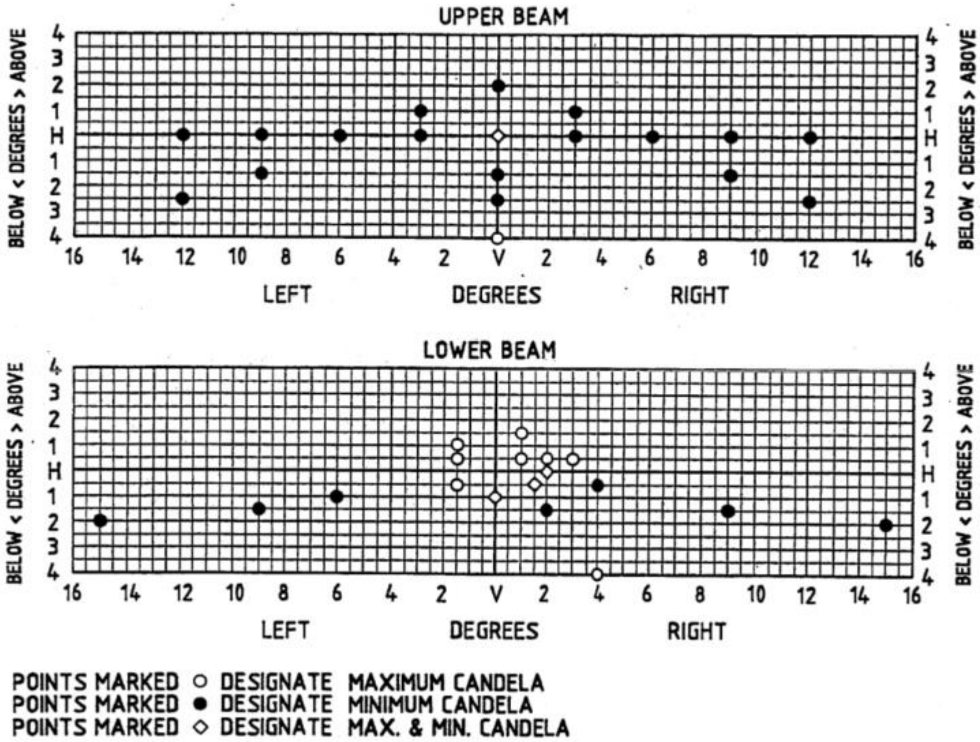


Figure 10 – SAE Regulations for Headlamp Angles [26]

3 Methodology

The methods to implement a temperature control system to prevent ice accumulation on the front of LED headlights was done in two main parts: enclosure and control system circuit. Designing and building the enclosure consisted of research of headlight properties, design of what enclosure is best suited for our purpose, simulations of temperatures inside and outside of enclosure, and the physical construction of the enclosure. Likewise, the control system circuit consisted of circuit design, circuit simulations (Multisim), building the circuit on a breadboard and a PCB, and lastly testing functionality.

3.1 Enclosures

In order to fully test our control system, an accurate depiction of the inside of a headlight must be brought to life. To build an accurate enclosure, the correct materials and dimensions are needed. Additionally, using the right dimensions and materials in a SolidWorks model gives us precise transient simulations of the temperatures in and out of the headlight enclosure. With the correct temperature values from these simulations, more accurate temperature bounds can be chosen for the temperature control system.

3.1.1 Headlight Enclosure

An enclosure which mimics the properties of a real headlight enclosure was necessary to test the functionality of the control circuit. The enclosure will be instrumental in verifying the practicality of the experimental results.

3.1.1.1 Design

In the design for the headlight enclosure, an existing Toyota Camry headlight was measured to be 6” x 5.5” x 4.5”. To simplify the design and simulations, the test enclosure design was built to be a 6” cube with a hole in the back face for the placement of the light bulb. A basic diagram of this design can be seen in Figure 11.

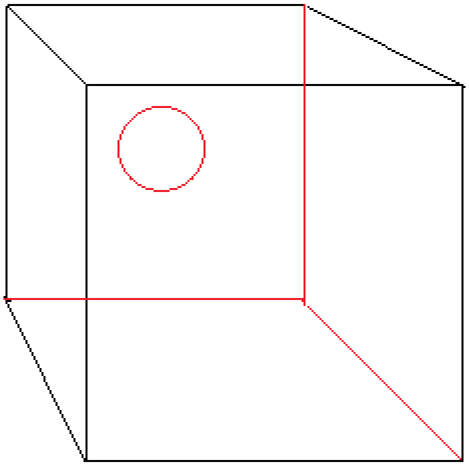


Figure 11 – Basic Enclosure Design

The design above was rebuilt in the SolidWorks Program for a more robust representation. Building the design in SolidWorks provided three benefits: it allowed for a good understand of the fit of the enclosure, for laser cutting of the design, and for accurate simulations to be performed within SolidWorks. The SolidWorks design of the enclosure is shown in Figure 12.

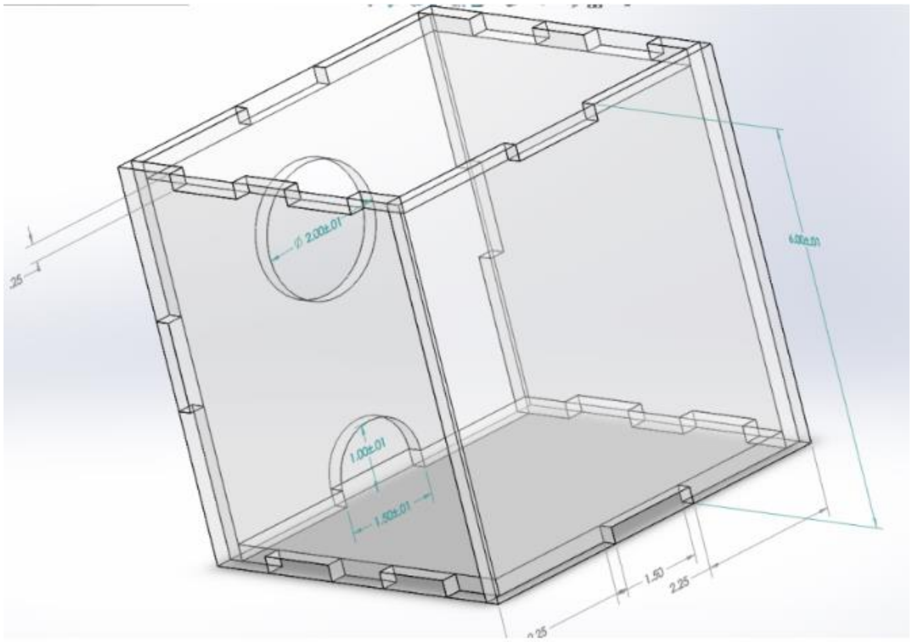


Figure 12 – SolidWorks design of Headlight Enclosure

Figure 12 shows the SolidWorks model of the headlight enclosure with certain dimensions marked. The width of each wall was chosen to be 0.25”, therefore a material of the same width is chosen in printing. The tabs used to join the box and provide stability are also 0.25” thick in order to allow a flush, smooth design. A semicircle cutout is added to the back wall of the design to allow wires to run through.

3.1.1.2 Materials and Assembly

The choice of the materials becomes important for the validity of testing the system. Section 2.5 details the materials in a headlight enclosure and mentions that the lens material is specifically made of polycarbonate. Impact-Resistant Polycarbonate was used to mimic the headlight lens. The choice of this material was important because its thermal properties must closely mimic those of a headlight lens in order to provide validity to any experiments.

One side of the enclosure is chosen to be the “lens” and is constructed of polycarbonate. The other five sides of the enclosure are made of a hard acrylic. This material was chosen because it is frequently chosen for different types of enclosures due to its lightweight, durability, and aesthetic appeal. Additionally, acrylic is easy to cut using a laser cutter, which is readily available for student use.

The laser cutter is a programmable tool, which cuts materials using a thin laser, following a user-provided design. The design must be provided as a 2-D drawing. Each face of the enclosure shown in Figure 12 is printed to a 2-D .DWG file using AutoCAD. This AutoCAD file is then given to the laser printer. The laser printer is calibrated and used to cut the 5 acrylic sides.

Polycarbonates cannot be cut on the laser cutter because the material will both catch fire and emit toxic gases, and so the polycarbonate was cut using a band saw. The drawbacks to this were slightly less precise dimensions and not as smooth edges as laser cutting.

The sides were attached with a combination of tabs, slots, and acrylic solvent. The slots and tabs fit together and the acrylic solvent helped to create an airtight seal between the sides. This finished enclosure can be seen below in Figure 13.

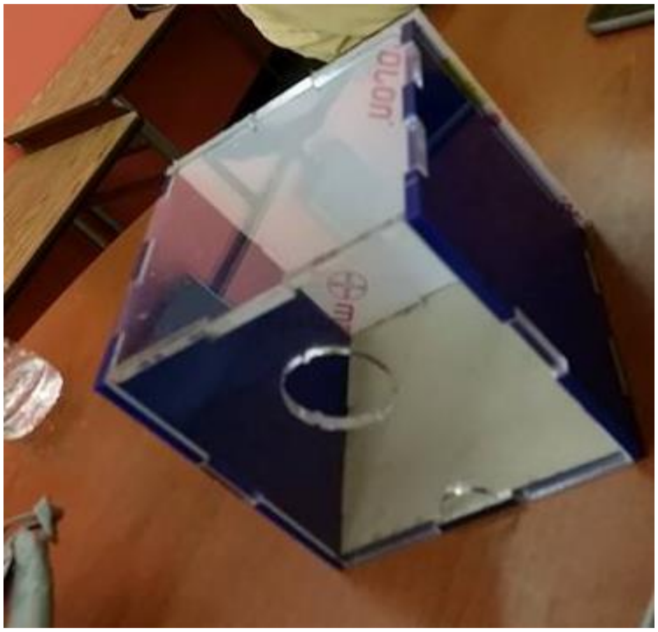


Figure 13 – Finished Headlight enclosure

3.1.2 PCB Enclosure

An enclosure for the PCB created is necessary to hold the created board. This section covers the design and assembly of the PCB enclosure.

3.1.2.1 Design

The PCB enclosure requires both durability and transparency. Durability is important for the robustness of the project, and transparency is important in order to show the PCB itself. The case must include 8 drill holes to affix standoffs and the PCB.

The case is designed in SolidWorks. Overall look of the case can be seen in Figure 14. The top and bottom pieces have the same dimensions so that the standoffs can screw easily into both sides. The sides determine the height of the enclosure. Figure 15 and Figure 16 show the dimensions of pieces.

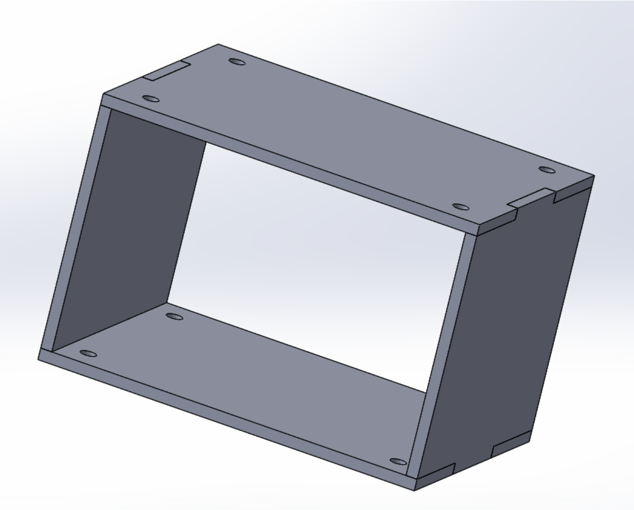


Figure 14 – PCB Case Design

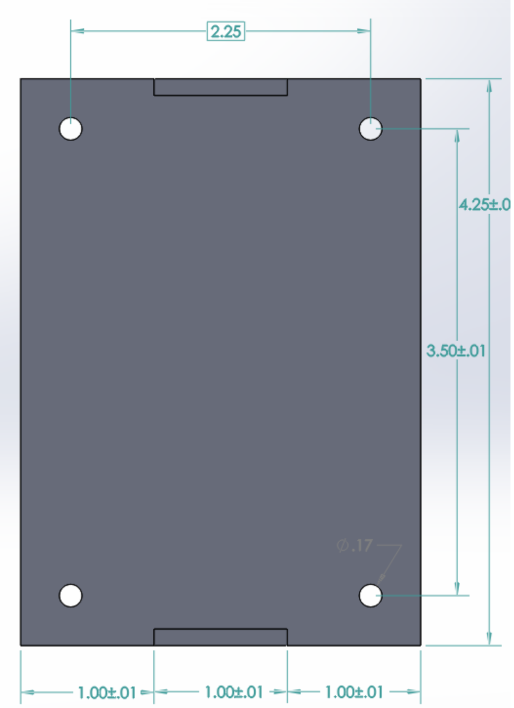


Figure 15 – PCB Case Long Side Dimensions

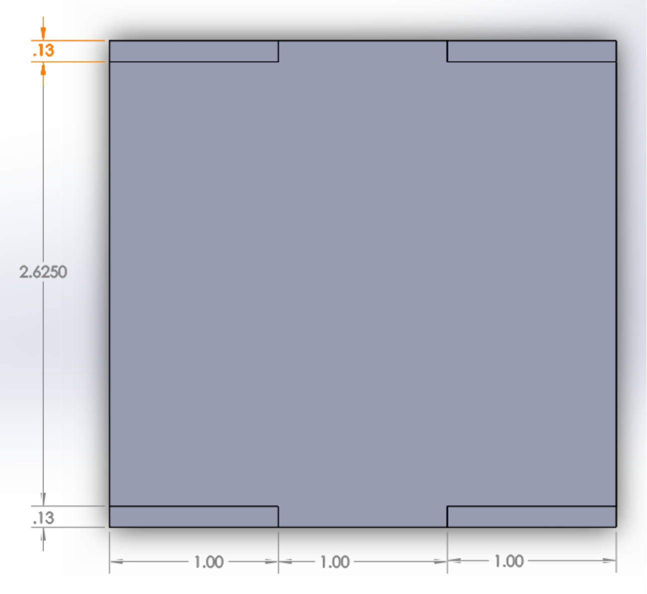


Figure 16 – PCB Case Short Side Dimensions

3.1.2.2 Materials and Assembly

The case is constructed of 0.125” clear acrylic. The material is cut by the laser cutter and assembled using acrylic solvent and the standoffs. Each corner consists of four aluminum standoffs with 8-32 thread size. The final PCB enclosure is shown in Figure 17.

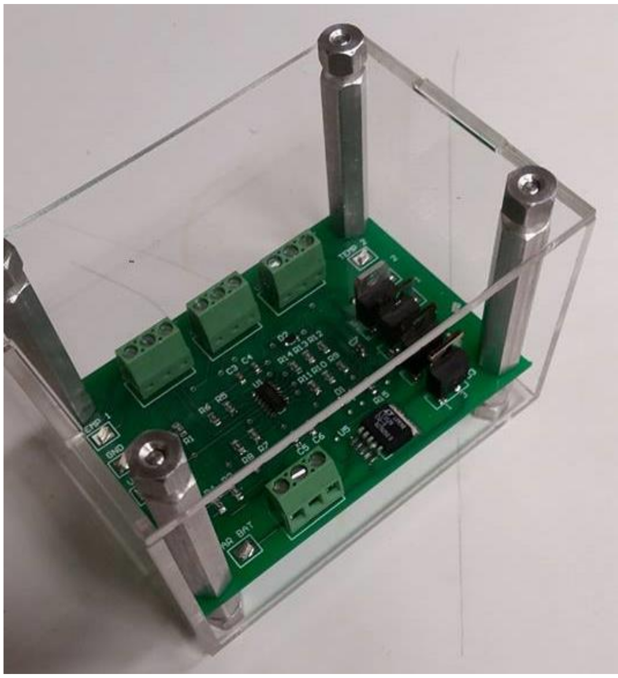


Figure 17 – Finished PCB Case

3.2 Fan System

The purpose of the circuit for this project was to determine the temperature of the inside of the headlight and determine whether the temperature inside of the enclosure needed to be increased. This section will discuss the first circuit developed for this purpose. The first circuit drove a Sunon fan in order to blow the heat from the headlight to the front of the headlight enclosure. One fan was used in the schematic for simplification, however in application, two fans would be used to expedite heat displacement within the enclosure.

There were three major decisions made during the design of the control system to determine how to drive the fans. First, we needed to select a temperature sensor that required low power and was ideally linear. Second, we decided to use two inverting Schmitt triggers to compare the temperature of the enclosure to a set threshold voltage. Lastly, an AND gate was constructed to turn on the fan when the temperature was too low. Once these decisions were made, we were able to develop the control system and run simulations to verify our calculations. In addition to testing the control system, we needed to test whether there would be enough heat generated by the headlight to raise the headlight enclosure to the desired temperature.

3.2.1 Circuit

The system starts with temperature sensing as shown in the system block diagram (Figure 18). The outputs from the temperature sensors are then amplified and then put into Schmitt triggers that produce either a high or a low output. The OR Gate reads the output from the Schmitt triggers and decides whether to turn the fan on or off. If either Schmitt trigger outputs are high, then the fan will be on. Otherwise, the output will remain off until the desired temperature drops below the threshold. The loop continues as the temperature sensors are constantly checking the temperatures inside the enclosure. The design can be seen in the block diagram Figure 18.

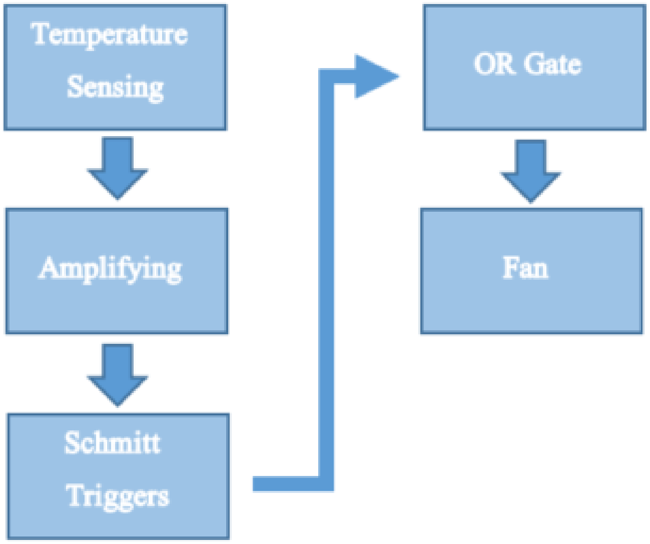


Figure 18 – System Block Diagram

The design of the temperature sensing circuit was based on the chosen temperature sensor, the TMP36. This device was chosen because of its positive temperature coefficient, and its linear relationship between temperature and output voltage. The TMP36 is a three terminal device: power, ground, and an output voltage. The output voltage’s relationship to temperature in degrees Celsius is shown as line “b” in the following figure:

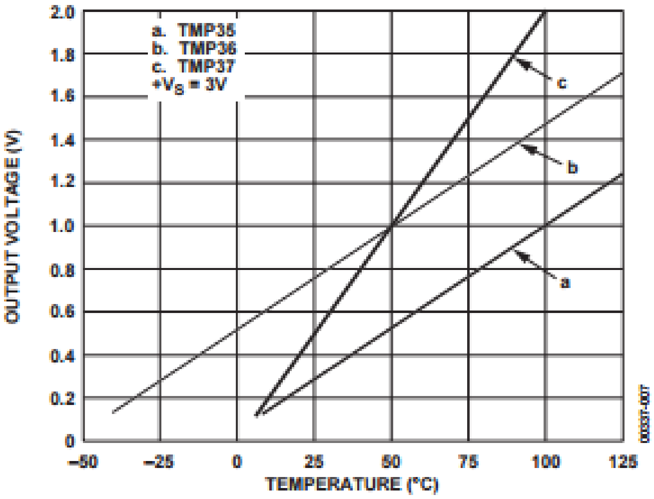


Figure 19 – TMP36 Temperature (°C) vs. Voltage (V) Graph [27]

The overall implementation of the designed circuit relies on positive feedback to create a hysteresis loop (shown in Figure 20). The phenomenon allows a set temperature to turn on the fan and another temperature to turn off the fan.

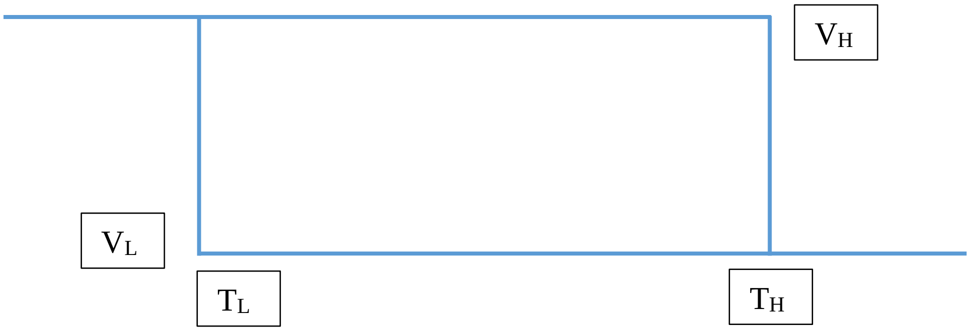


Figure 20 – Hysteresis Loop Visual

Extrapolated from Figure 19, the slope of the Voltage-Temperature correlation for the TMP36 (line b) is as follows:

$$V_{OUT} = \left(\frac{10mV}{°C}\right) \times T + 500mV$$

This formula was used to determine the output voltages of the selected T_L and T_H. The temperature sensor is accurate to within ±2°C.

For this hysteresis loop, T_L is the temperature in which the fan would turn on if the temperature was below this value. For testing purposes T_L was selected to be 50°F so that we could test the functionality of the rest of the circuit without being in freezing temperatures. T_H was selected to be 68°F. If this circuit was to be used in the actual application, these temperatures would be lower. To incorporate these temperatures into our Schmitt triggers, we calculated the V_{OUT} from the TMP36 using the equation above. Using inverting Schmitt trigger equations we calculated our resistor values. To verify our resistor values, we used a Schmitt Trigger Calculator [28]. These resistor values are shown in the schematic (Figure 21) as R7, R8, R9, R15, R16, and R17.

There are a few limitations when using a 12V battery as the power source. First, a single pole op-amp is needed so it can be referenced to ground. For this design, we chose to use the LMC6484, a single pole quad op-amp. Additionally, a car battery's voltage can fluctuate between 11.8V-14.4V, which can cause issues when the fan has a maximum input voltage of 13.6V. To resolve this issue, a diode was used to drop the input voltage by approximately 0.7V. The full schematic is depicted in Figure 21.

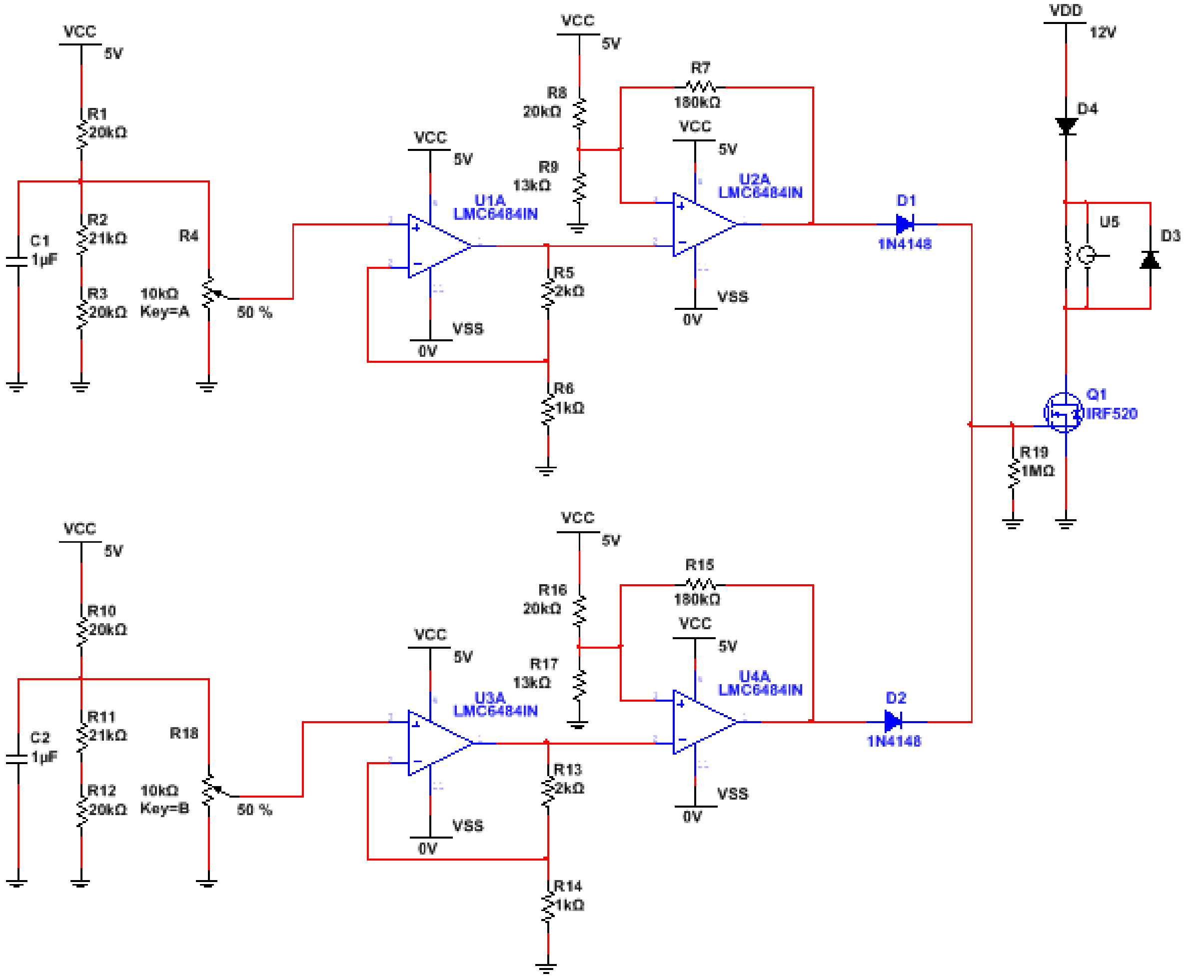


Figure 21 – Circuit Design for Fan Load

3.2.1.1 Prototype and Breadboard

The prototype of the fan circuit was built using two breadboards. The final assembly of the parts is shown in Figure 22.

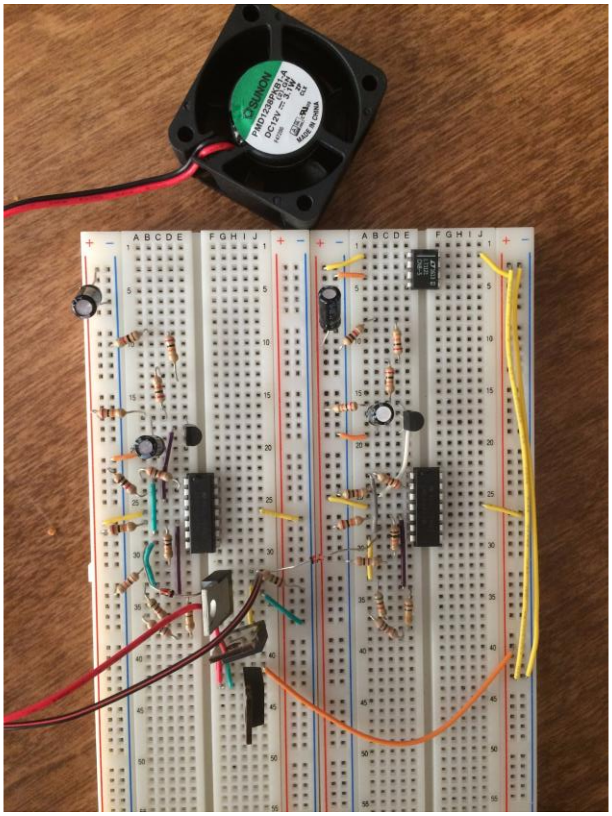


Figure 22 – Assembled Circuit on a Breadboard

3.2.1.2 Testing and Debugging

Since the group did not have access to a portable power supply of 12V, the group used a 9V battery instead, so testing could be done outside. Using a 9V battery does not change anything in the circuit because the DC fan can work over a range of 6V–13.6V. Also, the voltage regulator converts the 9V to 5V for the rest of the circuit. The unit successfully turned on the fan when the prototype was outside at a temperature below 50°F, our temporary T_L, and was turned off while inside as the lab was warmer than our T_H, 68°F. This testing proved that the full circuit was working correctly.

3.2.2 Simulations

Two types of simulations needed to be performed to determine whether our proposed circuit would work for our purpose. First, we needed to test if the circuitry was accurate and if the component values were correct in the circuit. To do this, we ran simulations in Multisim. In addition to circuit simulations, we needed to determine if the headlight would produce enough heat to raise the temperature of the headlight enclosure to the desired temperature. To perform these temperature simulations, we used SolidWorks to run thermal modeling on the headlight enclosure.

3.2.2.1 Multisim

Once the circuit was developed, Multisim was used to run simulations to verify calculations and overall system performance. The TMP36 was not included in the Multisim library, so they were modeled as potentiometers since the output voltages would change based on temperature. The exact diode used to cut the voltage for the fan was not in the Multisim library, so the diode was modeled as an ideal diode. Also, the Sunon fan was not in the Multisim library so an ideal motor was used instead. The fan circuit can be seen above in Figure 21.

In order to simulate the change in temperature, a DC sweep was run to show the different output voltages from the TMP36. The first simulation (shown in Figure 23) is a DC sweep from 0.2V-1.2V on one TMP36 device while the other is held constant at an output voltage that would simulate the temperature being above the threshold. It can be seen from this simulation that while the output voltage from the varying thermistor is below about 700mV, the fan is on as the voltage drop across the fan is just above 7.25V. 700mV corresponds to about 68°F, which was our T_H in Figure 20. The 7.25V corresponds to the ideal motor that was used in the Multisim and is not necessarily the voltage drop that the Sunon fans would have. Once the output voltage increases above 700mV, the voltage drop across the fan is 0V, meaning the fan is off.

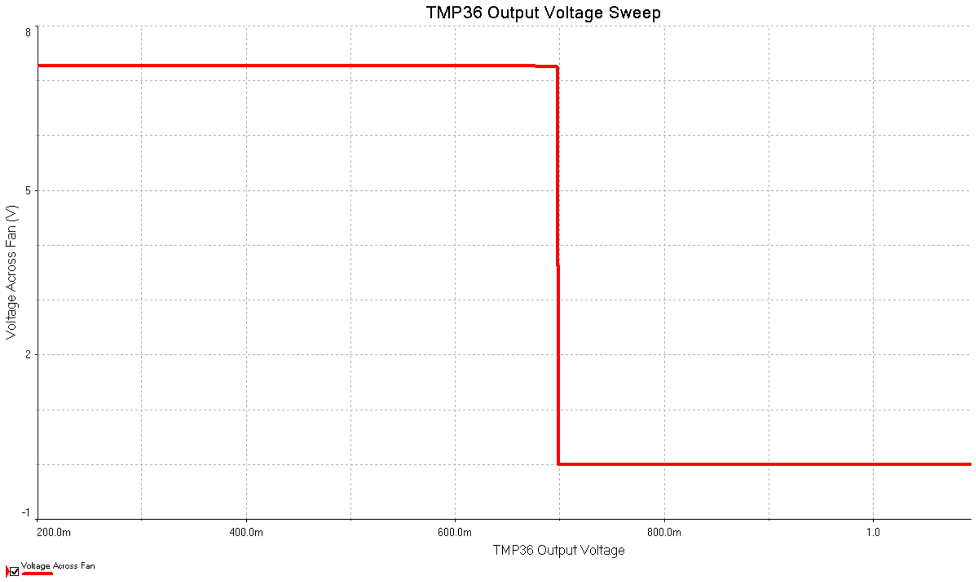


Figure 23 – Multisim Simulation – Fan Turning Off

In the second simulation, shown below in Figure 24, the same DC sweep was performed, but the second TMP36 device was held constant at an output voltage that would simulate the temperature being below the threshold voltage. As the output voltage from the varying thermistor rises above 700mV, there is slight drop in voltage across the fan from 7.53V to 7.26V, however, at these voltages, the fan would still be functioning. Both of these simulations show that the circuit is working correctly.

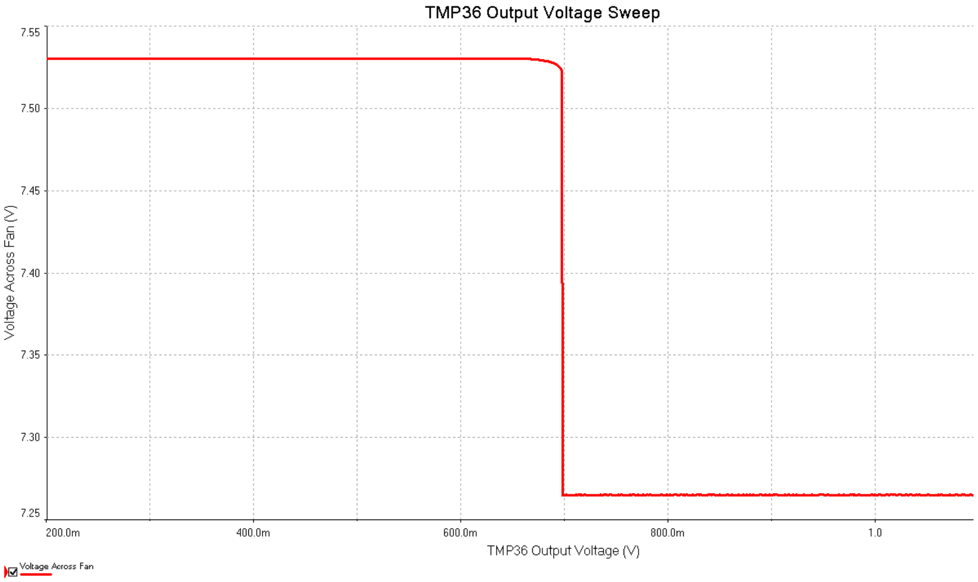


Figure 24 – Multisim Simulation – Fan Remaining On

3.2.2.2 Temperature

Heat simulations for the fan set up were conducted using the SolidWorks Flow Simulation package. These simulations were conducted in two parts: first without the heat sink within the enclosure, and then with the heat sink in the enclosure. The two different set ups can be seen in Figure 25.

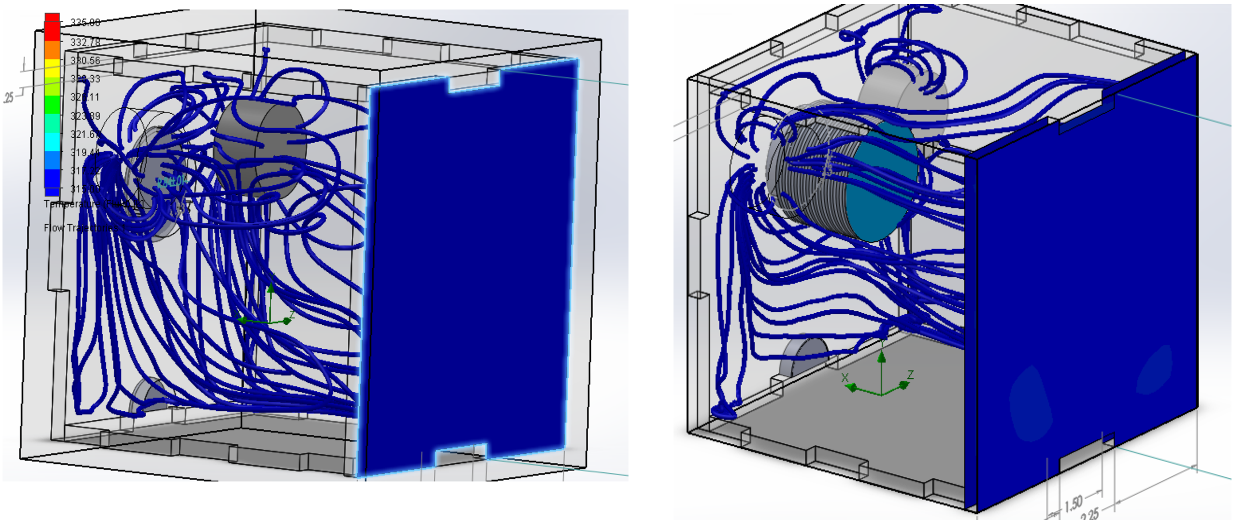


Figure 25 – Simulation Setup without Heat Sink Inside (Left) with Heat Sink Inside (Right)

Common to both set ups were two small (2” by 2”) Sunon axial fans. One fan was placed on each side of where the bulb would be placed. The purpose of these fans was to help circulate the heat within the enclosure, ideally heating up the polycarbonate faster. Additionally, it should be noted that both enclosures are the same size and material. 0.25” thick acrylic is selected as the material for five of the sides and 0.25” thick polycarbonate is selected as the material of the front lens.

All of the initial parameters are the. In this simulation, the “lid” at the back of the enclosure where the bulb is to be placed is representative of the headlight itself and the heat it would output. The temperature of this lid was chosen because it is the maximum rated temperature of the LED bulb, therefore any heat put off by the bulb should not exceed this. The initial temperatures are as follows:

Table 5 – Initial Temperatures

Location	Without Heat Sink	With Heat Sink
Steady state outside fluid	25°F = -4°C	25°F = -4°C
Steady “lid”	300°F = 149°C	176°F = 80°C
All other solids, initial	25°F = -4°C	25°F = -4°C

The goal of both versions of this simulation was to see if enough heat was produced and would conduct through the polycarbonate in order to melt the ice on the outside of the lens. The only functional difference between the two tests is the removal or addition of the heat sink inside the enclosure. A transient analysis is run to see the effect of time on the heating of space within the enclosure and the lens. The heat flow and solid temperature of the lens can be seen in the figures below at different time intervals.

The configuration without the heat sink inside was tested first. This was because in a real automotive headlight enclosure, the heat sink of an LED bulb is designed to fit outside of the enclosure due to space restraints and to allow for maximum heat dissipation, and was therefore the ideal situation. Simulation pictures without the heat sink were taken at several instances over a three-hour physical time period. Figure 26 shows the beginning of the simulation.

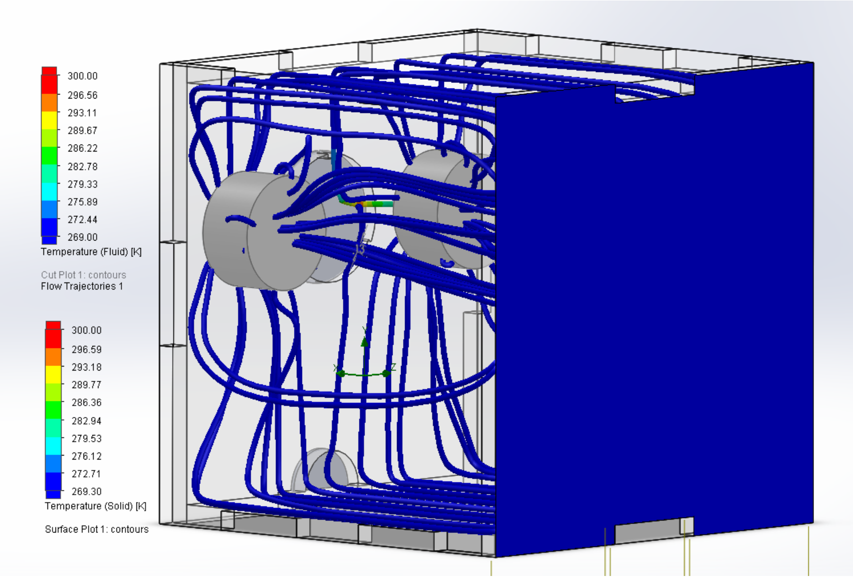


Figure 26 – No Heat Sink Inside at 30 seconds

The instance above in Figure 26 is taken at 30 physical seconds into the simulation. Here it can be seen that both the internal fluid of the enclosure and the temperature of the outside lens are both still well below freezing levels.

The image in Figure 27 shows the resulting fluid flow, and fluid and solid temperatures at 10 minutes. This result is disappointing because an ideal design would have had an external lens temperature high enough to melt ice by this point. The simulation at this point still shows an external lens temperature of below 269K (25°F), which is not sufficient to melt ice.

Although a melting temperature was not reached by the benchmark time, the simulation is continued to see when the external lens will reach the ideal temperature. At the 1 hour point, shown in Figure 28, the internal fluid temperature and lens are finally shown to be heating up and at around 273K (33°F).

The 4-hour point, shown in Figure 29, finally shows enough heat transferred to the polycarbonate lens to melt any snow accumulation. Here, it is shown that the external lens has finally reached a temperature of about 280K (44°F), which is sufficient to melt ice accumulation.

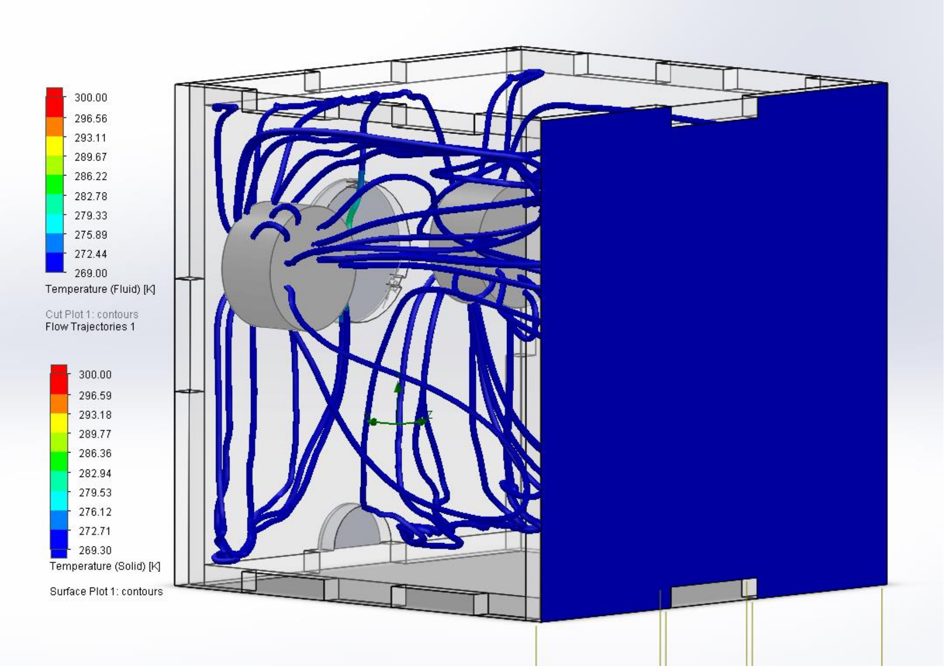


Figure 27 – No Heat Sink Inside at 10 minutes

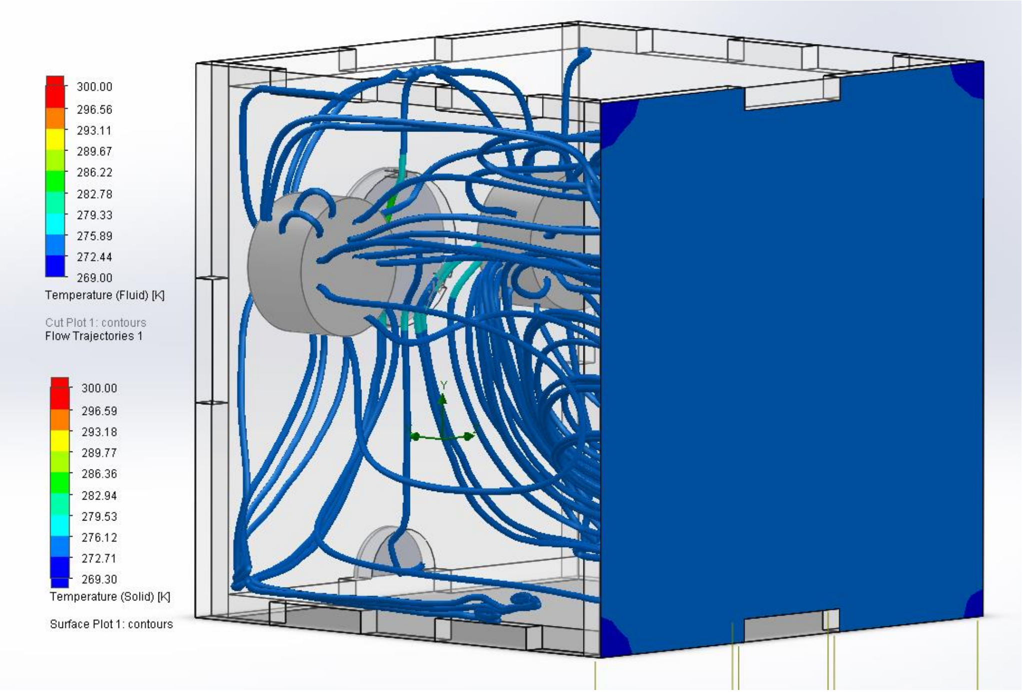


Figure 28 – No Heat Sink Inside at 1 hour

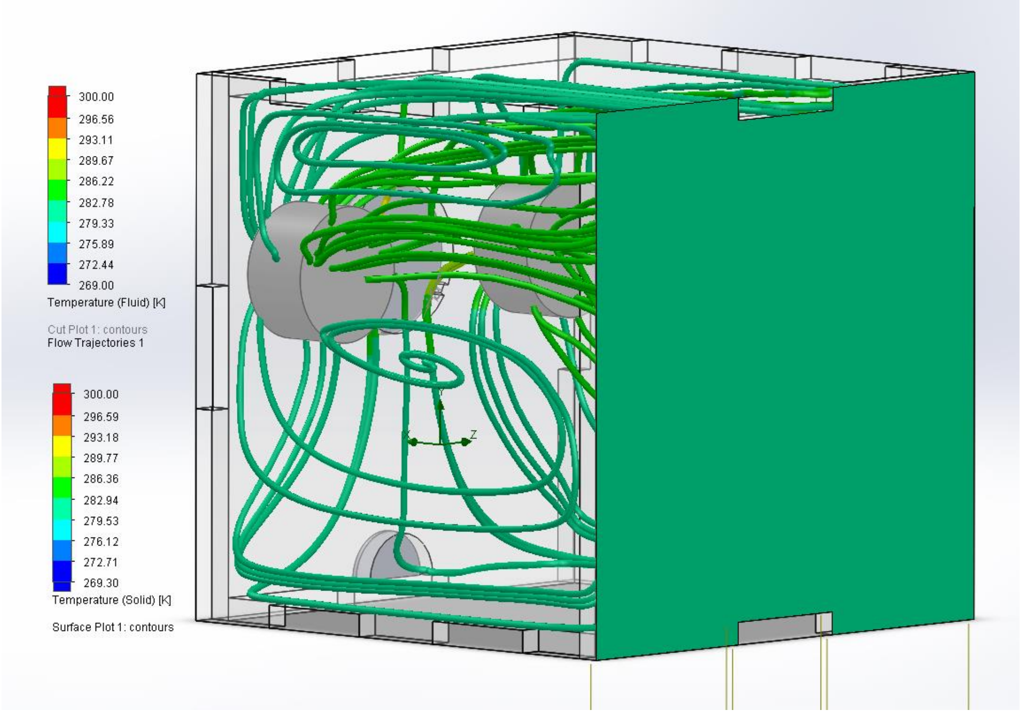


Figure 29 – No Heat Sink at 4 hours

The amount of time required to reach the minimum lens temperature in this version of the enclosure was not sufficient. Therefore, this simulation is repeated with the inclusion of the LED bulb’s heat sink, with the idea that the additional heat will be able to achieve a quicker response.

The heat sink added is shown in Figure 30 and is modeled after the actual heat sink attached to the LED headlight bulb. It is constructed of aluminum and measures 2 inches long. This component is added into the simulation performed above and run again to try to achieve more timely results.

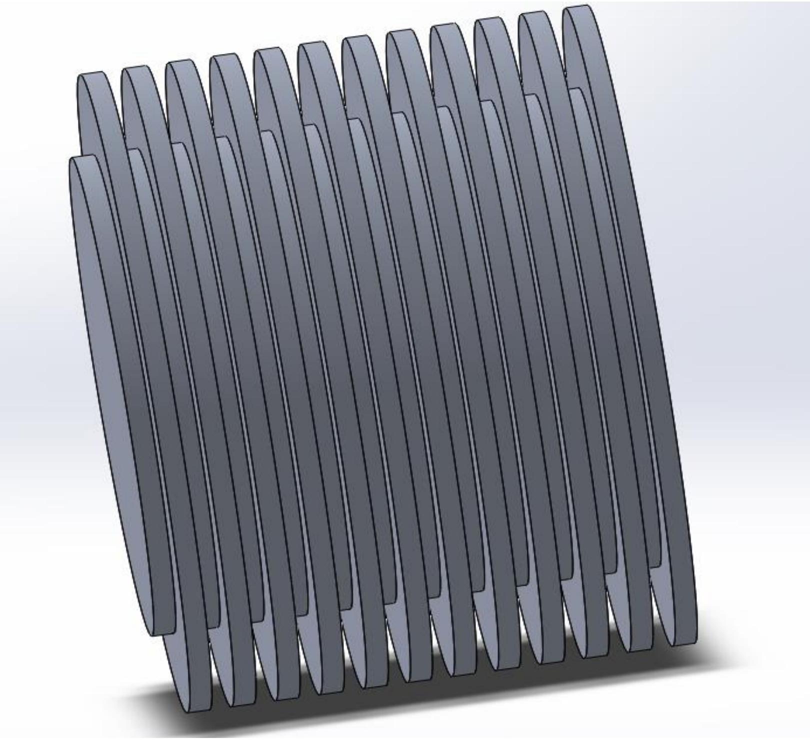


Figure 30 – LED Headlight Bulb Heat Sink Model

With the addition of the heat sink, the simulation is run again. The first snap shot is taken at 10 minutes and is shown in Figure 31. Here is can be seen that the surface of the heat sink is quicker to heat up than the internal fluid or the outside of the lens. At this point, the lens is still frozen, but the front of the heat sink is nearly at 272K (30°F), 5°F up from the rest of the enclosure.

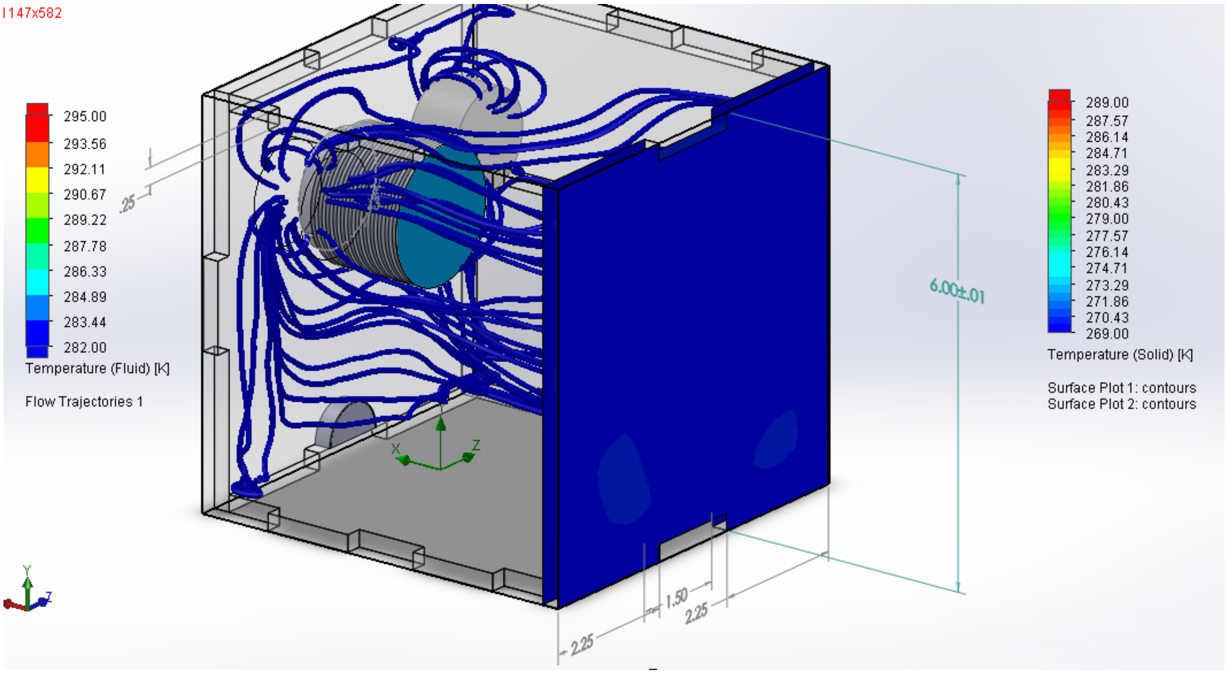


Figure 31 – With Heat Sink at 10 minutes

At 1 hour, shown in Figure 32, the heat sink is at 277K (39°F), the fluid is has not shown any appreciable temperature increase and the lens is still frozen.

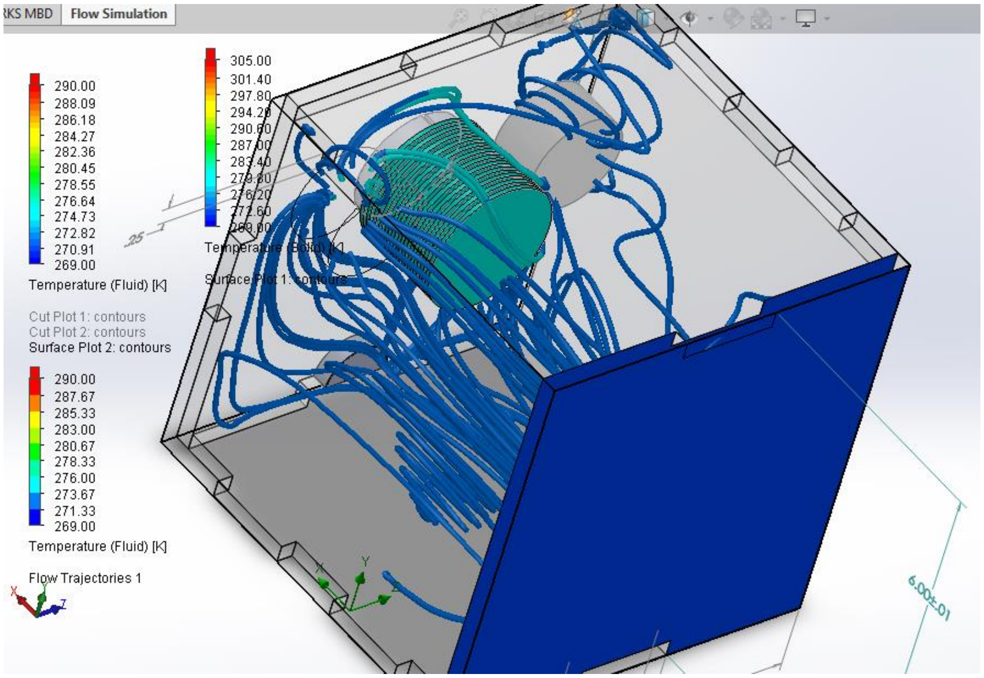


Figure 32 – With Heat Sink at 1 hour

The next instance of note is when the external lens finally heats up to a sufficient temperature. This happens at 4 hours and is shown in Figure 33. At this point the external lens has finally heated up to about 280 K (44°F). Although the heat sink produces more heat than the headlight, the simulation showed that it would take four hours for the lens to reach a melting temperature whereas the non-heat sink simulation showed three hours. The reason for this is that the initial temperature for the non-heat sink simulation was higher than that of the heat sink simulation. Either way, clearly 4 hours is much too long of a time to wait for the ice to melt off of a car headlight casing.

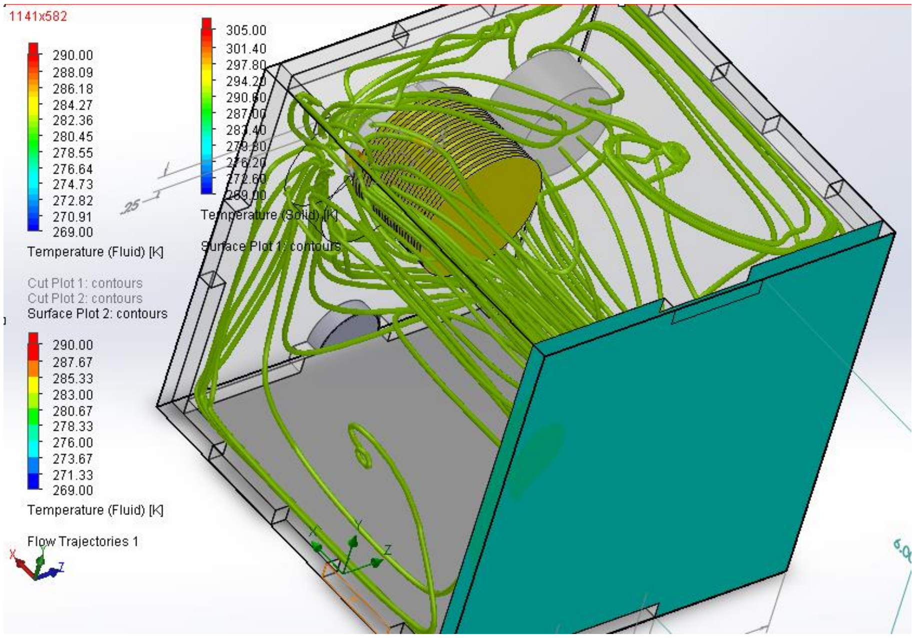


Figure 33 – With Heat Sink at 4 hours

3.2.3 Conclusion

The simulations from 3.2.2.2 showed two different configurations which attempted to demonstrate the same concept. This concept was using the residual heat from the LED headlight bulb to melt the ice accumulation on the lens with the use of fans to circulate the heat. These simulations showed that enough heat is not produced in order to complete the goal within a reasonable amount of time. While the first simulation used a higher initial bulb temperature, neither were successful in heating up the lens in an adequate amount of time. As a result, another method is now explored to solve this problem of ice accumulation on headlight lens. This new method explores the use of a transparent heat film.

3.3 Heat Film System

A heat film control system is the new solution to defrosting LED headlights, since temperature simulations deemed fan circulation as impractical. An indium tin oxide (ITO) heating film provides heat to the polycarbonate of the headlight.

3.3.1 Circuit

The new circuit is similar to the fan control system, however it has a few modifications. The block diagram of the design is shown in the following figure.

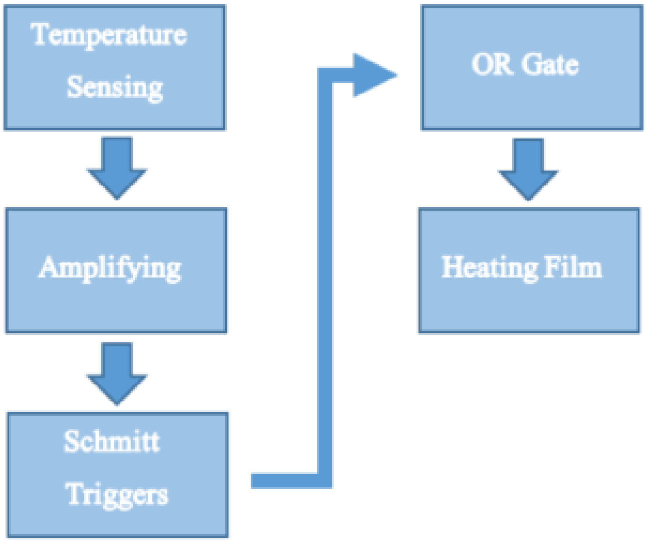


Figure 34 – Heat Film Block Diagram

The temperature sensing block of the circuit remains exactly the same, turning on or off the heating film based on the ambient temperature. Changes to the new circuit include the addition of the heating film with added diodes in series and a more robust NMOS transistor. These devices need to be more robust with the added current that will be flowing through the heating film. Also, the resistor values in the Schmitt triggers were modified to set T_L and T_H in the hysteresis loop to practical temperatures for commercial use. T_L was changed from 50°F to 35°F and T_H was changed from 68°F to 50°F. These new temperatures would allow the system to work accurately in an automotive environment. The new schematic can be seen in Figure 35.

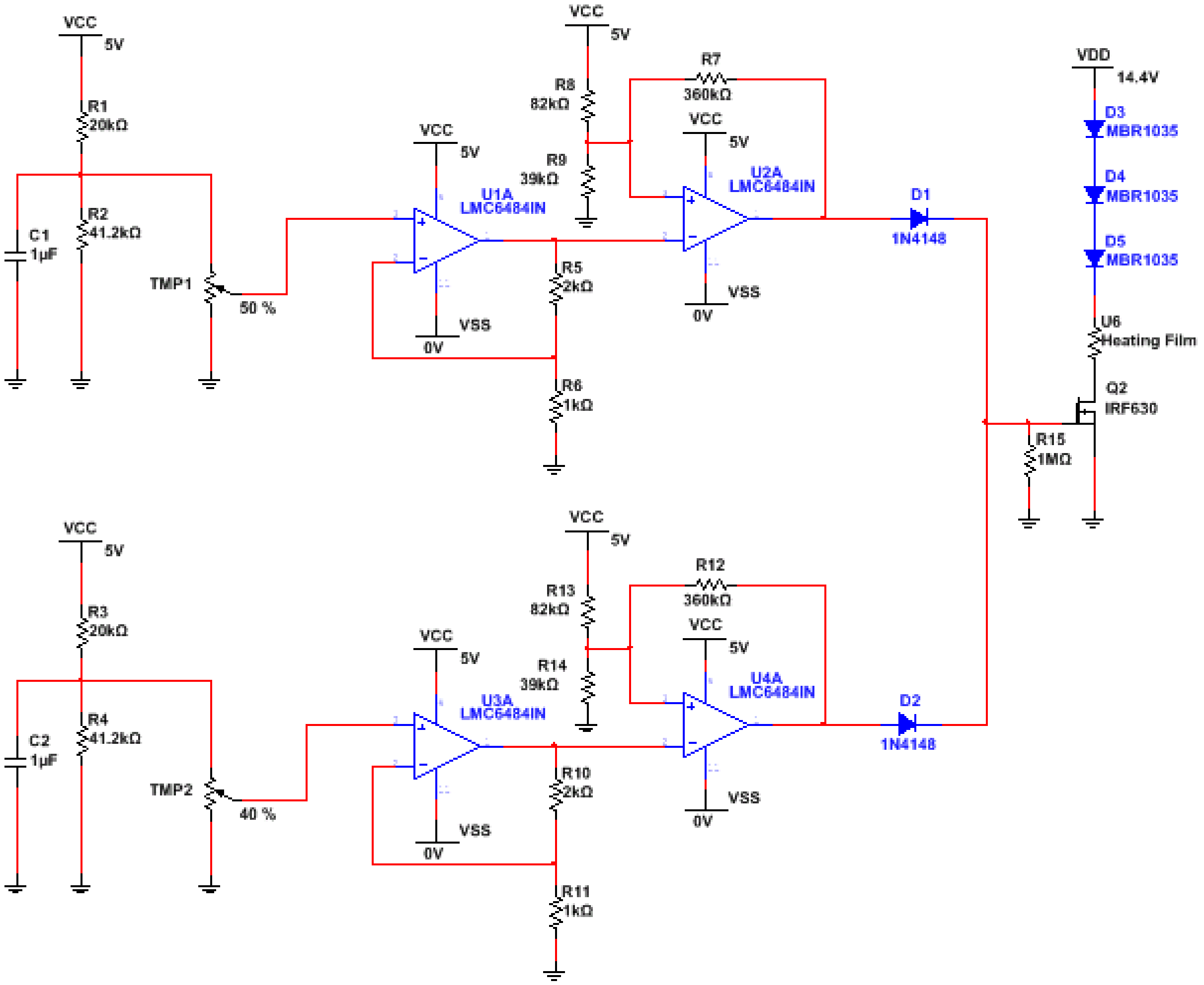


Figure 35 – Circuit Design for Heating Film Load

3.3.2 Simulations

Similar to the fan system described in section 3.2.2, we performed Multisim and thermal simulations on the heat film system to make sure that the design would fulfill our requirements.

3.3.2.1 Multisim

For the heating film circuit, the heating film was not included in the library, so it is modeled as a resistor. In order to simulate the change in temperature, a DC sweep was run to show the different output voltages from the TMP36. The first simulation (shown in Figure 36) is a DC sweep from 0.2V-0.9V on one TMP36 device while the other is held constant at an output voltage that would simulate the temperature being above the threshold. It can be seen from this simulation that while the output voltage from the varying thermistor is below about 612mV, the heat film is on as the voltage drop across the heat film is just above 12V. 612mV corresponds to about 52°F, which was close to our T_H. The 12V corresponds to the resistor that was used in the Multisim and is not necessarily the voltage drop that the heat film would have. Once the output voltage increases above 612mV, the voltage drop across the resistor is 0V, meaning the heat film is off. As the temperature decreases, the heat film will remain off until the thermistor output voltage reaches about 520mV. At this point, which corresponds to about 35°F, the heat film will turn back on to heat the system again.

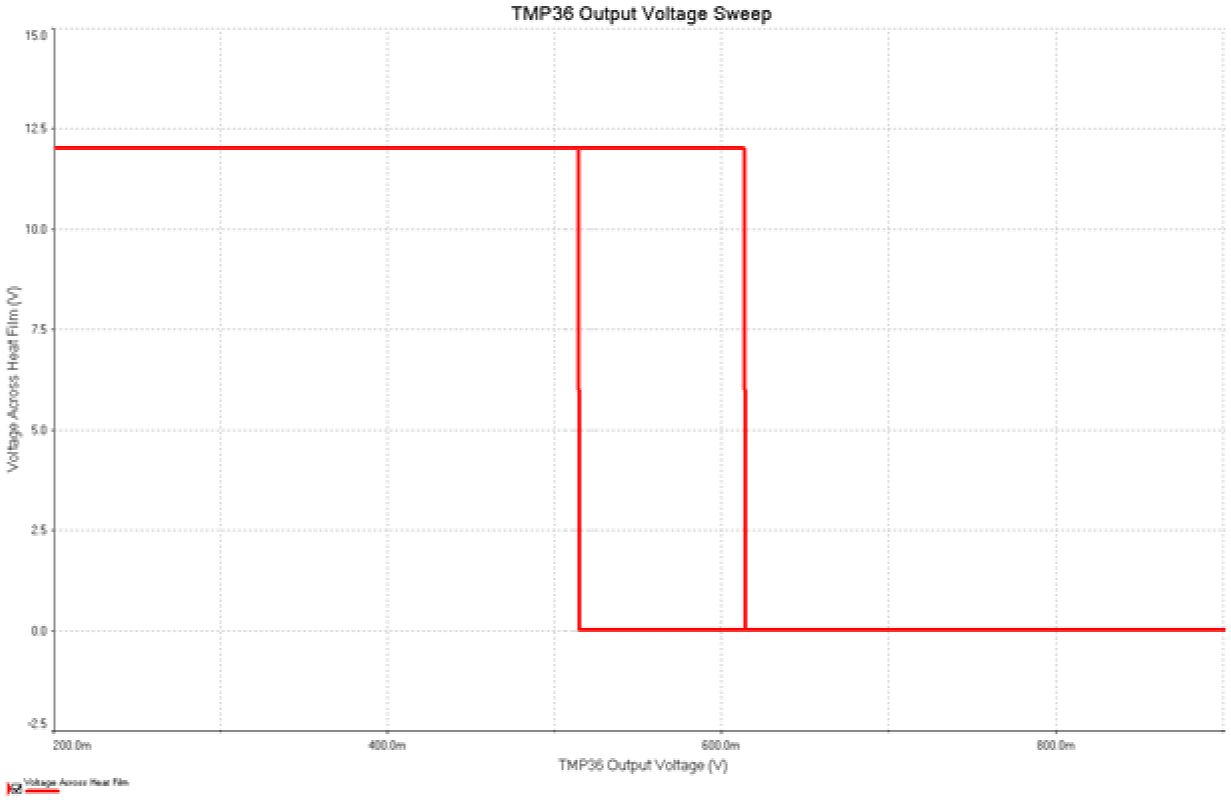


Figure 36 – Multisim Simulation – Heating Film Turning Off

In the second simulation, shown below in Figure 37, the same DC sweep was performed, but the second TMP36 device was held constant at an output voltage that would simulate the temperature being below the threshold voltage. As the output voltage from the varying thermistor rises above 612mV, there is no drop in voltage across the resistor showing that heating film would still be functioning. Both of these simulations show that the circuit is working correctly.

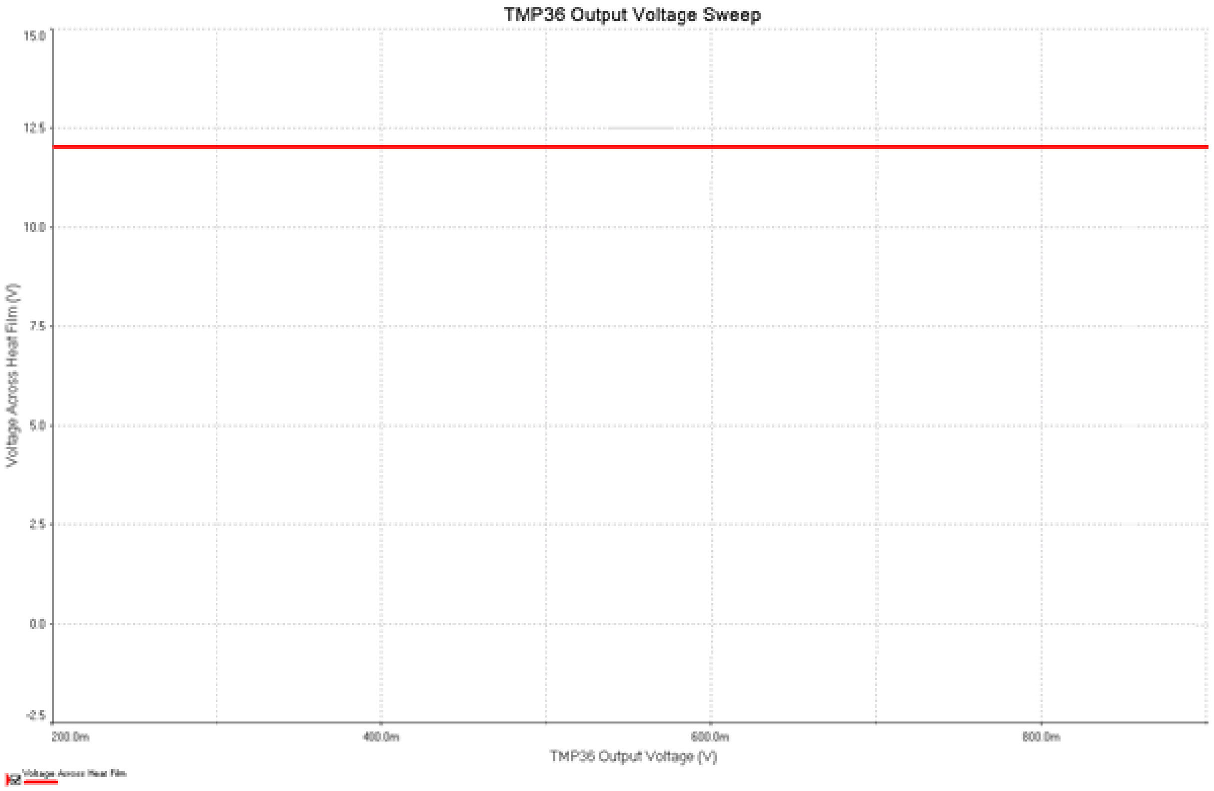


Figure 37 – Multisim Simulation – Heating Film Remaining On

3.3.2.2 Temperature

In a similar manner to section 3.2.2.2, heat simulations are conducted using the SolidWorks Flow Simulation package in order to determine the feasibility of this solution. In this simulation, a 5” x 5” silicone heater is attached to the front inside of the enclosure. The fans are removed. This can be seen in Figure 38. The internal initial temperature of the entire environment is 269K (25°F). The ambient outside temperature remains at this value, however the enclosure itself is allowed to heat up over time. The heater attached is modeled as silicone with a heat output of 0.65 W/in^2, a typical electric heat pad value. This heat is outputted only on the face in contact with the polycarbonate lens.

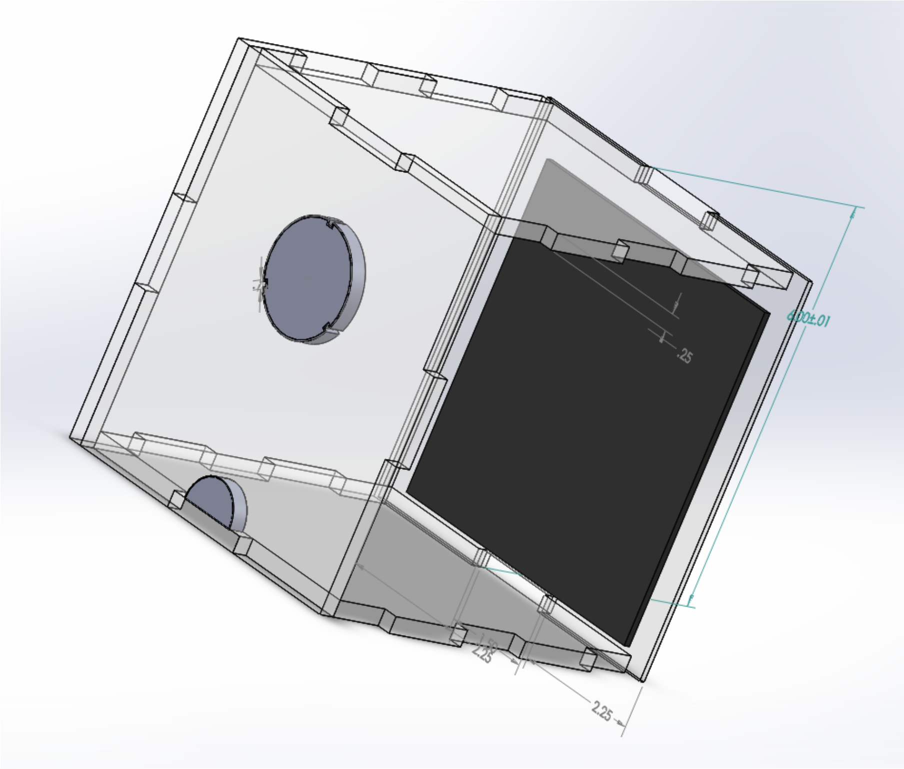


Figure 38 – Enclosure with Heat Pad

Running the model with these parameters yields promising results at 10 minutes. Figure 39 and Figure 40 display the outcomes. Figure 39 shows the distribution of the heated fluid (air) within the enclosure. At the ten minute point, some of the air within the enclosure is still cold. This is okay, and perhaps even preferable for the longevity of the LED bulb. The left side of the enclosure is shown to be hot due to the heat output from the bulb. At the 5” marker and near to the polycarbonate, the air is hot and approaching a maximum of 298 K (76.7°F). This simulation gives a good indication of the necessary temperature for the temperature sensor to look for in the air when determining whether the outside surface of the polycarbonate is sufficiently warm. Also, this simulation shows where we should place the temperature sensors in the enclosure for optimal results.

Figure 40 displays exciting results. At 10 minutes, the outside lens is more than warm enough to melt off snow and ice accumulation, but not so hot as to harm the polycarbonate lens or LED bulb. The maximum external lens temperature is shown to be 291K (64°F). The outside edges of the lens still show to be frozen, however the vast majority of the surface area is above 38°F which is more than suitable for this application.

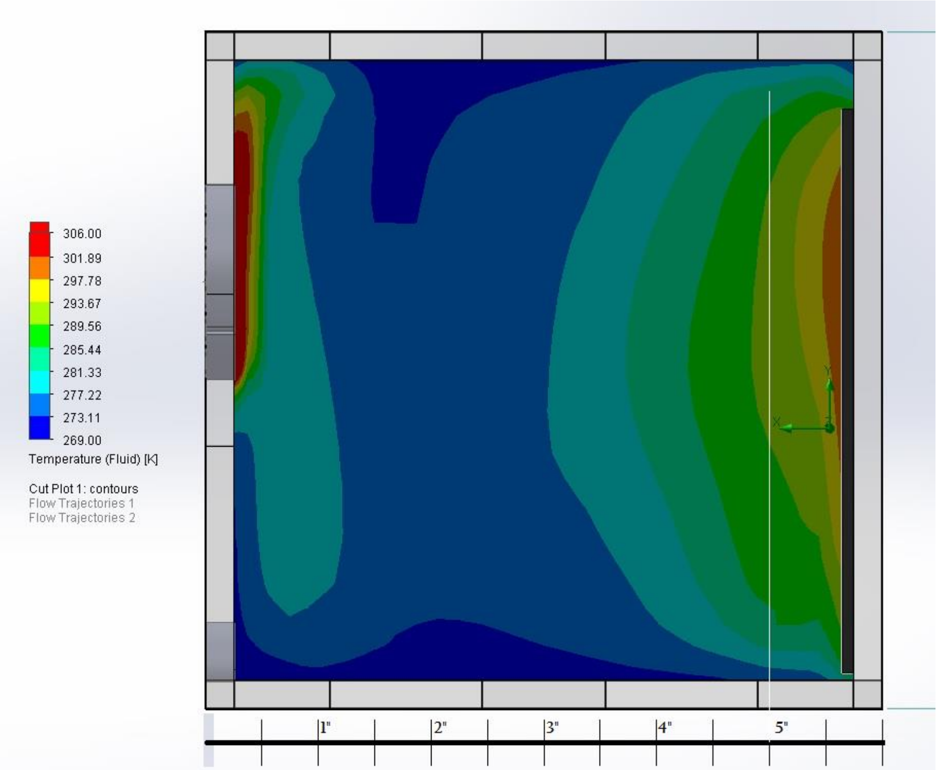


Figure 39 – Fluid Temperature Distribution within Enclosure with Heat Pad at 10 minutes

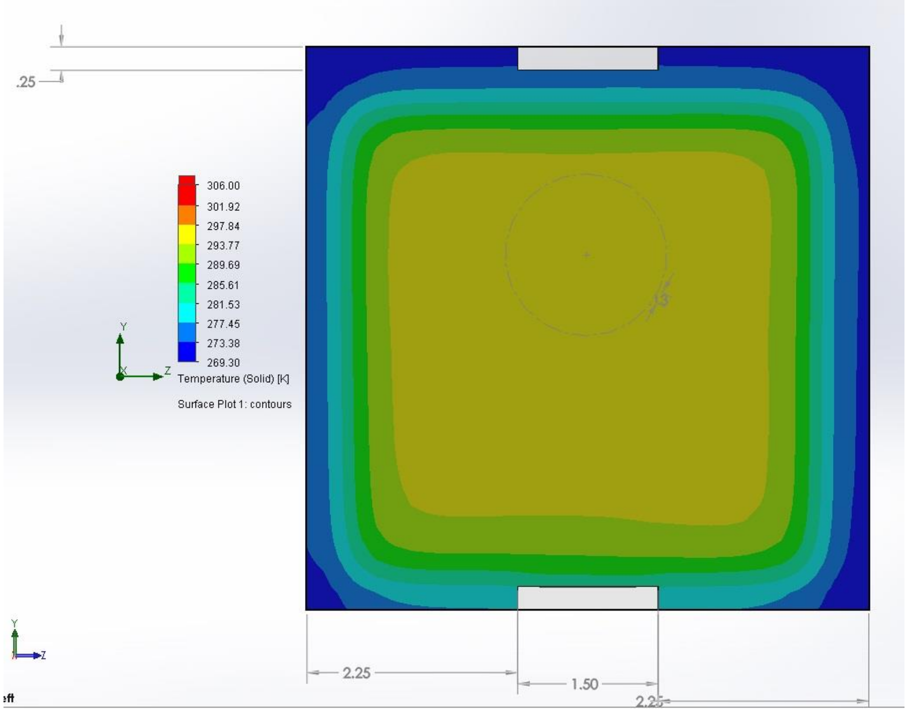


Figure 40 – Heat Distribution of Polycarbonate Lens with Heat Pad at 10 minutes

3.3.3 Conclusion

As a result of the simulations above, it can be concluded that adding a heating pad to the internal face of the polycarbonate lens would works as a sufficient means to remove snow and ice accumulation. A transparent heating pad that produces at least 0.65 W/in^2 is optimal. Due to the thermal conductive properties of polycarbonate, a lower powered and larger surface area heat pad is recommended over a smaller, more powerful heating element.

4 Results

This section discusses the design of the schematic and printed circuit board (PCB), as well as the testing and analysis performed to determine the functionality and effectiveness of the control system and heating film.

4.1 Circuit Design

The circuit that was designed and built for this project relies on a car battery for a power source. The car battery is connected to the board through a terminal block (U4 in the schematic shown in Figure 41). The voltage from the car battery is connected to a linear regulator (U5) which drops the voltage to 5V. This 5V is used by the temperature sensors and the operational amplifier. The temperature sensors (TMP36) run on 3.3V so a voltage divider was used to drop the voltage from 5V to 3.3V. The temperature sensors are connected to the board using terminal blocks which are shown as U2 and U3. The TMP36's output voltage range for the hysteresis loop is very small (0.45V – 0.60V). In order to provide better resolution for the Schmitt triggers, a larger range was needed. To do this, a non-inverting amplifier with a gain of 3 was used to make the voltage range 1.35V-1.80V. The non-inverting amplifiers are shown as U1A and U1B below. The outputs from the non-inverting amplifiers are the inputs to the Schmitt triggers (U1C and U1D). The positive feedback in the Schmitt triggers creates two hysteresis loops, which are explained in Section 3.2.1. Based on the input voltage, if the heating film needs to be on, a Schmitt trigger will output 5V, otherwise it will be 0V. Each output from the Schmitt triggers is sent through a diode (D1 or D2) and to the NMOS (Q1), constructing an OR gate. If either Schmitt trigger outputs high, then the heating film will be on. A resistor, R15, is placed before the NMOS to dissipate the voltage when the outputs from the Schmitt triggers go low. This makes sure that the NMOS can turn off and does not remain on when the temperature is hot enough. The heating film (shown as U6) is connected via a terminal block (U4) to the car battery through three diodes (D3, D4, and D5). The purpose of these diodes is to drop the 14V from the car battery down to about 12V for the heating film. The heating film will only have a closed circuit and a path to ground when the NMOS is switched ON.

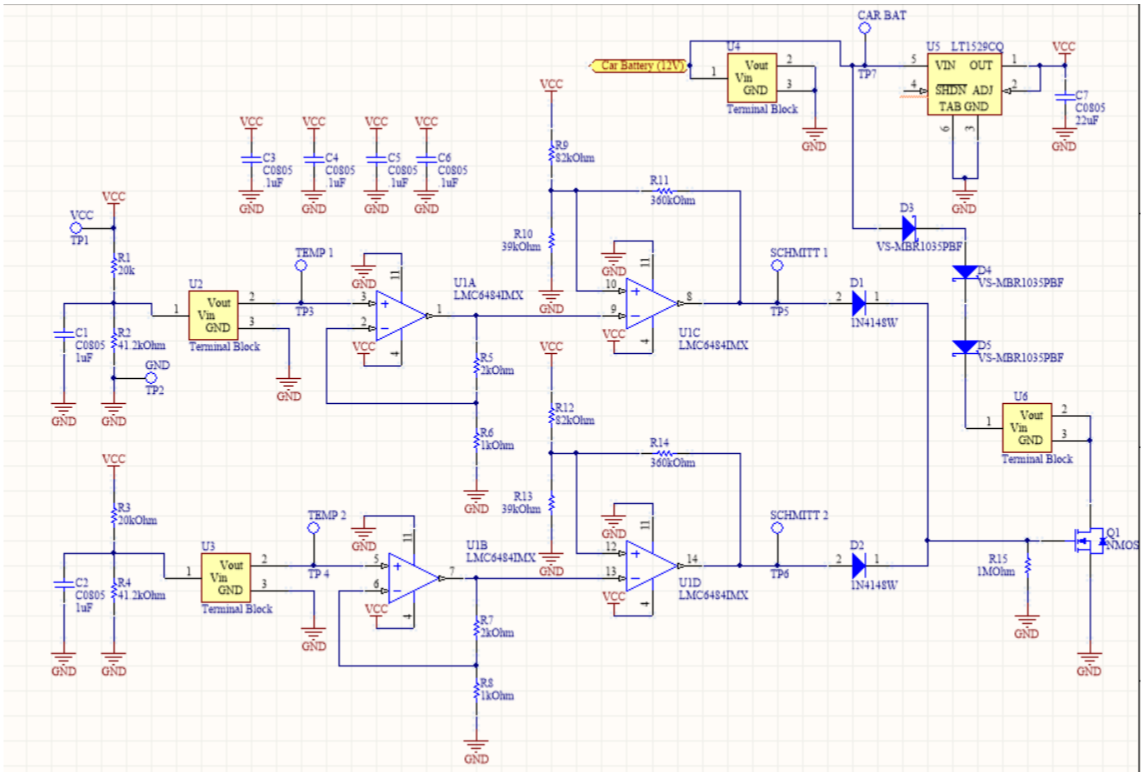


Figure 41 – Final Schematic in Altium

4.2 PCB Design

The printed circuit board (PCB) for this project was developed in Altium and is based on the schematic shown in Figure 41. The designed board (Figure 42) is a two layer board with all of the components placed on the top layer to make testing easier. In order to reduce the size of the board, all of the resistors and capacitors are surface mount along with the operational amplifier. Through-hole components are needed for the diodes (D3, D4, and D5) and the NMOS because a heatsink was needed for the high power dissipation. The dimensions of the board are 2.75” x 4”. Capacitors C3, C4, C5, and C6 were placed near the operational amplifier (U1) to reduce noise. There are seven test points placed on the board to make testing easier for commonly needed signals. Lastly, there is a hole in each corner to mount the board in the PCB enclosure discussed in Section 3.1.2.

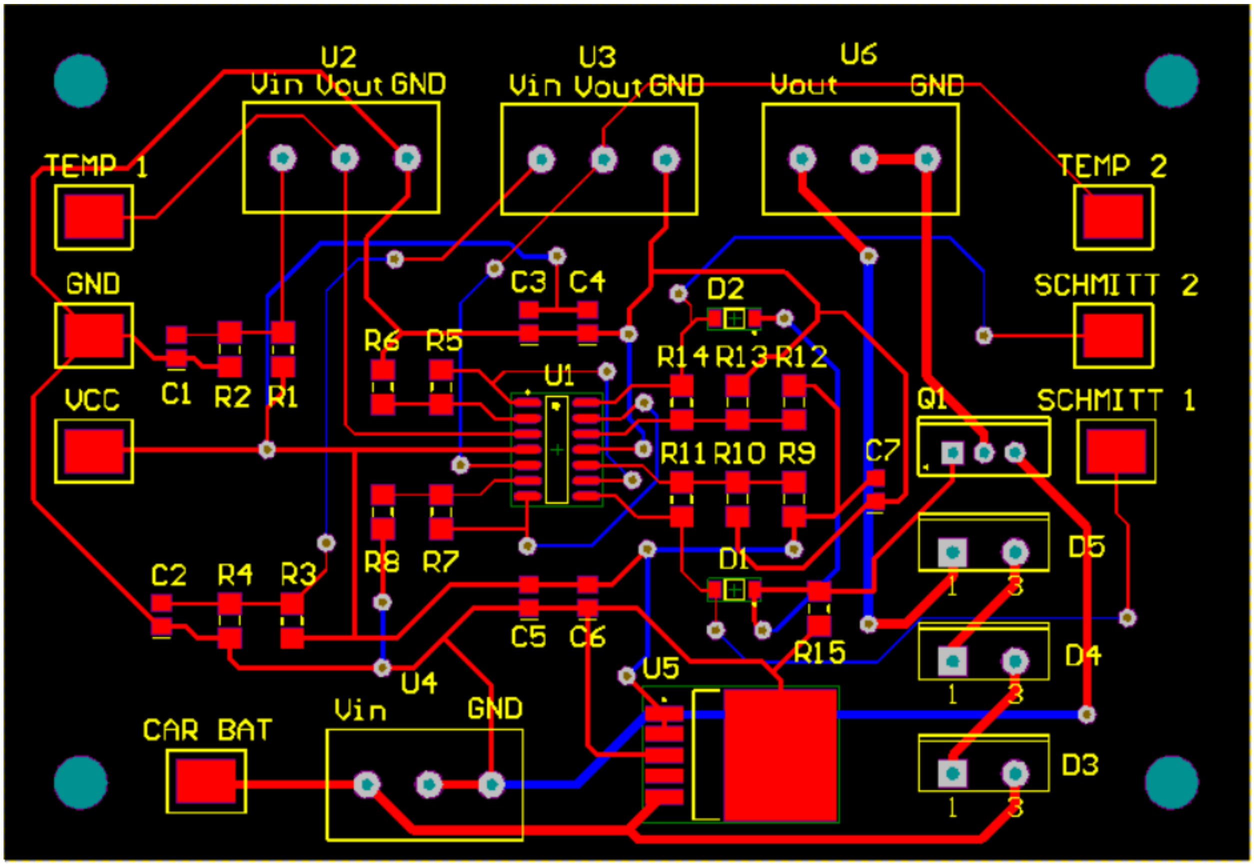


Figure 42 – PCB Design

4.3 Testing

To ensure the functionality of the circuit, tests were performed in both a laboratory environment and a natural environment for the application.

4.3.1 Laboratory

The functionality of the device’s OR gate, described in 3.3.1, and the voltage across the load were measured. The proper readings at these points indicated that the circuit is in good working order on both the signal and power side.

Two different voltage step patterns with a maximum voltage of 1.5V are fed into each Schmitt Trigger. These inputs can be seen in Figure 43. The maximum 1.5V is enough to trigger either comparator to a high output. Due to the functionality of an OR gate, whenever either Schmitt trigger is outputting high, the NMOS should conduct. This test proved successful. Whenever either or both of the inputs to the Schmitt are high, the voltage across the load, shown in Figure 44, is also high. This behavior is exactly as desired and proves correct operation of the circuit at the input to the Schmitt triggers and beyond. These two input signals and the output signal are shown out of phase and thus do not line up exactly. However, they show the basic operation of the OR gate.

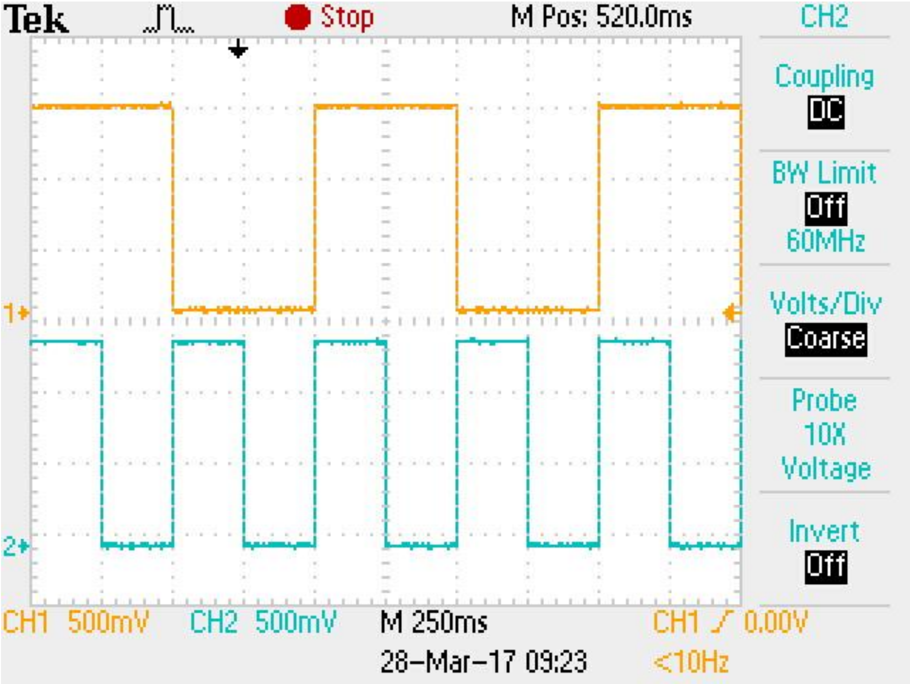


Figure 43 – Input to Schmitt Triggers

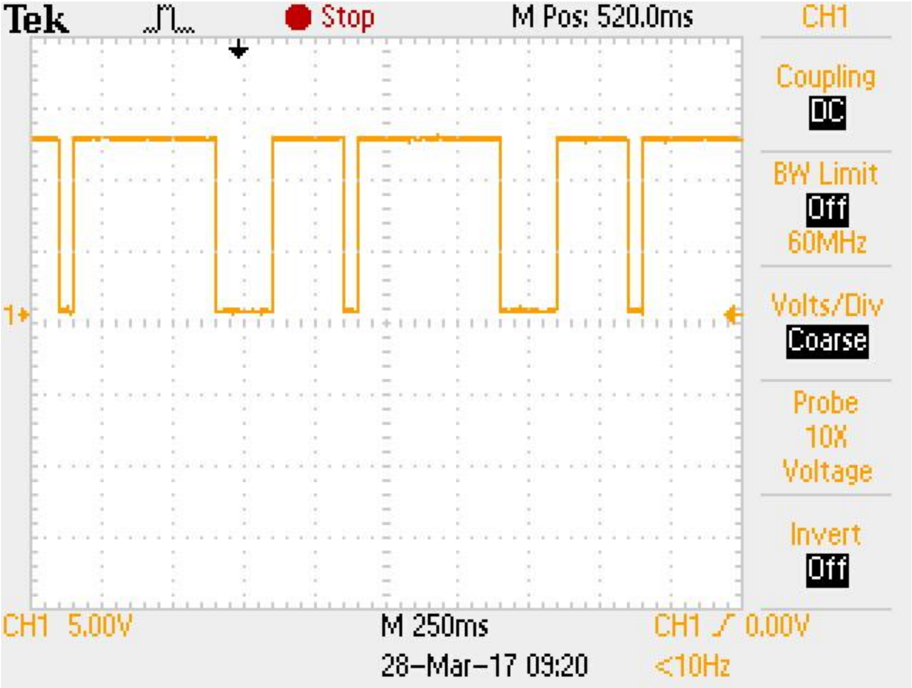


Figure 44 – Voltage across load

4.3.2 Natural Environment

As this device is intended to operate outside in cold temperatures off of a car battery, it is tested with these conditions. Additionally, the temperature sensors are also tested at this time. The test setup can be seen in Figure 45.

The temperature sensors are connected and the main power source for the circuit comes from a connection to the car’s cigarette lighter, which directly outputs 14V. As the ambient temperature was approximately 37°F, the temperature sensors were surrounded by ice packs to ensure the temperature would be cold enough to trigger a response.

This test involved measuring the voltage across the load and ensuring the proper response to a cold stimulus. When the temperature sensors are covered in ice, the expected response is for the NMOS to conduct and the heater to turn on. When the temperature sensors are in the ambient temperature, which is above the cut-off temperature, the heater should not turn on. However, once being stimulated with the ice and having the ice removed, the heater should stay on until the temperature reaches the cutoff point of 50°F.

With these expectations in mind, the test is conducted. The circuit performed exactly as expected. This verifies the functionality of the temperature sensors, the hysteresis loop, and supply of power from the car’s battery.

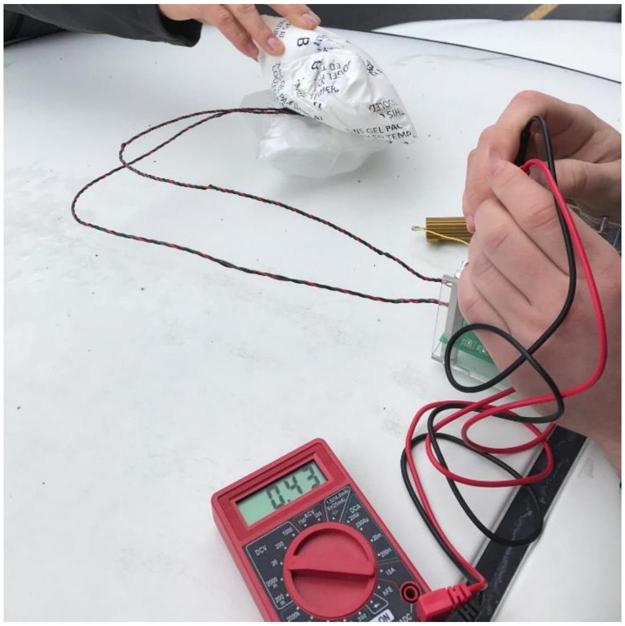


Figure 45 – Natural Environment Testing Set-up

4.4 Heat Film Testing

The following sections cover the process, test results, and problem that arose from the testing of the heat film.

4.4.1 The Process

A walk-in freezer provided a testing environment for the heating control system. The ambient temperature in this freezer was approximately 0°F. Once the headlight enclosure reached the ambient temperature, the circuit and battery were placed into the freezer (setup is shown in Figure 46). An initial temperature picture was taken with a FLIR camera (Figure 47), and then the control system was turned on. Temperature measurement of the outside of the polycarbonate were taken at one minute intervals with the FLIR camera for ten minutes.

Figure 46 – Heat Film Test Setup

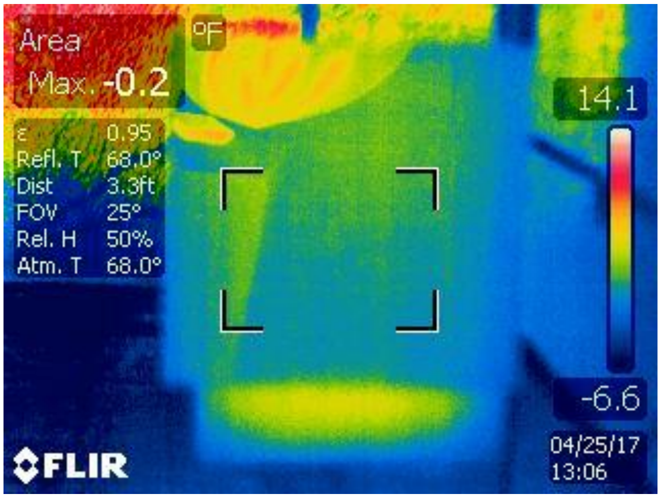


Figure 47 – Enclosure at Ambient Temperature (0°F)

4.4.2 Test Results

For our first test, we ran the heating film with the circuit as it would be used in a car. The battery we used to simulate a car battery was approximately 12V, which is 2V below a standard car battery's voltage when the car is running. Since our circuit drops the car battery voltage by approximately 2.1V due to 3 power diodes, our heating film was running off of approximately

9.9V instead of the 12V it is meant to run off of. The lower voltage reduced the speed at which the heating film increased temperature so the front of the headlight did not reach 50°F in 10 minutes. In order to test the heating film at 12V, we connected the heating film directly to the 12V battery and did not use the designed circuit. This better simulated the 12V that the heating film would receive while running off of a 14V car battery. The results for this test were much more promising. The temperature of the front of the headlight enclosure rose from 3.1°F to 66.4°F in 10 minutes which would work for our application. A picture from the FLIR camera of the headlight enclosure at the end of 10 minutes can be seen in Figure 48. The test data of the two tests can be seen below in Table 6. A graph of the data can be seen in Figure 49.

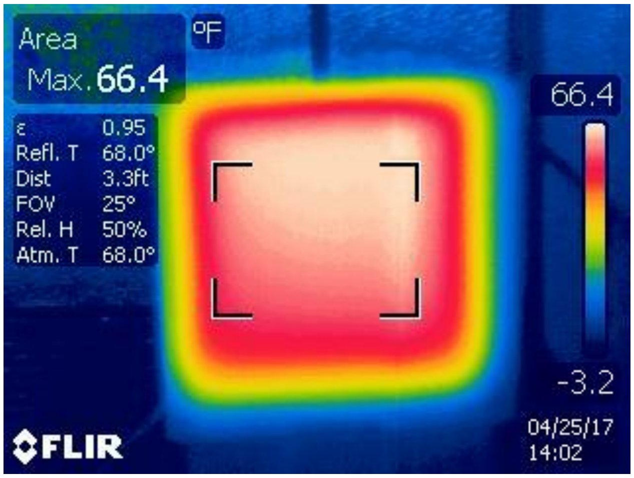


Figure 48 – Headlight Enclosure at 10 Minutes

Table 6 – Test Data

Time (Minutes)	10V Supplied to Heat Film (°F)	12V Supplied to Heat Film (°F)
0	0	3.1
1	6.8	8.0
2	9.9	17.2
3	16.0	25.5
4	21.0	33.5
5	26.2	40.0
6	31.3	46.1
7	35.4	51.3
8	38.1	58.1
9	41.5	62.6
10	44.1	66.4

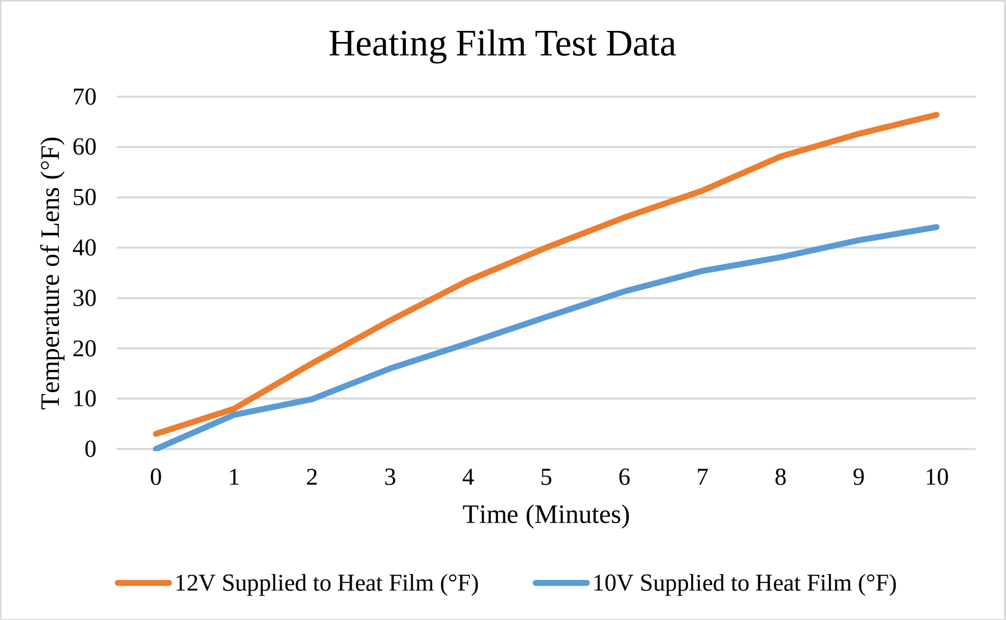


Figure 49 – Heat Film Temperature over Time

4.4.3 Problem

The main issue that we faced during our testing was that the temperature sensors were not picking up the change in temperature of the front lens, but rather held the ambient temperature of the freezer. This is an issue moving forward because in this scenario, the heating film will always be turned on, instead of turning off at the threshold temperature of 50°F.

5 Future Recommendations

As with any project, improvements can always be made. Suggested recommendations for the future of this system are outlined.

5.1 Alternative Heating Method

In order to improve the efficiency of heat transfer over the polycarbonate lens, a layered heat film approach is explored in simulation. Instead of a 0.25” polycarbonate lens, there would be a layered lens consisting of 3 layers. The first and third layers would consist of 1/12” polycarbonate for its durability and strength. The middle layer would be a 1/12” layered of a transparent ITO heater in a tempered glass substrate. The purpose of this would be to allow for faster heat transmission through the front lens.

Using SolidWorks heat flow simulation, this above described method is explored. Through iterations, the lowest heat used is 0.55 W/in^2 over five minutes. This is 0.1 W/in^2 less, and half of the time required to make a sufficient temperature for ice to melt than the method explored in this paper.

Figure 50 shows the heat distribution over the front of the modified lens. As can be seen, at the five minute mark the heat over the front lens is quite evenly distributed. The maximum temperature on the lens at this point is 292K (66°F), and the minimum is 282K (55°F).

Figure 51 exhibits the fluid flow distribution within the enclosure. Note the three layers shown in the left wall of the enclosure. Less heat is lost within the enclosure with this method than with the experimented method.

This method would have to be implemented at the car assembly level. It would not be a consumer add-on like the described method above. Car manufacturers would have to incorporate transparent heater technology into new headlight lens designs.

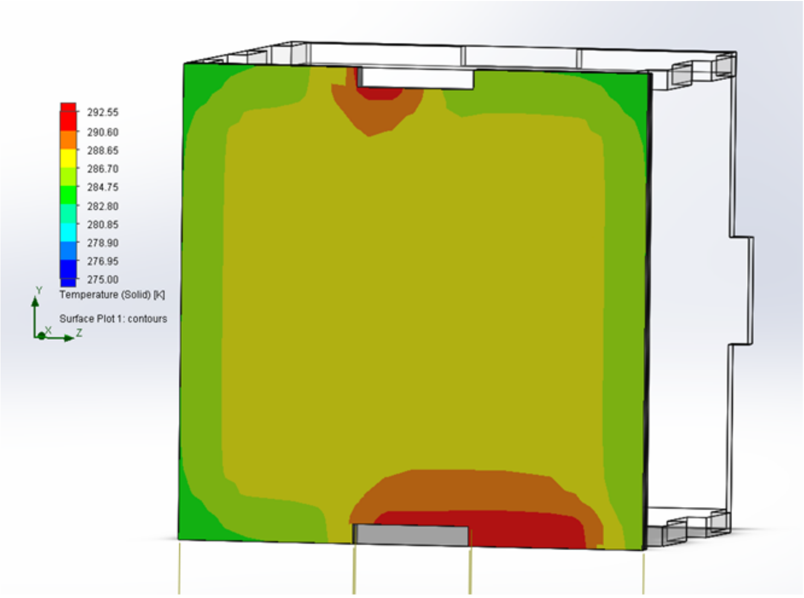


Figure 50 – Lens heat distribution at 5 minutes with layered heater approach

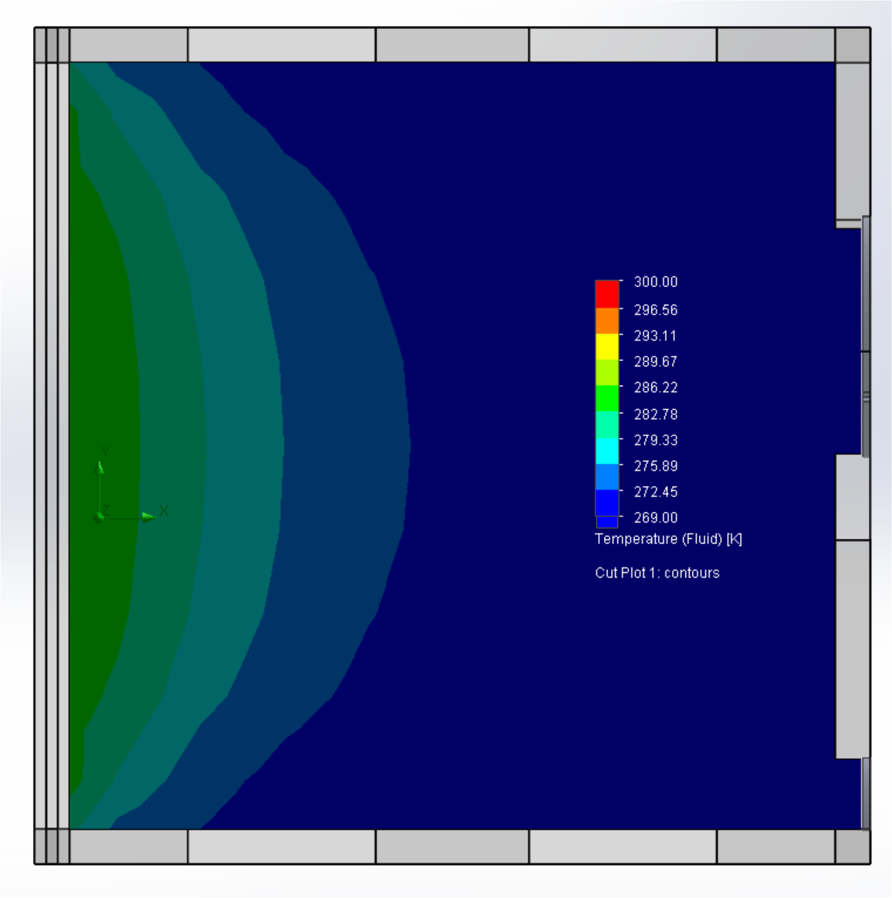


Figure 51 – Fluid temperature distribution with three layered approach

5.2 Pulse Width Modulation

The system proposed in this paper is already more efficient than a traditional halogen headlight system. The system proposed uses a maximum of about 21 W when it is operating in icy conditions, whereas a halogen headlight uses about 55W all of the time, which has been explored in 2.3. In order to introduce even more efficiency to this system, a pulse-width modulation (PWM) method of powering the heater can be explored.

PWM is a method of sending power to a device. The method proposed for the system above uses a steady-state power source. PWM, as the name implies, sends pulses of steady voltage in accordance with a predetermined duty cycle. This duty cycle determines how long the device is "on" for and how long the device is "off." A comparison of these two powering schemes is seen in Figure 52.

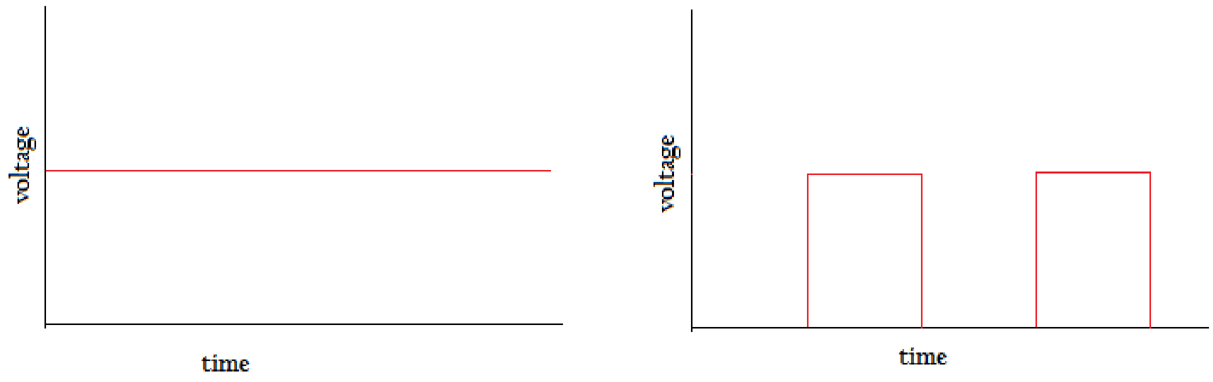


Figure 52 – A comparison of steady power to PWM power

An advantage of PWM is that the total power dissipated over a period of time is a function of its duty cycle, and as a result, the total power dissipated using PWM will be less than the power dissipated using a steady source of the same voltage. Equation 2 shows this relationship. T is the duty cycle, represented as a number between 0 and 1.

$$P = T * V * I$$

Equation 2 – Power with PWM

Using the equation above, one can think of a steady state power source as a PWM source with a duty cycle of 1.

A PWM power method is often employed in heating element circuits because heating elements tend to output heat for a while after power is disconnected. As a result, the system above may greatly reduce its power consumption if it were to implement a PWM method of powering the heater.

5.3 Alternative Sensors

The current system proposed relies solely on temperature to turn the heating film on and off. Although the heating film will keep the headlight enclosure above freezing temperatures, if there is not any snow or ice on the headlight then the heating film does not need to be on. If the heating film is on and there is nothing covering the headlight, then the current heating system will be wasting the car’s power unnecessarily. In order avoid wasting power, an additional sensor can be added to the system. A photosensor can be placed on the back side of the headlight enclosure to determine if any light from the bulb is being reflected due to any snow or ice on the front of the headlight. If the temperature is below freezing, but there is no light being reflected, then the heating system can be off and not consume much power. Adding a photosensor would reduce the amount of wasted energy by adding precision to the snow detection system.

5.4 Car Interface

Our control system is designed to be connected directly to the battery of the vehicle. In this configuration, there is constant sensing of the temperature even when the vehicle is off. If the vehicle is off and below our threshold temperature, the control system will still draw approximately 1.6A from the car battery to heat each headlight. Since there are two headlights, the system will draw 3.2A (1.6A for each headlight). Assuming a standard 45Ah car battery was fully charged, the battery would be completely drained in 14 hours, leaving the driver stranded in the cold. Future recommendations for this application would be for an added user interface in the vehicle so that the driver can turn on or off the control system feature. This will save energy when the car is at rest, and frosted headlights are not a problem.

5.5 Additional Temperature Simulations

The temperature simulations run during this project were based on a constant temperature outside of the headlight enclosure. To further simulate the environments that the headlight enclosure would be exposed to, temperature simulations should be performed with air flow blowing against the outside of the enclosure. This would simulate the wind blowing against the headlight as the car is moving. This simulation will likely show that the heat film will take longer to heat up the front of the enclosure due to the additional air flow.

5.6 Additional Temperature Sensor Configuration Research

As explained in section 4.4.3, the temperature sensor configuration that we used in testing did not work. In order to make this project work completely, additional research would be necessary to figure out how to configure the temperature sensors so that they can read the temperature of the front lens of the headlight. Alternatively, some heat films contain internal temperature sensors that might work better than the sensors that we used.

6 Conclusion

The problem addressed through this project was the fact that LED headlights do not produce as much heat as a halogen headlight. Due to the lack of heat, the lens of the headlight can frost over and result in dangerous driving conditions. To combat this issue, several solutions were explored. The final solution decided upon was the use of an ITO heating film to directly heat the lens of the headlight enclosure to melt the snow or ice as quickly and effectively as possible. Through testing, it was proven that given sufficient power, the selected heating film can increase the temperature of the polycarbonate lens from approximately 0°F to 65°F in 10 minutes. This testing proved that the use of an ITO film is a sufficient heating mechanism for a car headlight application. Though the proof of concept is valid, there is additional work that needs to be performed in order to fully integrate an ITO heating film into a headlight lens. This integration would make ITO heating films a viable solution to eliminate snow and ice accumulation on LED headlights.

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