Design and Analysis of the Power Electronics System for the Lean Operation Rotary Adsorption Cooling System

by

Wasay Anwer

Submitted to the
Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of

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ABSTRACT

The Lean Operation Rotary Adsorption Cooling System (LORACS) was developed in order to investigate avenues for more sustainable space cooling systems in the face of the growing threat of global warming. While traditional cooling systems rely on large amounts of grid electricity and a suite of environmentally harmful chemicals, the LORACS instead leverages thermal properties of water and desiccants to create cooling power from low-grade waste heat sources.

Although low-grade waste heat comprises of the majority of the LORACS power input, electrical power is still necessary to drive critical system components such as the fans, pumps, and instrumentation equipment. The LORACS system was designed to provide 3.5 kW of cooling with an expected electrical power input of roughly 475 W. Based on preliminary system testing, it was observed that the system produced roughly 2.7 kW of cooling power with 570 W of electrical power.

This paper seeks to outline the power electronics selection process for the initial LORACS prototype, as well as consider solutions and alternatives for future system revisions that would result in a higher coefficient of performance.

Thesis Supervisor: Douglas P. Hart
Title: Professor of Mechanical Engineering

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1. Background

As global energy consumption and emissions continue to accelerate the rate at which climate change occurs, the rapidly increasing levels of temperature and humidity worldwide will drive a significant increase in the need for space cooling. With current levels of emissions and global temperature increases, the climate of Massachusetts is on track to shift into the climate of significantly warmer latitudes, such as that of South Carolina. Resultantly, it is expected that by year 2050, the global demand for space cooling will increase from today's levels by 240%. [1]

Unfortunately, many of today's widespread cooling equipment rely on technologies and power sources that contribute to climate change, creating a feedback loop that threatens the life and comfort of people and wildlife all around the planet. Vapor Compression systems found in industrial AC equipment and refrigerators not only consume high amounts of electricity from the grid, but also rely on the use of extremely harmful refrigerants. R-22, one of the most common refrigerants in use today, has a greenhouse effect nearly 2000x as potent as CO2. [2]

The Lean Operation Rotary Adsorption Cooling System (LORACS) is a development initiative started through the Engineering Systems Design and Development (ESDD) program at MIT in cooperation with Lincoln Laboratory Beaver Works. LORACS aims to address many of the sustainability issues with modern cooling systems by transitioning from the use of grid electricity and refrigerants to more environmentally friendly methods such as waste energy use and recovery and the utilization of safer chemicals.

2. System Overview

LORACS generates cooling through the manipulation of various thermal properties of air and water. This is accomplished through the use of three different modular system blocks, which each carry out a different air treatment on our supply and return air streams. Figure 2.1 below displays each of these system modules: the desiccant wheel (DW) module, cascade heat exchanger (CHX) module, and the direct evaporative cooler (DEC) module.

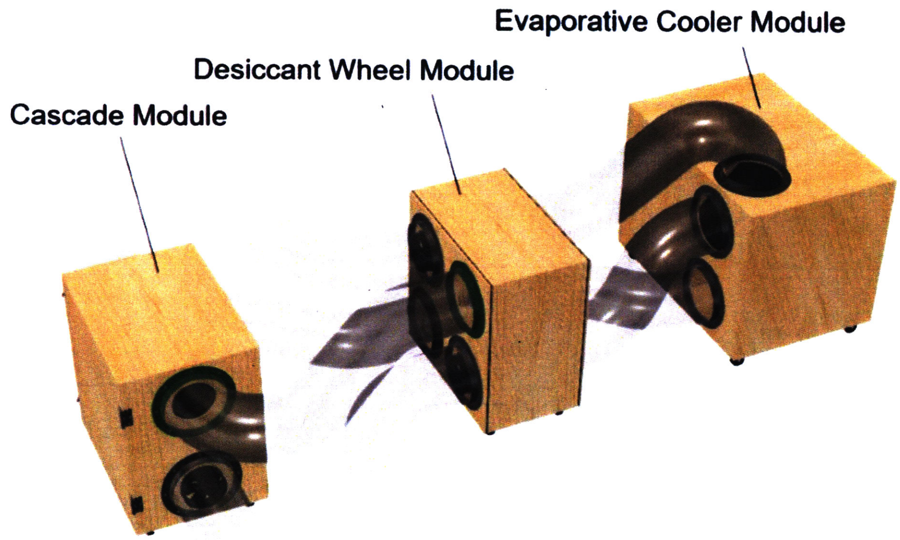

Figure 2.1: Final CAD model of the full LORACS system.

In simplest terms, the LORACS system effectively cools air by splitting the sensible and latent cooling work. Figure 3.2 details the entire airflow path through the LORACS system.

1. Hot and humid air enters the system from the outside environment, this air is then passed through the desiccant wheel, a silica-gel filled structure that removes moisture from the incoming air in exchange for heating it further.
2. The heated, dried air is sensibly heat exchanges with environmental air through the CHX, retaining the benefit of dry air while removing the excess heat created through the DW adsorption process.
3. The CHX process air is looped through the DW once again, drying and heating it further.
4. The DW second loop air is heat exchanged with the return air from the room via the DEC's sensible heat exchanger. This energy recovery step significantly reduces the energy needed to cool the room.

5. The process air passes through an array of misting nozzles and a moisture-wicking polyester foam screen. The mist evaporates into the process stream, increasing the humidity of the process air while significantly decreasing the temperature.

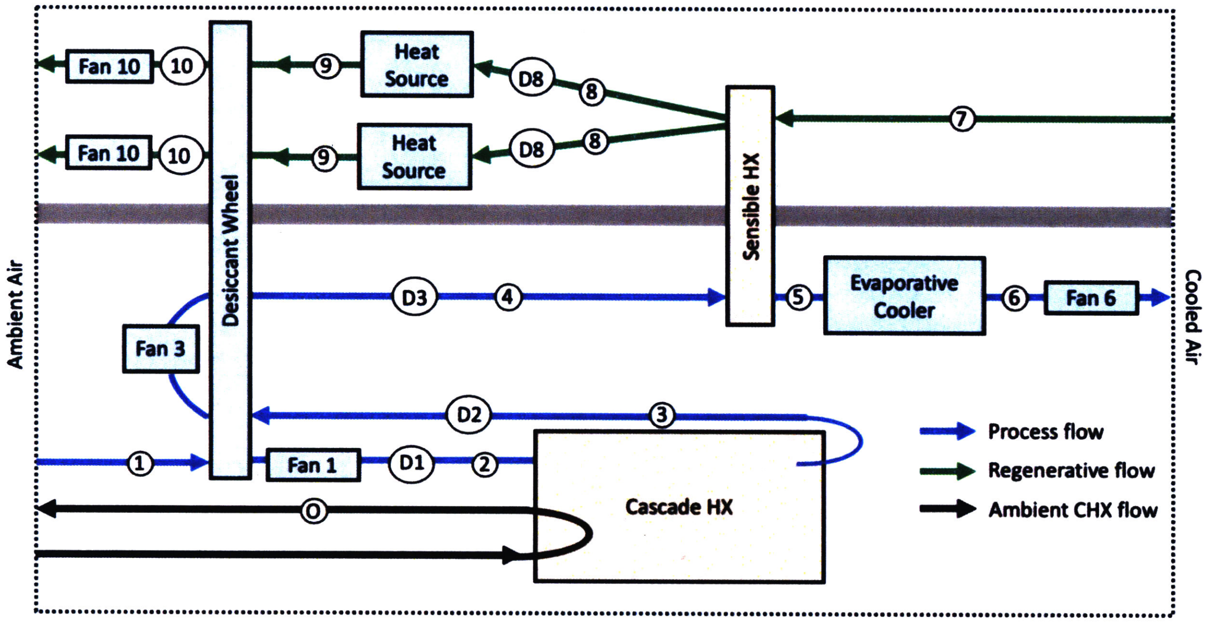

Figure 3.2: Total airflow diagram for the LORACS system.

The majority of the cooling power from LORACS comes from the evaporation of water into the process air. While evaporative cooling is already a widely used technology, it is severely limited based upon the humidity of the air being cooled. By coupling evaporative cooling technology with a desiccant, the LORACS system lowers the humidity of the incoming air significantly, allowing for a much greater temperature difference to be generated by the evaporative step. Meanwhile, unlike traditional vapor compression technologies that require significant electrical power, the regeneration of the desiccant wheel can be accomplished through the use of low-grade energy sources, such as waste hot water.

While the majority of the energy input to LORACS comes in the form of low-grade heat, some electrical power is still required to drive the supply and return air through the system, as well as power all of the system sensors and data collection equipment.

3. Component Selection

3.1 System Fans

An array of tubeaxial fans is responsible for providing the power to circulate air throughout LORACS. In order to maximize the effectiveness of the various process steps in our airflow cycle, fan parameters will need to be carefully selected in order to ensure that critical processes such as the drying and regeneration of the desiccant wheel are happening at efficient speeds. Much consideration was placed into the layout and selection of the LORACS fan array.

3.1.1 System Fan Configuration

The LORACS requires a total of 6 tubeaxial fans to fully circulate air throughout the system. These fans are placed in a variety of positions and orientations, depending on the flow and pressure drop required across each of the fans. The following diagrams will briefly outline the intended locations and operating conditions of each of the LORACS fans.

The desiccant wheel module contains 3 of the system fans. Fan 1 is used for the initial intake of the supply air and drives the air through the first pass of the DW. Fans 2 and 3 are placed in parallel configuration, each driving half of the return stream through one of the system's water to air heat exchangers. This creates the hot air that regenerates the LORACS desiccant using waste energy.

Fans 4 and 5 are contained on the cascade heat exchanger module. Fan 4 is placed in series with the airflow from fan 1 and continues pulling the air through the process side of the CHX. Meanwhile, fan 5 simply passes atmospheric air through the CHX and directly back into the environment to create the cascade cooling action required to prep the air for the second pass through the DW.

The final fan is positioned on the direct evaporative cooler module. Fan 6 pulls the second pass desiccant wheel air through the mist array and polyester foam, cooling it before depositing the process air in the cooled environment. Meanwhile, return stream air is pulled through the DEC sensible heat exchanger through ducts connecting the return stream to fans 2 and 3 on the DW module.

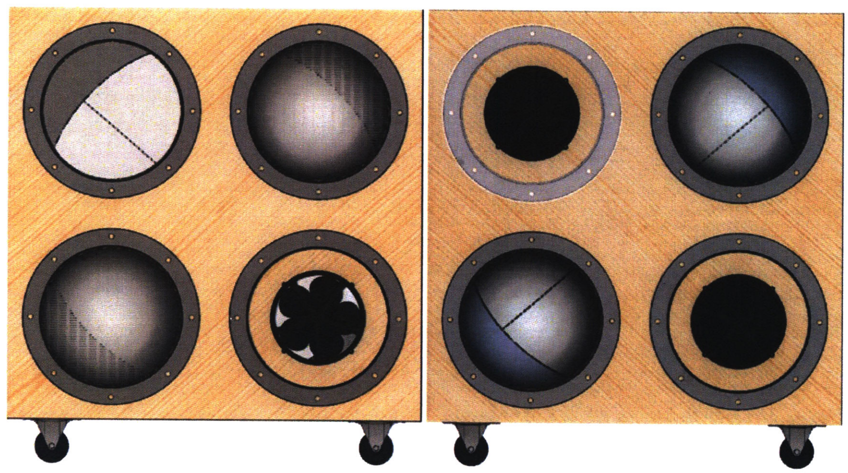

Figure 3.1.1.1: Right to left- Fans 1, 2, and 3 on the desiccant wheel module. Note that fans 2 and 3 are in a parallel pull configuration.

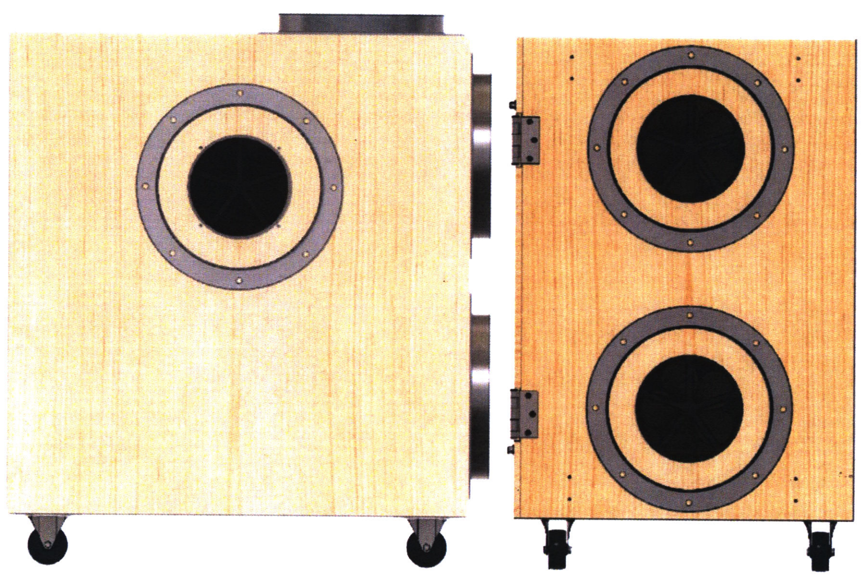

Figure 3.1.1.2: Clockwise, beginning with the top left- Fans 6, 5, and 4 on the DEC and CHX modules. Note that fans 5 and 6 are in series, pulling air through the DW and DEC.

3.1.2 Fan Selection

Given that the fan array is by far the majority of the system's electrical power draw, special attention was paid to the fan selection process. The combination of a high flow rate (roughly 550-600 CFM as described by the system requirements), as well as relatively high pressure drops across the various system components necessitates the use of relatively large industrial tubeaxial fans. Tubeaxial fans were considered given their ability to produce high flow with significant forward pressure.

Several different models of fans were considered for the system, but the R200A0-051-760D from NMB technologies was ultimately selected. The specs for the fan can be found below in figure 3.1.2.1. The R200A0 is rated for up to 783 CFM of flow and a static pressure of 1028 Pa. Using multiple of these fans in sets of series and parallel configurations allows us to reach the expected system operating point of 700 Pa at 550 CFM.

MODEL	Rated Voltage	Operating Voltage	Current	Input Power	Speed	Max. Air Flow		Max. Static Pressure		Noise	Mass
	(V)	(V)	(A)*1	(W)*1	(min⁻¹)*1	CFM*1	(m³/hr)*1	in H_2O	(Pa)*1	(dB)*1	(g)
R200A0-051-D0760	48	30 ~ 72	2.9	139	6500	783	1330	4.12	1028	74	1200

Figure 3.1.2.1: R200A0-051-D0760 specifications table.

Pressure drop and flow requirements for each fan vary significantly based on their location in the system. Figure 3.1.2.2 illustrates the R200A0's flow/pressure curve at full power. The different fan operating points for the system are all graphed on the same plot. The singular point to the left is the expected draw of the two individual intercooler fans on the regenerative stream. The cluster of points on the right are the crossflow heat exchanger fans, the DEC fans, and the desiccant wheel intake fan. As evidenced by the plot, the various operating points for each fan lies significantly beneath the max power curve for the R200A0, this demonstrates that the fan is capable at producing the desired output at every point without utilizing the full power of the fan.

Having only a single model of fan that is capable of operating efficiently at different flow and pressure levels simplified ordering, wiring, and simulation of the system.

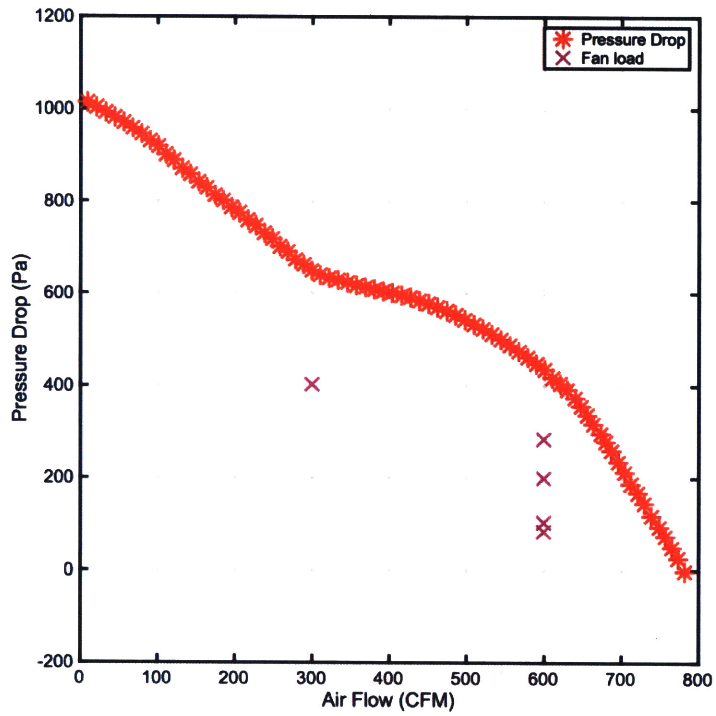

Figure 3.1.2.2: Above is a graphical representation of the different fan loads and how they compare when measured against flow rate and pressure drop within the system.

In order to drive the fan at controlled speeds, a Pulse-Width Modulation (PWM) input signal is required. Using a PWM signal changes the duty cycle of the fan to any value between 0 and 100%, doing so allows for efficient regulation of the fan's RPM. The fan manufacturer provided a PWM frequency spec of 25 kHz, this signal was generated using an off-the-shelf PWM signal generator and monitor, to allow for rapid adjustment of fan speeds.

Figure 3.1.2.3: PWM signal generator used to set and monitor fan duty cycle during operation.

The estimated power draw of the total fan array is predicted to be on the order of anywhere from 500W to 700W. This number will vary based upon factors such as fan efficiency, the real pressure drop across the various system components, and the presence of leaks throughout the system.

3.2 Pump

After the fan array, the DEC's misting pump is the component with the next highest electrical consumption throughout the system. Initially, the LORACS system was intended to use a simpler drip irrigation system that would slowly deposit water onto an evaporative media such as cardboard or Aspen straw. However, early stage testing throughout the development of the system indicated that direct misting into the process stream was much more effective at cooling than drip irrigation onto a cooling pad. As a result, relatively high pump pressures became necessary to properly drive water through a misting nozzle, which in turn necessitated the use of a moderately high-power pump.

Standard misting nozzles, such as the ones found on many gardening systems and equipment, tend to operate in the roughly 40-60 PSI range that residential water supplies typically run at. In order to ensure that multiple misting nozzles would function at the necessary pressure, a pump with an output in the 80-100 PSI range was selected. Based on analysis from 2.013, it was estimated that the LORACS system would require on the order of 4-6 Liters per hour of water circulation.

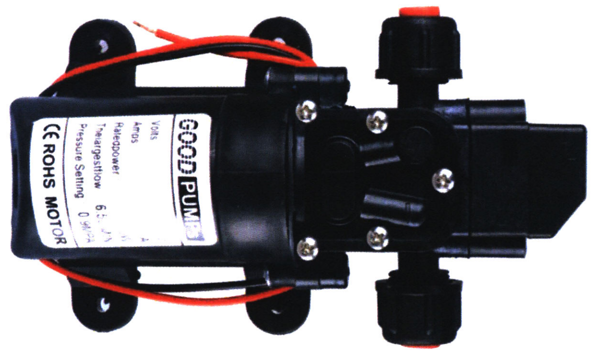

Figure 3.2.1: Amarine 12v self-priming pump. The pump powers the misters and water circulation loop in the LORACS DEC module.

Quite a few commercial off the shelf pumps met or exceeded the requirements determined by our analysis. The Amarine 12v pump was selected based on its low cost and rapid availability. The pump features a maximum working pressure of 130 PSI and a peak flow rate of 6.5 Liters per minute, both of which are more than sufficient for the needs of the LORACS evaporative cooler. While the pump's peak power rating of 80 W is potentially concerning from a consumption perspective, it was predicted that the LORACS DEC would require a maximum of 20 W to provide adequate misting, based off of the relatively low flow rate required.

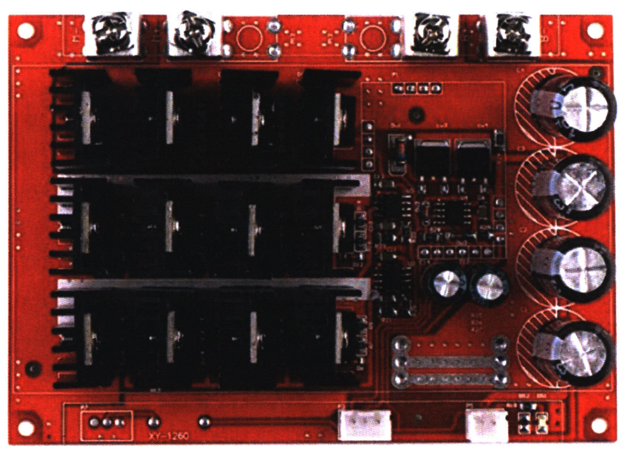

Figure 3.2.2: 10-50 V motor driver used to regulate output to the DEC fan.

In order to regulate the output of the pump and keep the mist generation at the proper levels, a motor driver was used to control the pump. Originally chosen to control the fans, these modules each support up to 60 A, ensuring that the pump would not ever burn out the driver, even at maximum power. Instead of a PWM generator, a simple potentiometer was wired into the driver, allowing for coarse control of the output.

4. Electrical Integration

After finalizing the major power-consuming components of LORACS, the power supply and distribution system was designed to cleanly and effectively provide power to all of the different system components. Some of the considered factors included total system power draw, required voltages of each system component, and the safety of wire gauges for different component runs.

4.1 Power Supply

In order to begin integrating the system electronics, a reliable power supply needed to be selected. While many AC to DC switching power supplies are commercially available, two 48 V 20 A power supplies were ultimately selected to provide the input electrical power to the LORACS system from the wall.

Given that the fan array comprised the majority of the system power draw, it was most efficient to select 48 V as the base system voltage. This decision eliminated the need for any more high-capacity voltage reducers, which would add cost and reduce the overall electrical efficiency of the system. In addition, switching power supply efficiency tends to increase with higher voltage, with some 48 V supplies functioning in the 85-89% efficiency range. [3]

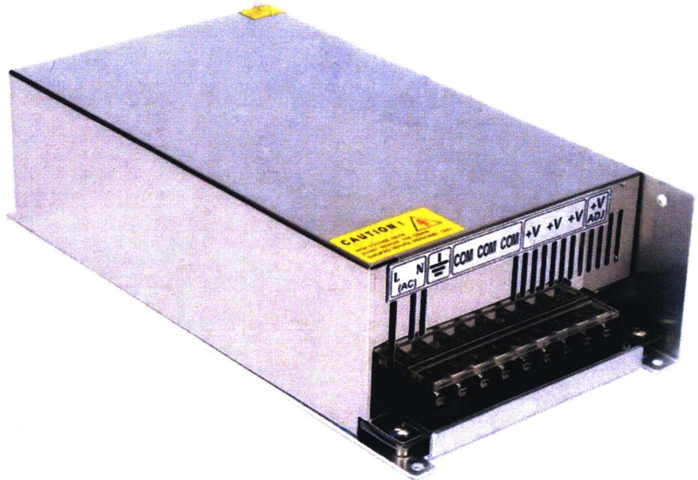

Figure 4.1.1: 48 V, 20 A, 1000 W Peak switching AC/DC power supply.

The selected power supply was rated for a maximum output of 1000 W. However, manufacturer guidelines recommended a limit of 80%, or 800 W for long-term sustained use. Because the fan array has a peak draw of 840 W alone, the decision was made to split the system power input to two power supplies, in order to prevent overheating of the switching power supplies. One power supply was placed on the desiccant wheel module and is used to power all three DW fans. The second power supply is mounted on the CHX module, and powers both CHX fans, as well as the DEC fan and misting pump. By splitting the loads between two units the max draws on the DW and CHX power supplies are limited to roughly 440 W and 520 W, respectively.

4.2 Power Distribution

While the majority of the LORACS power consumption is done natively off of 48 V power, many of the system components require either 12 V or 5 V power to run properly, such as the pumps, sensors, microcontrollers, and fan PWM drivers.

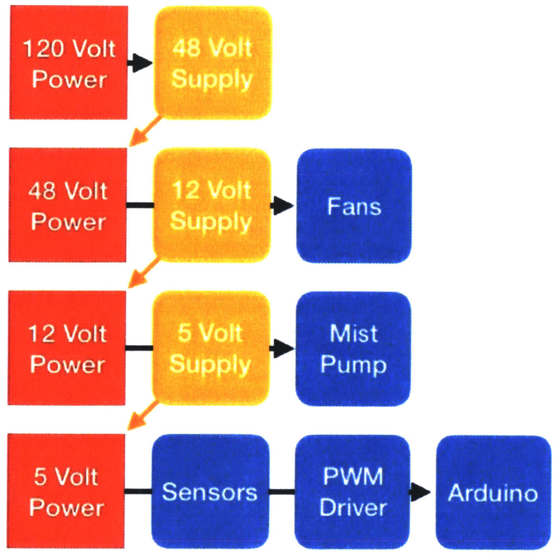

Figure 4.2.1: The above diagram presents a quick overview of the different electrical lines on the system and what each of them powers.

In order to provide power to the lower voltage components without damaging them, each 48 V power supply was wired connected to a 12 V and 5 V step-down voltage regulator. These devices provided regulated input power for the misting pump and its driver, as well as the sensors and microcontrollers.

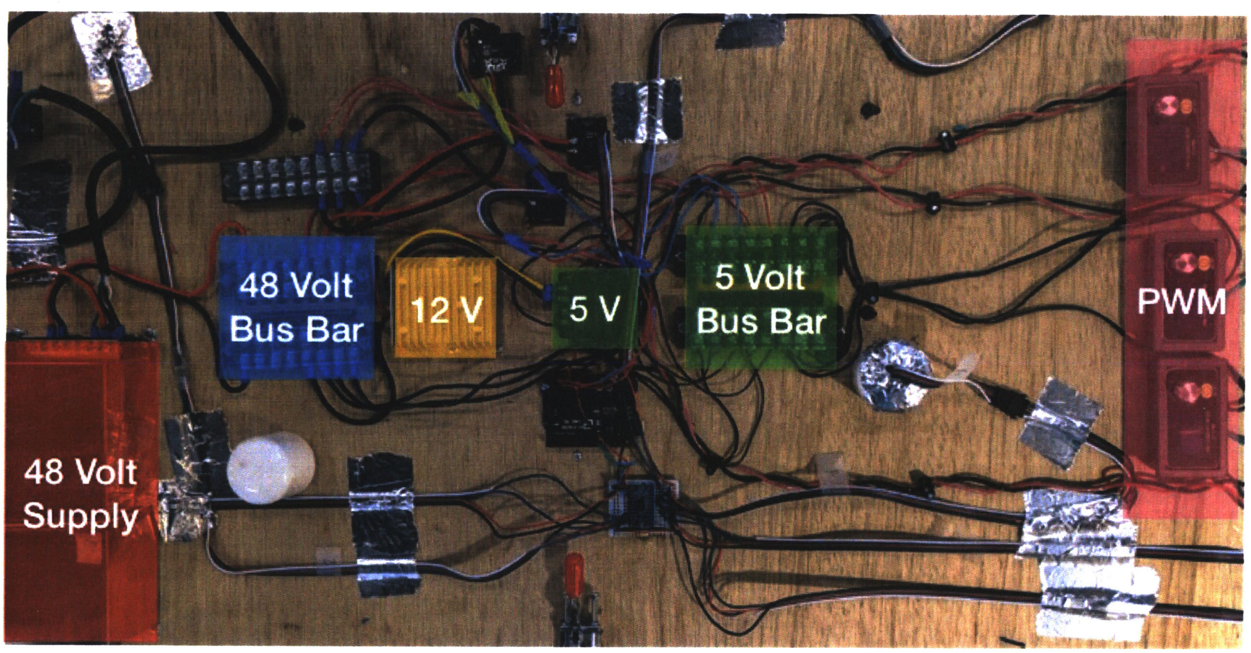

Figure 4.2.2: Top of the completed desiccant wheel module. All major electrical components are labeled.

During initial testing of the power supply system, there were some wire heating issues on the 48 V rail. While the system was ramping up and fans were at their peak current draw, some of the fan power wires began to overheat and burn through their jacket. A quick analysis of the power draw showed that at their 139 W peak, each fan was drawing 2.9 A of current through the wire, which was beyond the safety specifications of the 18 AWG wire that we had initially connected the fans with. The maximum recommended load for 18 AWG wire happens to be 2.3 A, which would correspond to a maximum load of 110 W at 48 V. [4] Given that each of the system fans has the potential to draw significantly more than that, the decision was made to replace the original fan wiring with higher gauge 14 AWG wire. This change more than doubled the power capacity of the 48 V distribution lines, allowing the system to remain within the recommended limits with significant overhead. The increased current capacity also facilitated the sharing of a single power supply between the DEC and CHX modules.

AWG	Diameter [inches]	Diameter [mm]	Area [mm^2]	Resistance [Ohms / 1000 ft]	Resistance [Ohms / km]	Max Current [Amperes]
12	0.0808	2.05232	3.31	1.588	5.20864	9.3
13	0.072	1.8288	2.62	2.003	6.56984	7.4
14	0.0641	1.62814	2.08	2.525	8.282	5.9
15	0.0571	1.45034	1.65	3.184	10.44352	4.7
16	0.0508	1.29032	1.31	4.016	13.17248	3.7
17	0.0453	1.15062	1.04	5.064	16.60992	2.9
18	0.0403	1.02362	0.823	6.385	20.9428	2.3

Figure 4.2.3: Physical dimensions, resistance values, and maximum recommended current for several common wire gauges.

Power-on tests were conducted after the full LORACS was outfitted with the proper wire gauges. Full system testing with all components at max output was stable, with no further signs of overheating and electrical burnout. As a final safety and control measure, 120 V machinery power switches were wired in between the 120 V wall plugs and the 48 V power supplies

5. Initial Results

Initial testing of our system indicated that LORACS operates reasonably close to its targeted performance. As may be expected of an alpha prototype, the system efficiency was lower than anticipated. The system required nearly 20% more electrical power than initially expected, while producing a little under 80% of the desired cooling. Nonetheless, as a first prototype, the LORACS proved to be reasonably successful.

A few key factors may have contributed to the inefficiencies observed in the results. The most impactful of these were environmental factors such as the humidity and temperature of the testing environment. While environmental factors are difficult to adjust for, there are a couple of system parameters that can be tuned in the future for better performance.

Lack of fan power optimization is probably the largest cause for the higher than expected power consumption. Due to time constraints, all fans were set to the same duty cycle for the duration of the testing in order to simply the setup and coarse tuning process. However, given that each system fan experiences a different pressure drop and flow rate, running each fan at the same duty cycle is less than optimal. With more time dedicated to tuning in future LORACS tests, adjusting the output of each fan individually could potentially lead to a decrease in system power consumption while also regaining some of the lost efficiency.

Parameters	Theoretical Value	Measured Value
Outlet Temperature [°C]	18.1	18.1
Electrical Power [W]	3500	2677
Cooling Power [W]	474	565
COP	7.37	4.79

Figure 5.1: Summary of initial results from the LORACS prototype test in the basement of MIT Building W59. Results indicated an average system power draw of 565 W and a cooling output of 2677 W. [5]

6. Conclusions

The complexity and component variety of the different modules of LORACS necessitated the organization of a robust and efficient power distribution system. Given that the intent of LORACS is to provide a pathway for an efficient alternative to current air conditioning systems, it is of the upmost importance that the power electronics components and system are optimized to reduce the system's electrical consumption as much as reasonably possible. The use of tubeaxial duct fans allowed for efficient airflow even across high pressure drops. Minimizing the number of voltage regulators by grouping components onto different buses reduced the amount of energy lost to DC switching and stepping. Ultimately the LORACS prototype was able to operate with a measured COP of 4.79, which is comfortably in the neighborhood of conventional vapor compression air conditioners. With more extensive testing and careful tuning of each component's output, it is likely that the system efficiency can raised even higher on future revisions of the LORACS.

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[1] Anwer, Wasay, et al. "LORACS LEAN OPERATION ROTARY ADSORPTION COOLING SYSTEM." Massachusetts Institute of Technology, 2018

[2] California Air Resource Board. "High-GWP Refrigerants". Web, 2019.

[3] Meanwell. "SP-480 Spec Sheet" Web, 2019.

[4] Solaris Shop. "American Wire Gauge Conductor Size Table" Web, 2019.

[5] Ali, Fayed, et al. "LORACS LEAN OPERATION ROTARY ADSORPTION COOLING SYSTEM." Massachusetts Institute of Technology, 2019