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ECE 492
Motor & Controller Cooling
4/26/16

# Cooling Results

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## I. Introduction

The purpose of this report is to determine the efficiency and characterize the way the HPEVS AC50-51-5X motor and controller setup dissipates heat. Data was collected and analyzed to determine if water cooling the vehicle's motor is effective. This study aims to determine whether or not the motor will need some form of cooling, and if an implemented water cooling solution provides any benefit to running the motor in its current lab setup.

## II. Hypothesis

This report aims to characterize heat energy dissipated by the motor and dynamometer setup. This will help determine the motors efficiency in normal operating conditions, as well as determining if an implemented sink motor cooling solution is an effective method for dissipating heat energy from the motor. The hypothesis for this report is that most of the system's power loss during normal operation can be characterized by losses due to heating, and that a water-cooled solution for the motor in its current setup could help improve uptime.

The second portion of this experiment, water cooling, aims to identify any efficiency improvements on the motor due to water cooling. If this is found to be the case, further research will have to be done to spec a water cooler to the motor.

## III. Data Collection

Data was collected using temperature sensors available on the current water cooling system integrated with the controller. An auxiliary temperature probe available with the water cooling system implemented for the curtis controller was attached to the motor to determine its external temperature. The internal temperature of the motor was measured using the curtis 1314 programming software. This software was set as a sample rate of measuring data every one second. All manually measured temperature data (from thermocouples in the lab and the controller cooling box) were recorded once every 35 seconds.

### A. Experiment 1 - No water cooling

The aim of collecting this data was to illustrate the motors temperature curve without water cooling. Temperature data was taken both from the curtis software (giving the temperature within the motor) and from a temperature sensor on the current water cooler for the curtis controller. To begin the experiment, the motor was run at a constant throttle and load until it reached a temperature near 100 degrees C (which we have determined to be the highest operating temperature and should not be exceeded). The sensor and dynamometer configuration used for this experiment can be found in **Appendix A.**

Test Setup

- Set Load to 76%
- Set Power supply to 89.7v
- Set Throttle to 33% ~2500rpm
- Run test until motor reaches a temperature above 75 degrees C
- Set Throttle to 0%

Record temperature data until the temperature has reached near steady state. Data was collected until about 77 degrees C which is nearing the max operating temperature.

Note: Temperature data was recorded the entire duration of this test to characterize heating up and cooling.

### B. Experiment 2 - Water Cooling

The second experiment was performed with a water cooling system made up of a hose coiled around the motor with water circulating through it from the sink and back into the drain.

Test Setup

- Set sink flow rate to 3.785 lpm
- Set Load to 76%
- Set Power supply to 89.7v
- Set Throttle to 33% ~2500rpm
- Run test until motor reaches same temperature as previous test
- Set Throttle to 0%

Continue recording temperature data until the temperature has reached near steady state.

## IV. Data Analysis

This section will compare graphs of the data sets collected when testing the motor with water cooling and without. To compare these data sets, due to the vast difference in the time it took to collect the data, the unit Time is either presented in seconds or % of a day. This makes t easier to normalize the data and compare properly.

### Heating Analysis

To calculate the heat energy lost during the heating of the motor in its air-cooled experiment, a sample of the first 500 seconds was taken, as seen in **Figure 1.** This time frame was chosen to obtain a statistically significant rate of heating for the motor and controller without having linearity of heating affected by ambient cooling. The rates at which the motor and controller heated during the air-cooled experiment were determined to be 0.0465 degC/s and 0.0136 degC/s respectively. These values are important later in calculating total energy loss due to heat. An identical strategy was used in the case of a water-cooled motor in order to find heating rates of .0498 degC/s and .0152degC/s for the motor and controller, respectively (see in **Figure 2)**.

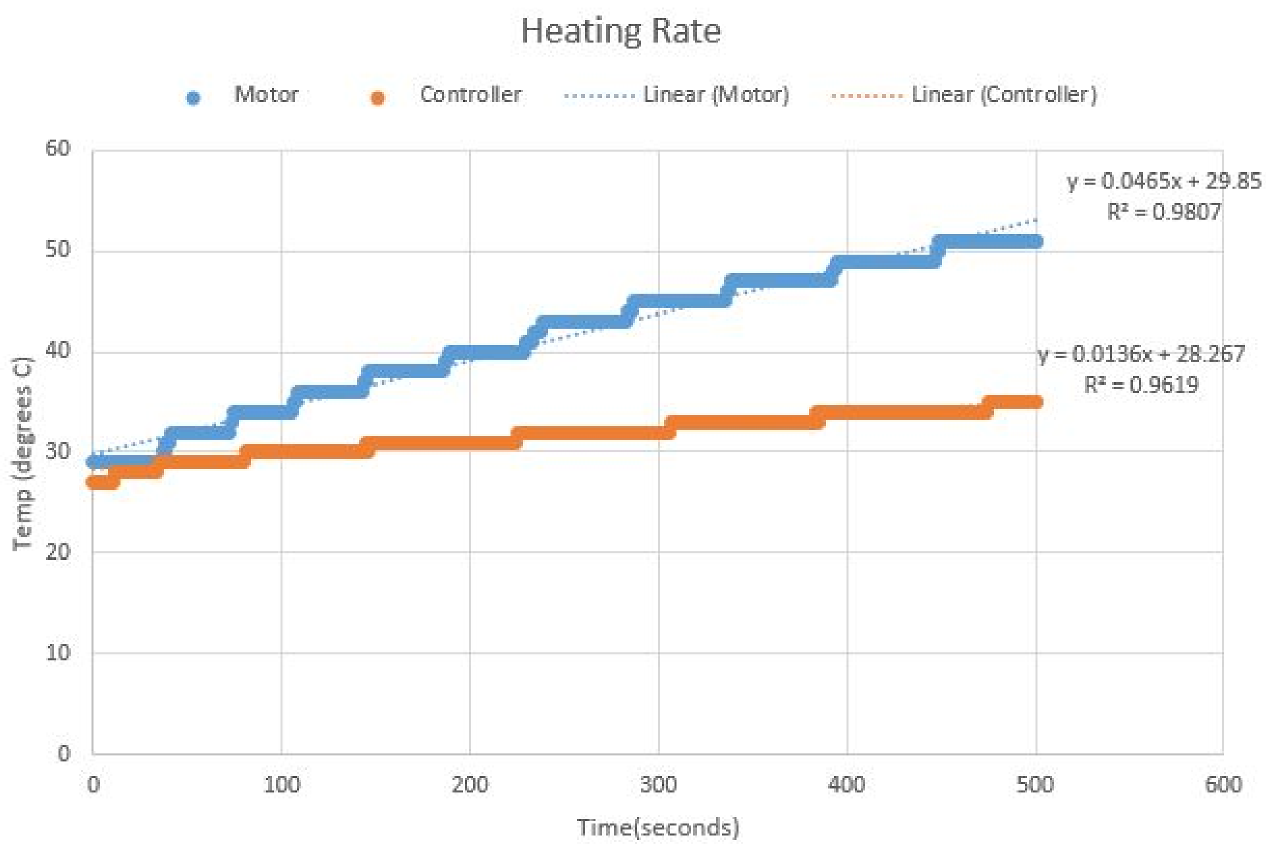


**Figure 1**

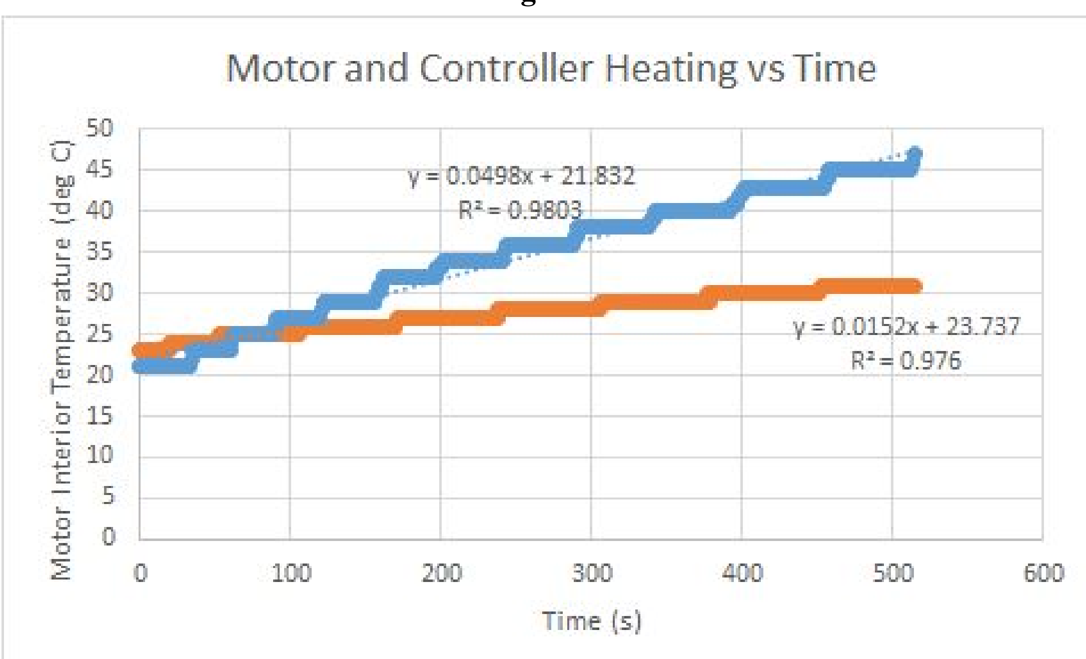


**Figure 2**

## Cooling Analysis

The cooling rate for the internal temperatures of the air-cooled and water-cooled motors was compared in order to determine whether the implemented sink cooling solution was effective. The two full experimental data sets for the internal temperature of the motor in each case is shown below in **Figure 3.** One useful metric which was determined for comparing the cooling ability of each setup is the "70 half life." That is, the amount of time that it takes for the motor internal temperature to decrease from 70 degrees C to 35 degrees C. For the air cooled setup, this amount of cooling took 15430 seconds. Using the sink water cooling solution, it took only 6074 seconds. This represents **60.6% improvement** in 70 half life using the sink cooling method. The change in rate of heating was of the motor was, unfortunately, close to negligible.

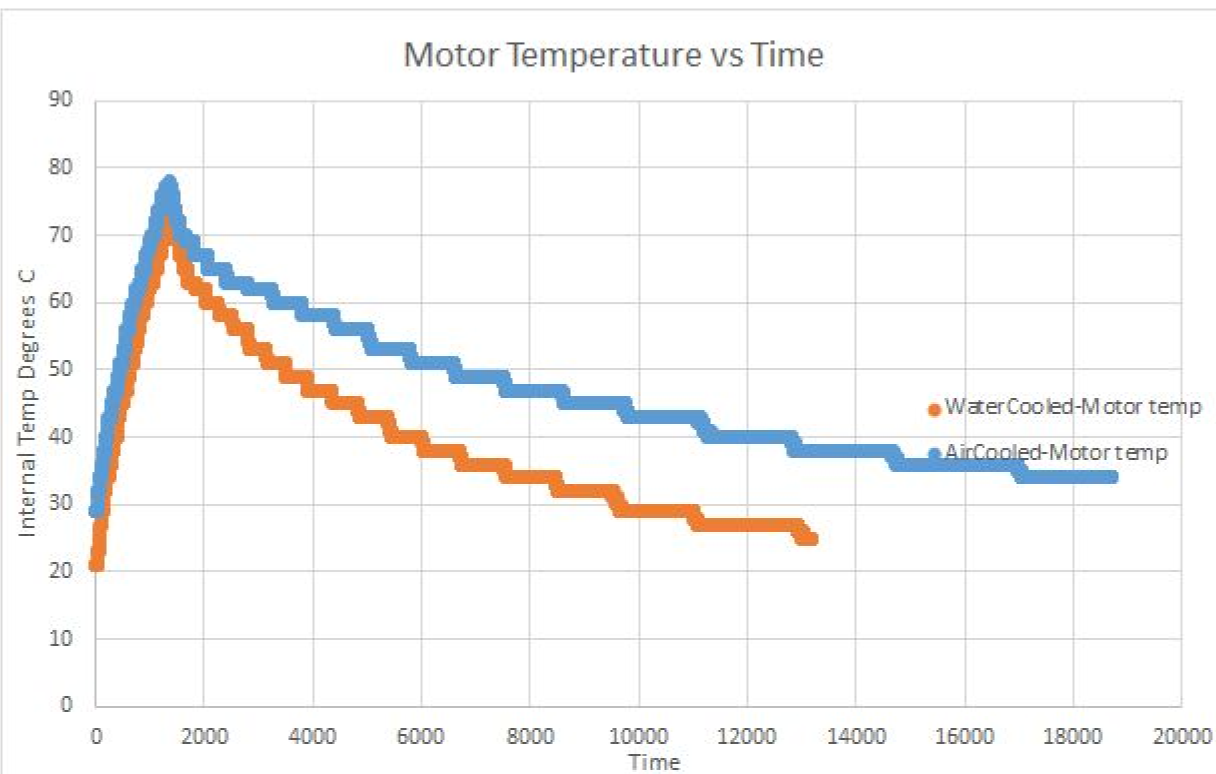


**Figure 3**

## V. Results and Conclusions

To determine the validity of our hypothesis that heat dissipated by the motor accounts for the majority of the energy loss from input to the output, different measurements were taken to determine heat change in the air, heat change in the dynamometer oil and heat change vs time in the heating curves of the controller and the motor.

To calculate the heat transferred, density of the heated element had to be calculated along with its volume and specific heat. The tables below will show measurements and calculations of each element which heat was transferred to. The end goal of these calculations is to have a value in Joules/Second or Watts.

**Air Cooled Energy Calculations**

| Oil Box: | | | Heat Energy dissipated in oil | | |
|---|---|---|---|---|---|
| Length | 46 | inches | Initial Oil Temp | 23.2 | degC |
| Width | 29.5 | inches | Final Oil Temp | 36.6 | degC |
| Height | 13 | inches | Oil Temp Change | 13.4 | deg C |
| Volume | 17641 | inches ^3 | Heating Time | 7561 | s |
| | 289083.067 | cm^3 | Heating Rate | 0.001772252 | degC/s |
| Mass | 231266.4536 | g | | 0.409862515 | kg*degC/s |
| | 231.2664536 | kg | Power Transfer | 0.684470401 | kJ/s |
| Spec heat mineral oil | 1.67 | kJ/kg*degC | | 684.4704006 | W |

**Table 1**

| Room: | | | Heat energy dissipated into Air | | |
|---|---|---|---|---|---|
| Length | 13 | feet | Initial Air Temp | 22.1 | degC |
| Width | 17 | feet | Final Air Temp | 25.7 | degC |

| | | | | | |
|---|---|---|---|---|---|
| Height | 7.5 | feet | Air Temp Change | 5.2 | degC |
| Volume | 1657.5 | feet^3 | Heating Time | 1344 | s |
| | 46.935096 | m^3 | Heating Rate | 0.003869047619 | degC/s |
| Mass of air | 57.4954926 | kg | | 0.2224527988 | kg*degC/s |
| | | | Power Transfer | 0.2224527988 | kJ/s |
| Spec heat air | 0.239 | kcal/kg*degC | | 222.4527988 | W |

**Table 2**

The composition of the motor was estimated to be 50% copper and 50% steel (as per Professor Helm). Based on this determination using the average specific heat of copper and steel gives the motor a specific heat of 0.105 kcal/kg*degC. Heating rate of the motor was determined by the slope of the heating data to be 0.0335 degC/s. This was accomplished by averaging the rate of heating for the internal temperature of the motor (**Figure 1**) and the external temperature of the motor **(Figure 4).** An estimate of the motors weight can be found on the HPEVS website [1].

| Heating Rate | | Spec heat motor: | |
|---|---|---|---|
| 0.0335 | degC/s | 0.105 | kcal/kg*degC |
| 3.8525 | lbs*degC/s | 439.32 | J/kg*degC |
| 767.7091 | J/s = W | 189.78624 | J/lb*degC |

**Table 3**

Heat transfer to the motor controller also had to be determined. The weight of the controller was found on the manufacturer’s website, and density of the controller was provided in the solidworks file on the manufacturer's website [2].

| Controller Heating Rate | | Controller Spec heat: | |
|---|---|---|---|
| 0.0136 | degC/s | 0.25 | kcal/kg*degC |
| 0.1632 | lbs*degC/s | 1046 | J/kg*degC |
| 77.43279 | J/s = W | 474.4656 | J/lb*degC |

**Table 4**

Putting it all together, the sum of all of the heat power (**Table 5**) is 1392 watts.

| Heat | Watts |
|---|---|
| Oil | 409.8625 |

| | |
|---|---|
| Motor | 767.7091 |
| Controller | 77.43279 |
| Room Air | 136.894 |
| Total | 1391.903 |

**Table 5**

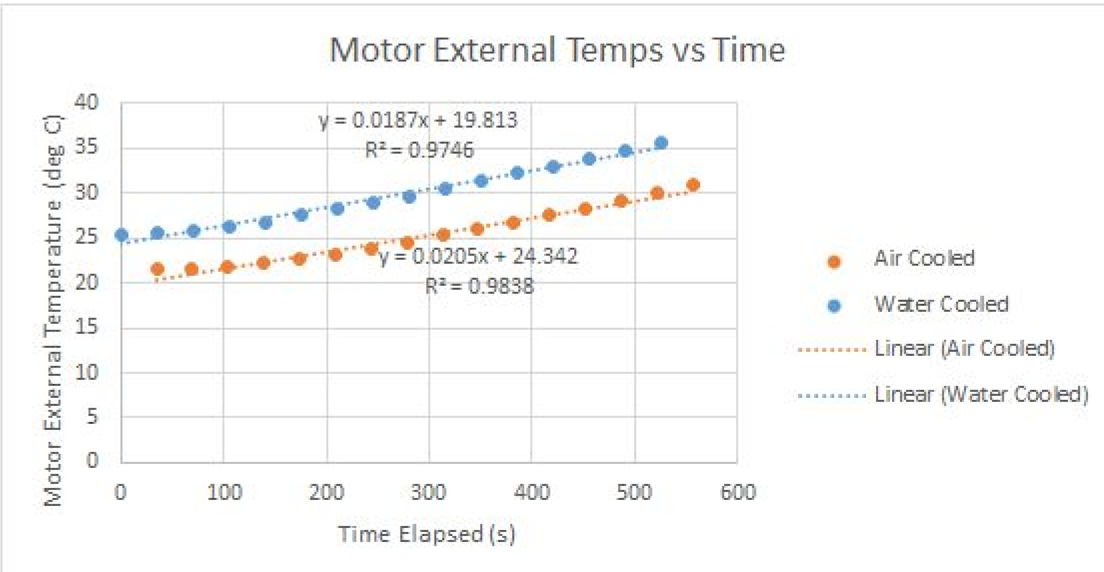


**Figure 4**

**Water Cooled Energy Calculations**

Below are the results from the water cooled motor efficiency and cooling test laid out in the same way. Constants for specific heats of the motor and controller are unchanged, but other parameters of the experiment have been modified.

| Oil Box: | | | Heat Energy dissipated in oil | | |
|---|---|---|---|---|---|
| Length | 46 | inches | Initial Oil Temp | 23.2 | degC |
| Width | 29.5 | inches | Final Oil Temp | 34.6 | degC |
| Height | 13 | inches | Oil Temp Change | 11.4 | deg C |
| Volume | 17641 | inches ^3 | Heating Time | 7561 | s |
| | 289083.067 | cm^3 | Heating Rate | 0.001507737 | degC/s |
| Mass | 231266.453 6 | g | | 0.348689006 | kg*degC/s |

| | | | | | |
|---|---|---|---|---|---|
| | 231.2664536 | kg | Power Transfer | 0.348689006 | kJ/s |
| Spec heat mineral oil | 1.67 | kJ/kg*degC | | 348.6890056 | W |

**Table 6**

| Room: | | | Heat energy dissipated into Air | | |
|---|---|---|---|---|---|
| Length | 13 | feet | Initial Air Temp | 22.1 | degC |
| Width | 17 | feet | Final Air Temp | 22.2 | degC |
| Height | 7.5 | feet | Air Temp Change | 0.1 | degC |
| Volume | 1657.5 | feet^3 | Heating Time | 1344 | s |
| | 46.935096 | m^3 | Heating Rate | 7.44E-05 | degC/s |
| Mass of air | 57.4954926 | kg | | 0.004278 | kg*degC/s |
| | | | Power Transfer | 0.004278 | kJ/s |
| Spec heat air | 0.239 | kcal/kg*degC | | 4.277938 | W |

**Table 7**

| Heating Rate | | Spec heat motor: | |
|---|---|---|---|
| 0.03425 | degC/s | 0.105 | kcal/kg*degC |
| 3.93875 | lbs*degC/s | 439.32 | J/kg*degC |
| 784.8966 | J/s = W | 189.78624 | J/lb*degC |

**Table 8**

| Controller Heating Rate | | Controller Spec heat: | |
|---|---|---|---|
| 0.0152 | degC/s | 0.25 | kcal/kg*degC |
| 0.1824 | lbs*degC/s | 1046 | J/kg*degC |
| 86.54253 | J/s = W | 474.4656 | J/lb*degC |

**Table 9**

Motor Controller cooling water flow rate could be seen on the motor controller cooling box as liters per minute, and motor cooling rate was determined by running the faucet at a fixed flow rate and making a measurement prior to the beginning of the experiment.

| Heat Transfer: (deg C) | | Water Flow Rate(lpm) | |
|---|---|---|---|
| Motor Cooling: | 0.4 | Motor Cooling | 3.785 |
| Controller Cooling: | 0.2 | Controller Cooling | 7.4 |
| Heat Transfer | | | |
| Motor Peak Heat Transfer (Watts) | | 105.4501 | |
| Controller Peak Heat Transfer (Watts) | | 103.082 | |

**Table 10**

| Heat | Watts |
|---|---|
| Mtr Cool | 105.4501 |
| Ctrlr Cool | 103.082 |
| Ht oil | 348.689 |
| Ht motor | 784.8966 |
| Ht Ctrl | 86.54253 |
| Hr Room | 4.277938 |
| Total HtPower | 1432.938 |

**Table 11**

**Efficiency Analysis**

The experimental throttle and load, at 89.7v, used for the data collected draws 109 amps of current from the power supply. Using a simple power calculation

$$Pe = I * V$$

the electrical input power is calculated to be 9777.3 Watts.

From previous experimental data collected, the torque at these settings is expected to be 23.4 ft-lbs, this was verified by the torque reading of the load cell. Using a mechanical power calculation

$$Pm = \omega * \tau$$

gives a mechanical power of 8306.06 watts. To calculate the efficiency of the system simple ratio must be taken of the mechanical power to electrical power.

$$Efficiency = \frac{Pm}{Pe} * 100\%$$

**Using this equation we conclude that the motor is 83.5% efficient.**

Additionally, this leaves 1471.2W of power loss which must be accounted for. From the power calculations above, data collected from the heating of the motor, controller, oil, and air all combined account for 1391.9W in the air cooled case. This leaves a remaining 79.3 Watts which must still be considered. It is not unreasonable to assume that these additional 79 Watts were used to heat up the precharge relay in the system, which is one point where temperature measurements were not taken.

In the water-cooled experiment, 1432.9W of power loss were accounted for through calculations, leaving 39W which were not measured in this experiment. It is interesting to note that the power which was transferred to the sink for water cooling was taken not from the rate of heating the motor, but instead from the amount of energy transferred to the oil. This is likely because the full system temperature using a water-cooled motor dropped to near-ambient temperature far sooner than it did in the air-cooled experiment. For this reason, the oil heated up far less over an equal duration of time.

The question must now be answered whether or not the sink water cooling solution works as an effective way to cool the motor after use. Looking at the data above presented from the graph in

**Figure 3,** the improvement in cooling rate using the sink cooling solution was quantified at **60.6%** using the 70C half life metric. Assuming that the motor is to be run at about 100A of power supply current, this corresponds with a heating time of about 1340 seconds. Assuming that the motor is in a "safe to run" state at an internal temperature of 35 degrees C, air cooling corresponds with a motor operating duty cycle (Heating Time/(Heating Time + Cooling Time) of **8%.** Water cooling begets a duty cycle of **18%**. Therefore, although sink water cooling is not an effective solution for decreasing motor heating rate, it allows the motor to be used sooner in its current lab setup after being run. Therefore, both hypotheses are accepted that the motor + controller system's energy loss can be characterized by its losses to heat, and that sink cooling is a quantifiably effective way to cool the motor.

**Appendix A - Dyno System Setup**
Electric Vehicle Systems

- HPEVS AC50-51-5X Motor
- Curtis Instruments 1238R-7601 Controller

Battery Simulation - Magna-Power(TSD 100-250/208) D.C. Power Supply

- 20kW P.S. 200A max rms @ ~100 Vdc

Dynamometer System and Sensors - Huff HTH-100 Dyno

- Load Adjustment
    - Oil Valve(CAT HY14-3200)
- Throttle
    - Voltage Output Module (DataForth - SCM5B49)

Data Acquisition Software

- Curtis 1314 Programming Software
    - Motor Temperature Data

Computer

- Dell Precision T1700
    - Accessed through Windows TeamViewer
    - Dyno software is run using a deployment of OpenSuse in Oracle's Virtual Box

**Detailed System Description**

The Magna-Power power supply takes in 3-phase 208VAC power and is programmed to output 89.6Vdc. With a maximum current output of 200A RMS, it can accurately simulate four battery packs at normal operating conditions. The curtis controller takes in 89.6Vdc from the power supply at convert it to 3-phase AC voltage for the HPEVS AC-50 motor.

The motor is attached to the Huff HTH-100 Dynamometer system with a pump to motor gear ratio of 90:36 or 2.5:1. The tachometer used is available through the Curtis 1314 Programming software, providing access to RPM information directly. The Curtis Controller communicates over CAN and interfaces with the computer using a USB to CAN interface. The proprietary Dyno software interfaces with the Curtis Controller and Magna-Power power supply to run the test.

**References**

[1] Motor Weight:
http://www.hpevs.com/HPEVS-AC-Electric-Motor-AC50-51-for-automotive-mining-utility-ground-support-vehicles.htm

[2] Controller Weight:
http://www.evwest.com/catalog/product_info.php?products_id=103