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DESIGN AND CONSTRUCTION OF A CHEMICAL ENGINEERING (CHEME) CAR USING THERMOELECTRICS

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Thesis Summary & Abstract

Six chemical engineering undergraduates at the University of South Carolina formed a team to compete in the 2014 AIChE Chem-E-Car competition at the Southern Regional Student Conference in San Juan, Puerto Rico, in March. In the Chem-E-Car competition, students must design and build a vehicle powered by an unconventional form of chemical energy to carry a specified weight over a given distance (1). The group used knowledge gained through undergraduate study to construct a small-scale vehicle that is powered by a set of thermoelectric generators utilizing a heat gradient between boiling water and an ethanol-dry ice mixture (2). An iodine clock reaction is used in conjunction with photoresistors and an Arduino microcontroller to stop the car after the reaction goes to completion. The group had a successful run at the regional competition in Puerto Rico, earning first place in the research poster competition and fourth place in the performance competition. The group was selected as one of five teams to advance to the national competition held at the AIChE Annual Meeting in November 2014 in Atlanta, Georgia.

Competition Overview

The AIChE Chem-E-Car competition is an annual event serving as an opportunity for chemical engineering undergraduates to utilize their knowledge and skills attained through engineering coursework and construct a small-scale vehicle powered by an unconventional source of chemical energy. The student-constructed vehicle is designed to carry a specified load of water over a given distance and stop as close to this distance as possible. Beginning in the spring, students from universities within each region compete with one another in a poster competition and performance competition. For the poster competition, each group must create a research-style poster displaying the design, key reactions, and safety features of the vehicle. A panel of judges visits with each group to discuss the vehicle and evaluate the poster and presentation, as well as approve the vehicle for participation in the performance competition.

To begin the performance competition students put on proper safety equipment including lab coats and protective goggles and set up their vehicles. A load in terms of milliliters of water and distance in terms of meters are specified, requiring students to use collected data for their vehicles to calculate the amount of reactants necessary for stopping the reaction powering the car at the specified distance. Each team is given two separate runs to achieve the specified distance, with the better of the two runs counting for the official score. Upon conclusion of the performance competition, a certain number of top qualifying teams, depending on the size of the region, are picked to advance to the national competition held in the fall at the AIChE Annual Student Conference. Top qualifying teams from each region then compete against each other in the same competition format on a national scale.

Original Design

The vehicle our group designed consists of separate processes for propulsion and stopping. Energy to propel the vehicle is taken from the transfer of heat between a container of boiling water and a separate container of ethanol and dry ice. The resulting heat flux is converted into electricity by a grid of thermoelectric panels which power the motor. The iodine clock reaction serves as the timed chemical process that stops the car after the reaction has reached completion. The reaction takes place while contained in a vessel, with a syringe connected to the top for injecting potassium iodide (KI) solution into a mixture of 1.0 M hydrochloric acid (HCl), 3% hydrogen peroxide (H_2O_2), 0.5% starch solution, and 0.025 M sodium thiosulfate solution ($Na_2S_2O_3$). (3) The mixture exists as a clear liquid at the start of the reaction before turning to a deep blue/black upon reaction completion. A small LED shines from one end of the vessel through the flask containing the reaction into a set of two photoresistors on the other side.

The thermoelectric generators, motor, and photoresistors were all connected through an Arduino microcontroller. A simplified schematic of the circuit is displayed below. The change in color of the iodine clock solution results in a change in the photoresistor's internal resistance (4). The resistance value is sent as an input signal to an analog pin on the Arduino. The Arduino then converts that value to an arbitrary value between 0 and 255. This value is saved as a variable and used later to control the motor.

The motor is controlled through the assistance of a TIP 120 Darlington Transistor. Transistors have three pins: a collector, base, and emitter. The transistor effectively functions as a switch by changing the amount of power that flows from the collector to the emitter based off of the state of the base pin (5). The Arduino code utilized several ifelse statements to establish the state of the motor based off of the variable determined from the photoresistors. When the iodine clock solution turns black, the photoresistor yields a value below the allowable level and a digital output signal is sent to stop the flow of electricity through the transistor (6). This breaks the circuit and shuts down the motor. The duration of the iodine clock reaction is dependent on the concentration of KI used in the reaction, allowing for the manipulation of how far the vehicle can travel at a constant velocity (3).

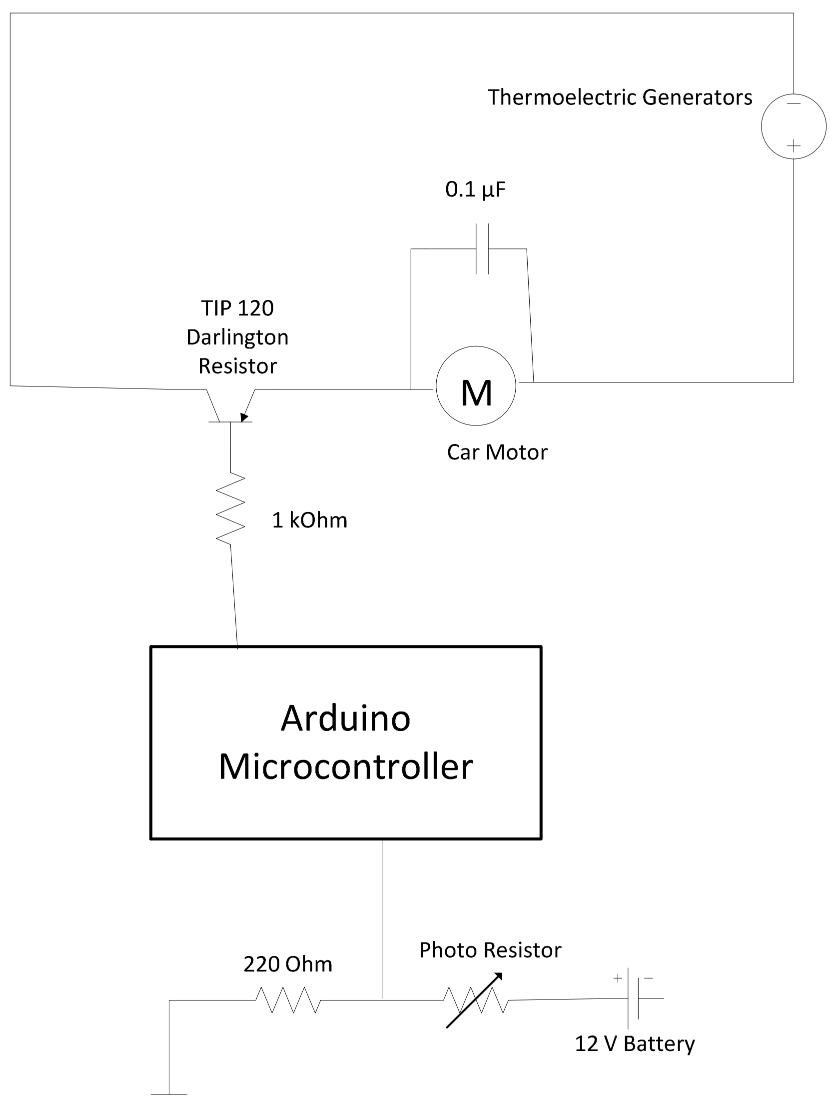

Fig. 1: Simplified schematic of electrical circuit

Standard Operating Procedure

Sequence of Steps	Hazards (7)	Prevention	Mitigation
Start-up Procedure			
1. Turn on circuit to check for iodine clock reaction light source. 2. Prepare iodine clock reaction injection syringe, double amount of hot water, and ethanol-dry ice mixture. 3. Add ethanol-dry ice mixture to cold side of reaction boxes. Simultaneously add one part of hot water to hot side of reaction boxes. 4. Place iodine clock reaction injection syringe onto iodine clock reaction housing.	1. Exposure to alcohol vapors. 2. Skin contact with dry ice. 3. Skin contact with alcohol. 4. Skin contact with hot water.	1. Area will be well ventilated. 2. Proper PPE will be worn at all times when handling chemicals and car.	1. First aid kit and first aid responders will be on site at all times of competition.
Run Time Procedure			
1. Siphon off one part of hot water from hot water side of the reaction boxes. 2. Replace with fresh hot water to hot water side of reaction boxes. 3. Secure lids on both reaction boxes. 4. Place car on starting line. 5. Inject iodine clock reactants into iodine clock reaction housing. 6. Immediately after injection of iodine clock reactants, flip switch to ON position to start car. 7. Step back from now moving car.	1. Exposure to alcohol vapors. 2. Skin contact with dry ice. 3. Skin contact with alcohol. 4. Skin contact with hot water.	1. Area will be well ventilated. 2. Proper PPE will be worn at all times when handling chemicals and car.	1. First aid kit and first aid responders will be on site at all times of competition.
Shutdown Procedure			
1. Flip switch to OFF position to turn off car. 2. Move car to end cleanup table.	1. Exposure to alcohol vapors. 2. Skin contact with dry ice, alcohol, and hot water.	1. Area will be well ventilated. 2. Proper PPE will be worn at all times.	1. First aid kit and responders will be on site at all times of competition.
Cleanup/ Waste Disposal			
1. Siphon off hot water and replace with room temp water. 2. Siphon off ethanol-dry ice mixture and replace with water. 3. Remove syringe and spent chemicals. 4. Safely dispose of all spent chemicals.	1. Exposure to alcohol vapors. 2. Skin contact with dry ice. 3. Skin contact with alcohol. 4. Skin contact with hot water.	1. Area will be well ventilated. 2. Proper PPE will be worn at all times.	1. First aid kit and first aid responders will be on site at all times of competition.

Table 1: Standard operating procedure and safety concerns

Safety Features

The vehicle has a number of features that provide for safer operation. Instead of an acidic reaction, hot water is used as the source of heat for the thermoelectric generators, decreasing risk of chemical harm. The two hot and cold containers, as well as the iodine clock reaction housing, feature double containment as a means of preventing exposure. Double containment and arrangement of equipment provides a large degree of separation between liquids and circuitry. Low voltage and current levels are used in powering the vehicle, preventing harmful electric shock. Equipment on the vehicle is properly secured in order to prevent movement aboard the vehicle while it is in motion. In addition, wiring present on the vehicle is safely placed to avoid interference with moving parts. The power source for the Arduino is placed on the front edge of the vehicle in order to maximize distance from liquids present on the vehicle. The vehicle has a wide stance and low center of gravity, minimizing potential for tipping over while in motion.

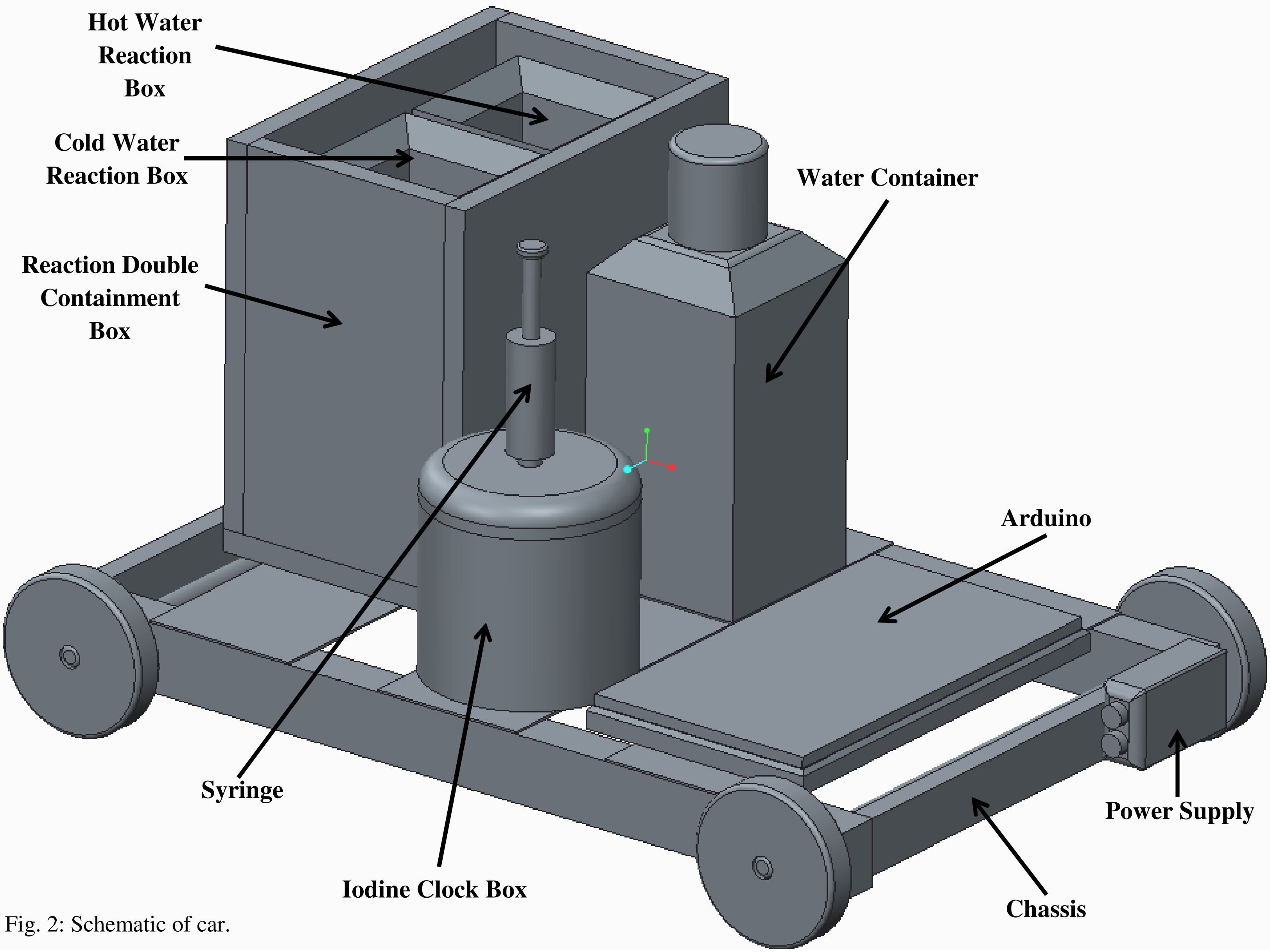

Fig. 2: Schematic of car.

Experimental

In preparation for the competition several experiments were conducted to determine specific properties and parameters that effect performance of the car.

Thermoelectrics

Our primary experiment helped to characterize the operating conditions and performance of the thermoelectrics. Eight thermoelectrics were sandwiched between a hot and a cold sink. The hot sink utilized in this experiment was boiling water (~100 ˚C) and the cold sink was a mixture of dry ice and ethanol (~ -72 ˚C). A multimeter was used to determine the current and voltage output of each thermoelectric, and those with similar performance were paired and connected in various series and parallel configurations. Additionally, after these connections were established current and voltage measurements were collected over a period of 10 minutes to verify that the thermoelectrics functioned as a constant power source.

Gearing

From the previous experiments we were able to determine that our thermoelectrics function as an approximately constant power source, which in turn causes the car to travel at a constant speed. However, this speed is also dependent on load and gear ratio. Out of these parameters, gear ratio is the most significant because it helps to balance the speed and torque for our car (8). Several AA batteries connected in series were used to simulate a power source equivalent to the thermoelectrics and various gear ratios were tested under three different weight conditions (no load, half load, and full load). The time taken for the car to travel a distance of 10 meters was collected and used to determine the velocity of the vehicle under those conditions. In addition, a multimeter was used to determine the voltage and current supplied to the motor during each trial.

Iodine Clock

The final parameter determined was the calibration of the iodine clock. The reaction consisted of 3 different solutions: a KI solution, a sodium thiosulfate-starch solution, and a catalyst solution. A 0.1 KI stock solution was made by adding 1.66 grams of granular KI to 100 mL of water. Several 10 mL solutions were made from this stock solution and served as the KI solution for the reaction (3). Table 1 below shows the respective volumes of KI and water used to make each concentration.

Concentration of KI Solution (M)	Volume of KI Stock (mL)	Volume of Water (mL)
0.05	5.01	4.99
0.03	7.01	2.99
0.02	8.00	2.00
0.01	9.00	1.00
0.0075	9.25	0.75
0.005	9.50	0.50

Table 2: Formulation of KI Solution

The sodium thiosulfate-starch solution consisted of 1 mL of a 0.025 M sodium thiosulfate solution (0.310 g of granular sodium thiosulfate in 50 mL of water) and 10 mL of a stock 0.5% starch solution. The catalyst solution consisted of 10 mL of a 3% H_2O_2 and 6 drops of 1M HCl. For each trial, the catalyst and sodium starch solutions were mixed well in a flask on a stir plate. The KI solution was then injected into the flask and the time taken for the solution to change from clear to black was recorded, and three trials were conducted for each KI concentration.

Results and Discussion

Figure 1 shows the relationship between the load attached to the car and its speed. With a full load of 500 g the car maintained an average speed of 0.32 m/s (minimum speed), while with no load (0 g) the average speed was 0.33 m/s (maximum speed), resulting in a 3.9 % difference.

The same conclusion can be drawn from Figure 2. The car travels a distance of 30 meters in 90 seconds with full load and in 95 seconds with no load. Therefore, we can conclude that the effect of the load to the speed of the car is negligible.

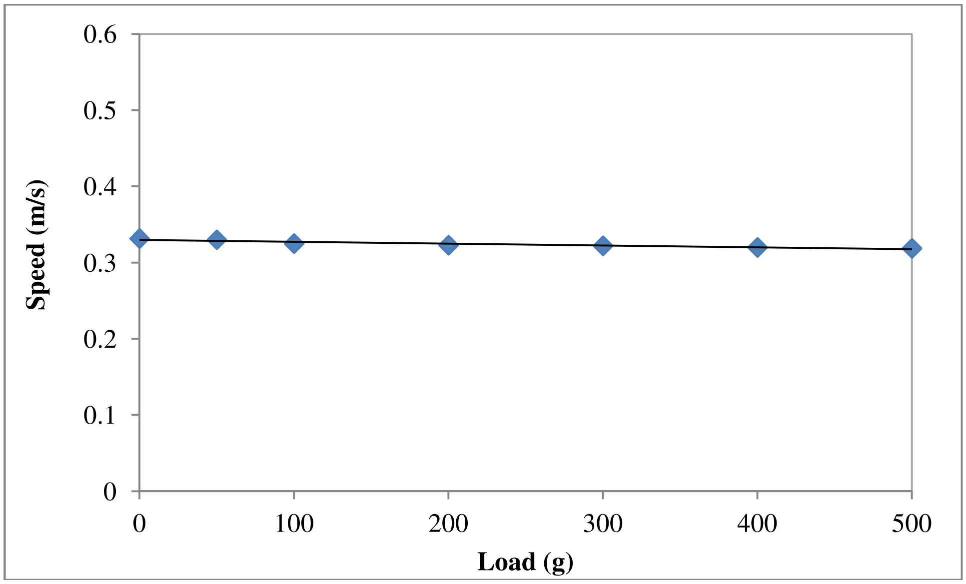

Figure 3: Speed of ChemE Car versus load. Speed remains constant for different loads varying from 0 g to 500g.

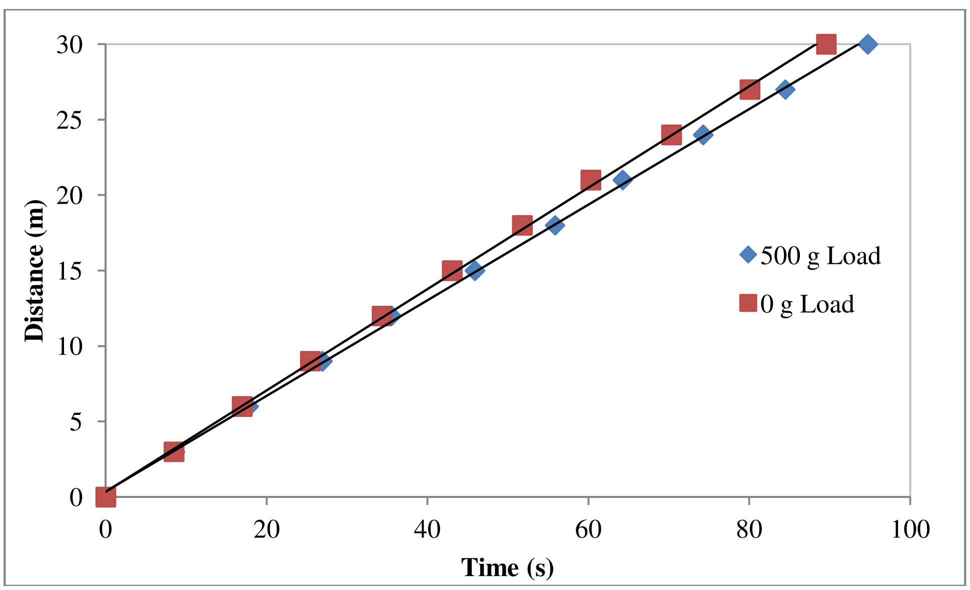

Figure 4: Distance travelled versus time for (a) full load (500 g) and (b) no load (0 g).

Several experiments were carried out for the car's stopping mechanism (iodine clock reaction). The reaction time was repeatedly measured for different KI concentrations. Figure 3 shows how the time of the iodine clock reaction decreases exponentially when increasing the KI concentration. These experiments were repeated four times and the error bars on Figure 3 indicate that the experimental error was negligible, with an exception of a few low concentrations. This plot enables us to calculate the KI concentration necessary for the car to run for a certain time interval and therefore travel a given distance. However, it is important to notice that this calculation is only valid with the assumption of a constant speed.

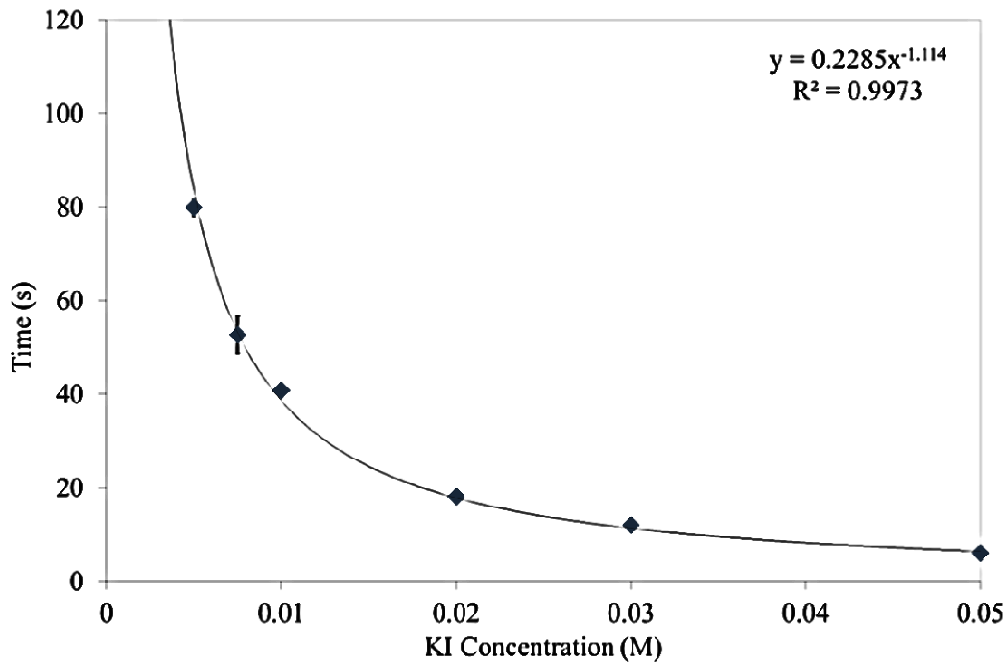

Figure 5: Time versus KI Concentration for the iodine clock reaction (stopping mechanism)

Upon arrival at the competition preliminary testing of the clock reaction revealed that the newly purchased chemicals behaved significantly differently from those used in testing. The speculated reason for this is degradation of the starch complex, which caused the reaction to run to completion before the addition of the catalyst, much sooner than anticipated. Two significant changes were developed to work around this issue: the first involved swapping the contents of the syringe, while the other concerned modifying the old data to fit the new behavior of the chemicals.

In order to modify the equations we began gathering new experimental data on the behavior of the chemicals, effectively estimating the right concentrations. This was done using new experimental data (a concentration and time measured with the fresh chemicals, see table below) to solve for a new coefficient of the rate equation. Using this new coefficient the rate equation was used to estimate the concentration needed to run the required time.

KI Conc. (M)	Time (s)
0.001	75.84
0.0013	51
0.0014	46

Table 3: KI conc. and times.

Future Recommendations

When selecting teammates choose people who are motivated and organized as well as able to work under stress. This is vital due to the intense competition environment. Also, AIChE allows other engineering majors to be members of the professional organization; therefore, students from various engineering disciplines may be a part of this team. For an example, an electrical engineering teammate would be very valuable if any circuitry is involved in the car design.

Course Credit and Funding

Although this project was completed to fulfill the requirements of Senior Design 2, ECHE 466, we suggest providing course credit via ECHE 499 as means to continue and encourage participation in the project. Provided that the ChemE car group project will count as course credit for ECHE 499, students should begin to research possible car designs (or design edits) prior to the first faculty advisor meeting. Whether the team is working to compete at the Regional or the National level, it is imperative to be organized and productive right out of the gate. Also during this time it is necessary to apply for funding through university grants as well as company sponsorships. Suggested University of South Carolina grants include: the Magellan Voyager, the Magellan Mini-Grant, and the Honors College Senior Thesis Grant (Note that university grants operate on a reimbursement policy so there will not be funding upfront). Next officially register the ChemE car through the appropriate AIChE competition website. Also have each team member register for the competition individually.

Construction

Once a car design is chosen, the first step should be to contact the mechanical shop to build any parts if needed. Next, order all required parts for the vehicle with some spares where appropriate. While waiting for these parts, be sure to secure appropriate lab space to conduct all experiments. Be sure to run all experiments with new chemicals so the quality of chemicals used in the laboratory matches what will be available at the competition. Chemicals at the competition will be new because all chemicals must be ordered and shipped directly from the supplier to the host school for the Regional or National AIChE competition. However, some basic chemicals will be provided by the host university so be sure to contact them before ordering chemicals and sending them to the host school. Maintain an excel worksheet with precise details regarding the brand and cost of all parts and chemicals, as this information will be needed when completing the Engineering Documentation Package (EDP) prior to the competition. Also keep all receipts for university grant reimbursement purposes.

Division of Labor

Once the initial research and purchasing stage is completed, higher project efficiency is accomplished by dividing up tasks among group members. For example, put one team member in charge of an area such as electrical circuitry, chemical reactions, EDP, logistics and rule review, and chassis construction. While some portions of the project can progress individually, it is essential for communication and success to meet at least once a week outside of weekly reviews with the ECHE 499 professor. The initial draft of the EDP will be due roughly a month before the date of competition so that it may be edited by judges and sent back to the team for revisions. A hard copy of the revised EDP must be present with the team at the poster competition in order to pass a safety inspection, which is a requirement for the car to compete. With respect to trials while at the University of South Carolina, record all data in excel because even trials with negative outcomes provide valuable data for improvements. Create an experiment that does not require extensive preparation, because there is only one minute of preparation time at the on-deck table at the competition.

When the final operational procedure is determined, be sure to make a list of all required laboratory equipment to ensure nothing is forgotten due to last minute stress. Bring as much laboratory equipment as possible, because the small amount of laboratory equipment provided at the competition is shared amongst all teams. Basically, assume that nothing will be available at the host university except for a mass balance; thus small items such as weigh-boats and glassware labels are great to bring. At this time, review the final draft of the EDP with the AIChE Chem-E car competition rules at hand to prevent disqualification due to an inadequate EDP. Judges review this document page by page at the competition, and teams are disqualified at the competition without the ability to have their car compete.

Competition

In the competition phase, the car, laboratory equipment, and safety equipment can all fit into one hardshell suitcase. Purchase bubble wrap to protect all glassware and individually wrap all pieces. Also purchase packaging peanuts to fill up the remaining space in the suitcase as a safety mechanism protecting all materials during travel. Have the poster printed a week prior to the departure date for the competition. If traveling by plane, arrive at the airport with additional time to allow for the luggage carrying the car to be unpacked and repacked in security.

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