ENGINEERING ANALYSIS IN THE CHEM-E-CAR COMPETITION

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Since 1999, Chemical Engineering undergraduate students have had the opportunity to participate in the Chem-E-Car Competition at the regional and national level under the direction of the American Institute of Chemical Engineers (AIChE). The competition was initiated by AIChE members to (1) provide an opportunity for students to participate in a team competition at the national level, (2) encourage professional society interaction, and (3) increase the awareness of chemical engineering in the public.[1] Examples of national competitions in other engineering disciplines include the concrete canoe race (civil engineering), mini-baja race (mechanical engineering), and International AIAA/ONR Design, Build, Fly contest (aerospace engineering).

The Chem-E-Car competition involves the design and construction of a chemically powered car that has to travel a specified distance (50-100 ft) while carrying a certain amount of water (0-500 ml). The car must fit into a box no larger than 40 cm × 30 cm × 18 cm and the team must be composed of members from at least two undergraduate classes. Additional rules are applicable to the competition.[1] The objectives of the competition are applicable to numerous ABET educational outcomes including "an ability to design a system, component, or process to meet desired needs," "an ability to function on multidisciplinary teams," and "an ability to communicate effectively."[2]

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To promote the competition among Oklahoma State University (OSU) chemical engineering students and to provide an additional design experience in the undergraduate curriculum, the competition was implemented in 2000-2001 as part of a spring sophomore course (Introduction to Chemical Process Engineering) and a spring junior course (Chemical Reaction Engineering). The juniors initially worked on designing the cars and were eventually joined by the sophomores who primarily helped with the calibration, poster, and safety aspects. The teams (six-eight students) currently compete in the middle of the spring semester for the opportunity to represent OSU at the AIChE Regional Chem-E-Car Competition.

The evolution of the competition at OSU was recently presented.[3] In brief, funding for the OSU competition was initially provided by the department, but ChevronPhillips now provides funding for equipment costs, T-shirts, the awards banquet, and travel to regional and national competitions. Further, ChevronPhillips personnel provide extensive safety reviews on students' reports. Liquid effluent was allowed to discharge from the car in 2001, only water was allowed in 2002, and no liquid discharge has been allowed since 2003.

The Chem-E-Car competition involves the design and construction of a chemically powered car that has to travel a specified distance while carrying a certain amount of water.

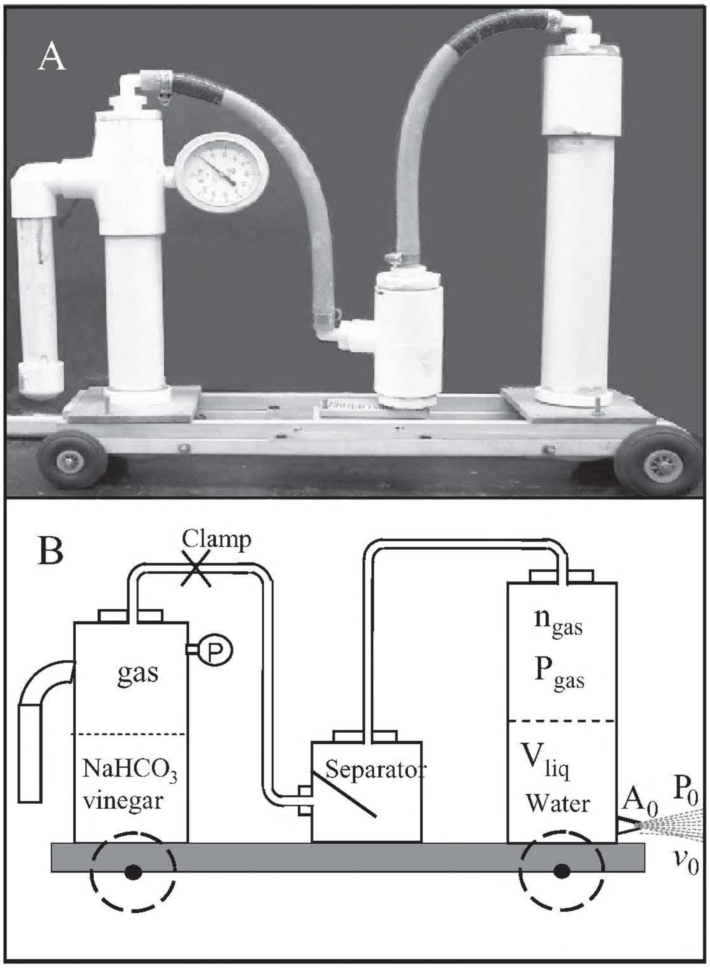

Figure 1. *Picture* ***(A)*** *and diagram* ***(B)*** *of the Chem-E-Car. The left chamber was used to generate gas from a sodium bicarbonate ($NaHCO_3$) and vinegar reaction. The right chamber contained water that was forced from the chamber following the removal of the clamp. The expelled water propelled the car forward. The parameters and values are shown in Table 1.*

In 2003, an additional fall junior course (Thermodynamics) was included in the competition to enable the students to spend more time working on their cars.

As part of the integrated sophomore and junior team, the students are required to write a safety and environmental report, provide a detailed sketch of the car, build a prototype, provide preliminary and final calibrations, provide an engineering analysis, give a poster presentation, and participate in the department competition. The engineering analysis is performed solely by the junior students, although they have traditionally provided a vague analysis such as using empirical equations, providing detailed equations without any solutions, and identifying fundamental equations that may not be applicable.

Engineering analysis is not required at the national competition and is often not applied. Rather, students rely on calibration data and trial and error to predict the distance traveled by their cars.

To demonstrate and encourage the use of detailed engineering analysis among the students in predicting the distance traveled by a car, a model was developed for a car (previously used in the competition) in which pressure generated by a chemical reaction resulted in car movement via the discharge of water. This work presents the model for predicting the travel distance based on the initial pressure and various car parameters.

Although discharged water must now be contained such that the model may not be applicable to current car designs, this work provides an example of how students can effectively apply engineering analysis. An advantage to engineering analysis is that it allows students an opportunity to determine the effects of design components (*e.g.,* vessel size, car weight, liquid volume, nozzle size, for this example) on the distance the car travels.

MATERIALS AND METHODS

Car Design and Experimental Runs • The car, shown in Figure 1, was designed and built by Ali Moshfeghian, Christ Schulte, and Kyle Sharon (junior chemical engineering students at the time) and was used in the 2002 competition at OSU. The key car parameters are provided in Table 1. The left chamber, shown in Figure 1B, was initially filled with 125 ml of a saturated aqueous solution of sodium bicarbonate ($NaHCO_3$). Glacial acetic acid (vinegar) was then added to the solution, causing a chemical reaction to form CO_2 that increased the chamber pressure. The acetic acid was added according to the amounts shown in Table 1 and, when necessary, additional water was added so that the acetic acid/water addition equaled 10 ml. Although acetic acid and sodium bicarbonate were used to generate the gas pressure, any pressure-generating chemical

TABLE 1
Parameters and Values Used in Engineering Analysis

Run #	*Acetic Acid (ml)*	*Initial gas pressure (atm)*	*Adjusted initial pressure (atm)*	*Distance (feet)*
1	2.5	4.39	2.78	4.3
2	5.0	8.14	4.76	19.3
3	7.5	11.20	6.37	32.6
4	10.0	13.24	7.43	41.7

Parameter	*Description*	*Value*	*Units*	*Note*
A_c	Area of water chamber	11.4	cm^2	Constant
A_0	Nozzle area	0.087	cm^2	Constant
C	Head loss coefficient	0 to 0.2	unitless	
g	Gravitational constant	9.81	cm/s^2	Constant
h_i	Water height above nozzle			
h_0	Nozzle height			
m	Mass of water	374	g	Initial value
m_{car}	Mass of car	2470	g	Initial value
n_{gas}	Moles of gas			
p_{gas}	Adjusted initial pressure	See above	atm	Initial value
p_0	Atmospheric pressure	1.0	atm	Constant
R	Gas constant	82.06	$cm^3 atm/molK$	Constant
T	Temperature	298	K	Constant
v_{car}	Car velocity	0	cm/s	Initial value
V_{gas}	Gas volume	390	cm^3	Initial value
V_{liq}	Water volume	375	cm^3	Initial value
V_{tot}	Gas and initial water volume	765	cm^3	Constant
v_0	Water velocity	Eq. (8)	cm/s	Variable
x_{car}	Car distance	0	feet	Initial value
ρ_{liq}	Water density	0.997	g/cm^3	Constant
μ_k	Friction coefficient	0.07	unitless	Figure 4

reaction would be sufficient for operation of the car. It is important to note that the generated pressure should not exceed the pressure limits of the materials to prevent material failure. A clamp was used to keep the gas pressure in the left chamber until the pressure reached equilibrium. The right chamber was filled with 400 ml of water (V_{liq}). Following pressure equilibration, the clamp was removed and the rear nozzle opened. The pressure above the water (P_{gas}), related to the moles of gas (n_{gas}), forced the water to exit the rear nozzle (cross sectional area of A_0) at a given velocity (v_0). P_0 represents the atmospheric pressure. The separator was added to minimize foam, generated in the left chamber, from entering the water chamber. The exiting velocity produced a thrust that moved the car forward. When the water ran out, the car rolled to a stop and the distance the car traveled was measured. As noted in Table 1, four experiments were performed. The experiments were performed on a smooth brick surface.

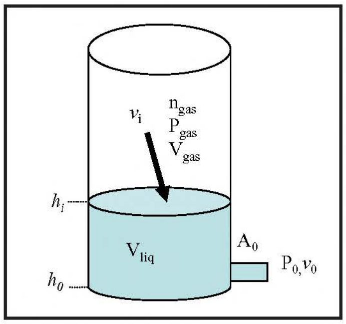

__Figure 2.__ Diagram of model used for the engineering analysis. The model represents the chamber that contains the water. The parameters and values are shown in Table 1.

__Model Development__ • A model was developed to predict the distance the car would travel based upon the initial pressure above the water. The model was used as a comparison with the experimentally measured distance. Figure 2 shows a representation of the water chamber that was used for the model. V_{liq} is the water volume, h_0 is the height of the nozzle (assigned a value of zero), h_i is the height of the water above the nozzle, v_i is the surface velocity of the water at h_i, A_0 is the nozzle cross-sectional area, v_0 is the water velocity leaving the chamber, and P_0 is the pressure of the surrounding atmosphere. P_{gas}, V_{gas}, and n_{gas} represent the pressure, volume, and moles of the gas above the water, respectively.

A material balance on the total mass of the car (m_{car}), which is equivalent to a constant mass plus the mass of the water in the chamber (m), shows that the mass changes with time according to

$$\frac{dm_{car}}{dt}=\frac{dm}{dt}=-\rho_{liq}v_0A_0 \tag{1}$$

where ρ_{liq} is the liquid density. The right term represents the mass flowrate of water leaving the water chamber (and the car). Since $m=V_{liq}\rho_{liq}$, and if ρ_{liq} is assumed constant, the water material balance shows how V_{liq} changes with time according to

$$\frac{dV_{liq}}{dt}=-v_0A_0=-\frac{dV_{gas}}{dt} \tag{2}$$

The change in V_{gas} is also shown with time in Eq. (2) since any water volume decrease results in the same increase in the gas volume (*i.e.,* the total volume, V_{tot}, is constant and equal to $V_{gas}+V_{liq}$).

To assess how the gas pressure (P_{gas}) changes with time, the ideal gas law was assumed where $P_{gas}V_{gas}= P_{gas}(V_{tot}-V_{liq})=n_{gas}RT$. Since V_{tot} is constant and $n_{gas}RT$ is constant as the water is leaving the nozzle (assuming negligible temperature change and no new gas is generated once the experiment starts), the time derivative of the ideal gas law gives

$$\frac{dP_{gas}}{dt}=\frac{P_{gas}}{\left(V_{tot}-V_{liq}\right)}\frac{dV_{liq}}{dt}=\frac{-v_0A_0}{\left(V_{tot}-V_{liq}\right)}P_{gas} \tag{3}$$

Eq. (2) was substituted into the middle term of Equation 3 to obtain the term on the right.

The velocity of the car with time was predicted from a momentum balance on the car. The momentum balance states that the change of momentum (mass of the car, m_{car}, times the velocity of the car, v_{car}) is equal to the sum of the forces acting upon the car:

$$\frac{d\left(m_{car}v_{car}\right)}{dt}=m_{car}\frac{dv_{car}}{dt}+v_{car}\frac{dm_{car}}{dt}=\rho_{liq}v_0^2A_0-\mu_k m_{car}g \tag{4}$$

The first term on the far right side of Eq. (4) represents the thrust force that pushes the car forward.[4] Only thrust occurring when water leaves the chamber was considered. Once the water runs out, residual gas pressure greater than atmospheric pressure will cause some thrust but the thrust is likely negligible since the gas density is small compared to liquid. The second term on the far right side represents the friction force between the car and the ground, with μ_k as the friction coefficient.[4] The negative sign signifies a force that decreases the car velocity. The drag force between air and the car was neglected. Substitution of Eq. (1) into Eq. (4) gives

$$\frac{dv_{car}}{dt}=\frac{\rho_{liq}v_0A_0\left(v_0+v_{car}\right)}{m_{car}}-\mu_k g \tag{5}$$

Once the water runs out of the chamber, the first term on the right side is zero and the velocity of the car will decrease as a result of friction until the car stops. The distance (x_{car}) at which the car stops was predicted from the definition of velocity,

$$\frac{dx_{car}}{dt}=v_{car} \tag{6}$$

To predict the velocity of water leaving the car (v_0) for application in Eqs. (1)-(5), the mechanical energy balance,[5] with the inclusion of frictional head loss due to the exit nozzle, was utilized such that

$$\frac{C}{2}v_0^2+\frac{1}{2}\left(v_0^2-v_i^2\right)=g\left(h_i-h_0\right)+\frac{\left(P_i-P_0\right)}{\rho_{liq}} \qquad (7)$$

The subscripts i and 0 refer to the values at the gas-liquid interface and the nozzle exit, respectively. C is the head loss constant. Since $P_i = P_{gas}$, $(h_i - h_0) = V_{liq}/A_c$ (where A_c is the cross-sectional area of the water chamber), and if $v_i << v_0$ (the liquid velocity leaving the chamber is much faster than the velocity of the water surface at the gas-liquid interface) then

$$v_0=\sqrt{\frac{2}{(1+C)}\left[g\frac{V_{liq}}{A_c}+\frac{\left(P_{gas}-P_0\right)}{\rho_{liq}}\right]} \qquad (8)$$

Eqs. (7) and (8) are only valid when water is present in the chamber. Thus, once the water completely runs out of the chamber, Eqs. (7) and (8) no longer apply and v_0 is zero in Eqs. (1)-(5).

Eqs. (1)-(3), (5), and (6) [with the definition of Eq. (8)] were numerically integrated using Polymath[6] to obtain values of the integrated parameters as a function of time. When the model results showed that the water ran out ($V_{liq} = 0$), v_0 was set to zero for reasons stated above. At this point, only Eqs. (5) and (6) were numerically integrated.

The initial values for solving the model were m_{car}=2470 g, V_{liq}=375 cm^3, v_{car}=0, and x_{car}=0. For the water volume, the volume initially added to the chamber was 400 ml. Since 25 ml was below the nozzle and did not leave the chamber, the initial water volume was modeled with a value of 375 ml. The values of P_{gas} for the four experimental runs are shown in Table 1. Since the initial gas pressure (P_{init}), as shown in Table 1, was measured prior to opening the clamp, the adjusted initial pressure was determined by P_{gas}=(205/390)*P_{init}+(185/390)*1atm. The adjustment was based on the assumption that the pressure above the water chamber (with a volume of 185 ml) was 1 atm and that the initially measured pressure (with a volume of 205 ml) equilibrated (in the total volume of 390 ml) after the clamp was opened and prior to the opening of the rear nozzle. A value of C=0.1 is consistent with fluid leaving a large reservoir and entering a small rounded-edge entrance (*i.e.*, similar to liquid leaving the chamber and entering the nozzle).[5] Table 1 summarizes the model parameters with their associated values. Unit consistency was ensured when solving the equations.

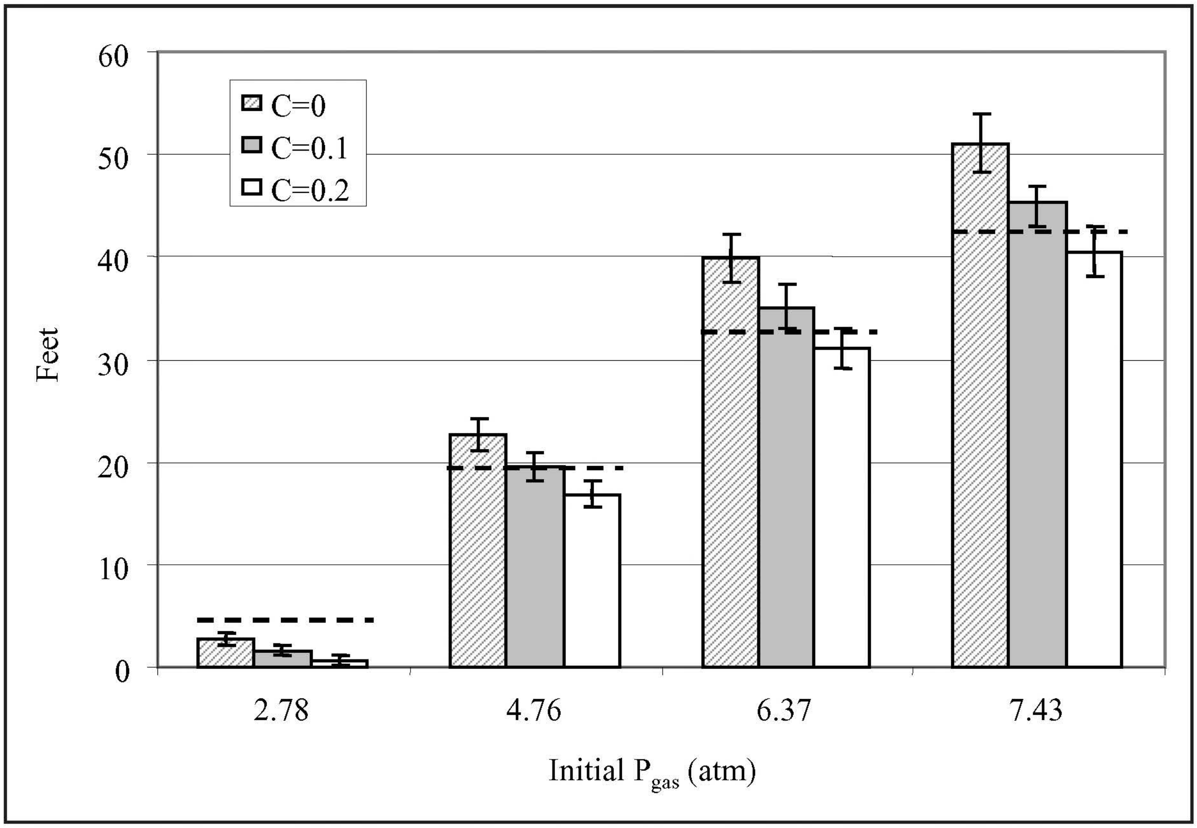

Figure 3. *Measured (dashed lines) and predicted distance (bars with μ_k = 0.069) traveled by the car as a function of initial gas pressure (P_{gas}) above the water. The error bars show the predicted range with 0.066 ≤ μ_k ≤ 0.072.*

Friction Factor Analysis • The friction coefficient (μ_k) shown in Eq. (5) was needed for solving the system of differential equations. The coefficient is dependent upon the type of surface and the type of wheels contacting the surface. Thus, the coefficient can vary and must be measured for each surface upon which a car is tested. For this work, the friction coefficient was measured by pushing the car by hand, measuring the initial car velocity ($v_{car,0}$), and then measuring the final distance (x_f) at which the car stopped from the point at which the initial velocity was measured. The initial velocity was measured a short distance from where the car was pushed to ensure that the car was decelerating during the analysis. A ruler was placed at the initial velocity measuring point while a video camera recorded the time for the car to travel a given distance of the ruler (5-13 inches). An average initial velocity was obtained by dividing the distance by the time.

Since there was no thrust between the initial velocity point and when the car stopped, Eq. (5) states that $dv_{car}/dt = -\mu_k g$. Integration of Eqs. (5) and (6) gives

$$\int_{v_{car,0}}^{v_{car}} dv_{car} = \int_0^t -\mu_k g\,dt \quad \Rightarrow \quad v_{car} = v_{car,0} - \mu_k g t \qquad (9)$$

$$\int_0^{x_f} dx_{car} = \int_0^{t_f} \left(v_{car,o} - \mu_k g t\right) dt \quad \Rightarrow \quad x_f = v_{car,0} t_f - \frac{\mu_k g t_f^2}{2} \qquad (10)$$

Since $v_{car}=0$ at t_f (the time for the car to travel the entire distance), $t_f = v_{car,0}/(\mu_k g)$ according to Eq. (9). Substitution into Eq. (10) gives

$$x_f = \frac{1}{\mu_k}\frac{v^2_{car,o}}{2g} \qquad (11)$$

Thus, a plot of x_f versus $v^2_{car,0}/2g$ gives an inverse slope of the friction coefficient.

RESULTS AND DISCUSSION

Experimental Runs • The distances the car traveled during the four experiments are shown in Figure 3 with the dashed lines. The furthest distance traveled was 41.7 feet at an adjusted pressure of 7.43 atm as shown in Table 1. The traveled distance increased with initial pressure as expected.

Friction Factor • The results of the friction factor experiments are shown in Figure 4. Six experiments were performed such that the distance traveled varied between 10 and 30 feet. The wide range of distances allowed for a more complete analysis of the friction coefficient. The plot of x_f versus $v^2_{car,0}/2g$ yielded a straight line, which is in agreement with Eq. (11). Regression analysis resulted in an inverse slope of $\mu_k = 0.069 \pm 0.003$ (95% confidence) for the friction coefficient.

Model Predictions and Comparison • Figure 3 shows the model predictions based on $\mu_k = 0.069$ and a head loss coefficient (C) ranging from 0 to 0.2. The error bars show the range of model predictions when μ_k ranges from 0.066 to 0.072 (the

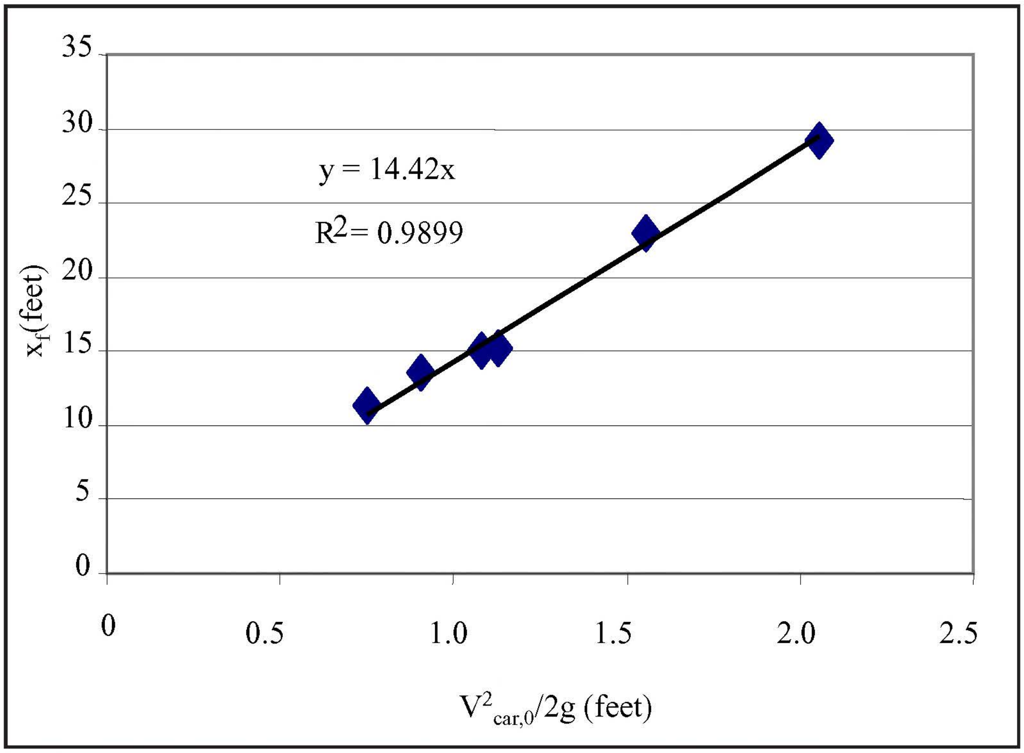

Figure 4. *Friction coefficient analysis as described by Eq. (11). The inverse of the slope represents the friction coefficient. The distance traveled (x_f) is shown as a function of the initial car velocity ($v_{car,0}$).*

As part of the integrated sophomore and junior team, the students are required to write a safety and environmental report, provide a detailed sketch of the car, build a prototype, provide preliminary and final calibrations, provide an engineering analysis, give a poster presentation, and participate in the department competition.

95% confidence interval). As shown in Figure 3, the model predictions were in good agreement with the experimental results when C=0.1. With C=0, the model predictions were much higher than experimental measurements for the three highest initial pressures. However, C=0 is unreasonable since head loss occurs as a result of the nozzle. Model predictions with C=0.2 are lower than experimental measurements for the three highest initial pressures. The model predictions with a range of C values are shown to demonstrate the effect of C on model predictions.

With C=0.1, the predictions had a difference of 1.0%, 7.3%, and 8.6% from experimental values at initial pressures of 4.76, 6.37, and 7.43 atm, respectively. It must be remembered, however, that the only fitted parameter in the model was the friction coefficient, and the coefficient was measured via a different experiment than the experiment for which the model was used. All other parameters were car dimensions, the initial starting pressure, or the value of C. Thus, considering all of the model assumptions, the model did a reasonable job in predicting the traveled distance.

There are several possibilities as to why the model had some disagreement. The first possibility was that the initial starting pressure was lower than the adjusted initial pressure used in the model. In the future, the measurement of the initial pressure following the removal of the clamp would be beneficial. A second possibility was a potential gas leak, such that the contributing pressure to the thrust of the car would be lower. No noticeable gas leaks were observed when running the car, however. A third possibility is a change in the value of the friction coefficient, μ_k, during the course of experiments due to wind conditions and axle friction (since μ_k was a function of the experimental conditions). No noticeable wind changes were observed and the distances utilized in the evaluation of μ_k were similar to the experimental runs. The effects of changing μ_k, however, are noticeable by the error bars in Figure 3. The validity of assumptions is an area that could be further explored.

With the successful demonstration of the model predictions with the experimental results, the impact of car parameters on the traveled distance can be explored. For instance, the effects of varying the rear nozzle diameter, water volume, initial pressure, or friction coefficient (representing an increase or decrease in friction due to changing the type of wheels or the type of surface on which the car travels) can be assessed with regard to distance traveled. This type of exercise allows a student to have a better understanding of how engineering design can affect the function of the car, without the need for numerous experimental designs.

CONCLUSIONS

This work describes the effective utilization of engineering principles in a model to predict the distance traveled by a Chem-E-Car using the acetic acid/baking soda reaction.

Although the model is specific for one type of car-propulsion system, this work demonstrates how engineering analysis is applicable to the Chem-E-Car competition.

One could extend the engineering analysis to include calculation of the theoretical pressure build-up in the reactor, and correlate the theoretical pressure to the experimentally observed pressure in the chamber. Similar analysis could be performed for hydrogen peroxide-catalase reaction systems that generate pressure. Engineering analysis is also applicable to other Chem-E-Car models, such as the iodide clock reaction used to stop a car via breaking an electronic circuitry. For example, the kinetics of the reaction could be incorporated with the momentum equation to predict the time at which the reaction stops the circuitry and the distance at which the car stops. In conclusion, engineering analysis concepts introduced through the Chem-E-Car competition not only provide an opportunity to reinforce theoretical concepts but also provide a tool for the design of the cars.

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