

SIMULATION, DESIGN AND VALIDATION OF A SOLID OXIDE FUEL CELL
POWERED PROPULSION SYSTEM FOR AN UNMANNED AERIAL VEHICLE

by

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of the requirements for the degree

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LIST OF SYMBOLS

Symbol	Description	Units
a	Motor phase a	-
b	Motor phase b	-
c	Motor phase c	-
C_P	Propeller coefficient of power	-
C_T	Propeller coefficient of thrust	-
D	Motor controller duty cycle	-
E_{cell}	Ideal individual fuel cell voltage	V
e_n	motor phase n back emf	V
I_c	Current at fuel cell stack terminals	A
I_{cell}	Individual fuel cell current	
I_m	Effective motor current	A
i_n	Motor phase n current	A
I_0	Motor no-load current	A
J	Advance ratio	-
K	Motor speed constant	V s/rad
L	Propeller diameter	m
L_m	Motor inductance per winding	H
N_c	Number of series connected fuel cells	-
n_p	Propeller speed	rev/s
R_m	Motor resistance per winding	Ω
R_{th}	Thevenin equivalent approximated fuel cell ohmic resistance	Ω
S	Air craft speed / Measured wind tunnel velocity	m/s
T	Propeller thrust	N
V_c	Voltage at fuel cell stack terminals	V
V_{cell}	Individual fuel cell voltage	V
$V_{cell,act}$	Individual fuel cell activation voltage loss	V

LIST OF SYMBOLS – CONTINUED

Symbol	Description	Units
$V_{cell,con}$	Individual fuel cell concentration voltage loss	V
$V_{cell,ohm}$	Individual fuel cell ohmic voltage loss	V
V_m	Effective motor voltage	V
v_n	Motor phase n voltage	V
V_{oc}	Linear approximated open circuit fuel cell stack voltage	V
V_0	Motor no-load voltage	V
Greek Symbols		
α_n	Coefficients of quadratic approximation of propeller coefficient of power C_P	-
α'_n	Coefficients of quadratic approximation of motor torque τ	-
β	Motor drag coefficient	N-m s/rad
ρ	Air density	kg/m ³
τ	Motor torque	rad/s
τ_e	Motor torque of electric origin	rad/s
ω	Motor speed	N-m

ABSTRACT

This thesis presents a physically-based model for design and optimization of a fuel cell powered electric propulsion system for an Unmanned Aerial Vehicle (UAV). Components of the system include a Solid Oxide Fuel Cell (SOFC) providing power, motor controller, Brushless DC (BLDC) motor, and a propeller. Steady-state models for these components are integrated into a simulation program and solved numerically. This allows an operator to select constraints and explore design trade-offs between components, including fuel cell, controller, motor and propeller options. We also presents a graphical procedure using the model that allows rapid assessment and selection of design choices, including fuel cell characteristics and hybridization with multiple sources. To validate this simulation program, a series of experiments conducted on an instrumented propulsion system in a low-speed wind tunnel is provided for comparison. These experimental results are consistent with model predictions.

INTRODUCTION

In recent years, fuel cells have received increased interest for their ability to effect efficient, quiet, and clean conversion of chemical to electrical energy. These attributes also make fuel cells an attractive power source for electric propulsion and a possible alternative to gasoline powered internal combustion (IC) engines in Unmanned Aerial Vehicles (UAVs). Potential advantages of fuel cell / electric UAV propulsion include decreased emissions, increased efficiency, increased range and loiter time, and quieter, lower profile flight. Additionally, because fuel cells are chemical to electrical energy conversion devices, while IC engines are chemical to mechanical, an added advantage is the readily available electricity for UAV payloads such as surveillance equipment.

Current State of Fuel Cell Powered UAVs

To date, several fuel cell powered UAVs have been built and successfully flown [1, 2, 3]. However, documented design and optimization processes have been limited. In 2004, Ofoma and Wu [4] presented a design methodology for developing a fuel cell powered UAV used as a remote sensing tool, finding that fuel cell selection was a major driver in aircraft design. While this study investigated many important facets of propulsion system and aircraft design, the study was not integrated and often only qualitative in nature. The study did compare simulated propeller thrust values and air foil lift values generated with the web-based software code, Javaprop and Javafoil to experimental results, but the thrust experiments utilized batteries which have significantly different current/voltage characteristics from fuel cells. Further, the criteria used for fuel cell selection was limited to power ratings, weight and cost

with no investigation into the current and voltage coupling requirements between the fuel cell and motor.

In 2005, Soban and Upton [5] described a completely integrated qualitative mapping scheme designed to narrow the classes of UAVs best suited for fuel cell propulsion. In this study, propulsion architectures were broken down into classes of components, i.e. fuel cell type, fuel type, and fuel storage systems, and their associated measures of effectiveness such as fuel consumption rates, emissions, and power density. Aircraft architecture was split into classes of UAVs represented by current UAV systems such as Pioneer and Predator, with each class assigned common vehicle performance ratings for performance requirements such as range, altitude, and rate of climb. Through a combination of several commonly used qualitative assessment tools, optimal propulsion designs were assigned to different UAV classes. The findings of the study suggested that while current fuel cell technology was inferior to conventional propulsion systems, the anticipated advances in fuel cell technology, particularly that of solid oxide fuel cells (SOFCs), hold significant advantages in UAVs designed for long range and long endurance flights.

Between 2005 and 2007, members of the Aerospace Systems Design Laboratory at the Georgia Institute of Technology designed and built a proton exchange membrane (PEM) fuel cell demonstration UAV [1, 6, 7]. In [6], the authors describe the two level approach used in design and construction of the aircraft. The top level of this approach is a conceptual task used to explore the design space for optimal UAV designs. The design space is comprised of five contributing analyses (CAs): aerodynamic simulation, propulsion system analysis, weights tabulation and calculation, performance analysis and hydrogen storage. These CAs are assembled into a design structure matrix allowing assessment of millions of combinations of UAV designs and components. The optimal conceptual design is selected based on thrust margin, the

thrust available divided by thrust required for a given air speed, and overall propulsion efficiency. Using this conceptual design, the low level task provides a more in depth analysis focusing on design and integration of the fuel cell system and improvements upon the aerodynamic design of the aircraft. From this study, a demonstrator fuel cell UAV was constructed utilizing a 32 cell, 500 W PEM fuel cell power plant [7]. The results of this project suggest that the proper matching of motor and propeller to the characteristics of a given fuel cell is the most important aspect of a successful design.

While these studies point to fuel cell technology as a promising alternative to conventional IC engine propulsion systems, they also emphasize the importance of fuel cell selection and propulsion system component matching to fuel cell characteristics in the design of the aircraft. This thesis presents a steady-state optimization approach and a graphical procedure for investigating the performance implications of various propulsion system components and fuel cell models.

Steady-state Optimization Approach

For long endurance UAVs, the aircraft spends the majority of its flight time in steady flight mode, i.e. constant velocity. Thus, the propulsion system should be optimized at its required operation point for steady flight. Figure 1.1 shows fuel cell data for a typical flight test of the Georgia Institute of Technology demonstrator UAV described in [6, 7].

The figure shows three regions of operation. Region one is idle operation with the propeller static. The low level current draw seen here is the result of powering auxiliary equipment and the balance of plant of the fuel cell. Region two starts around the 6 second mark and is the high powered condition corresponding to take

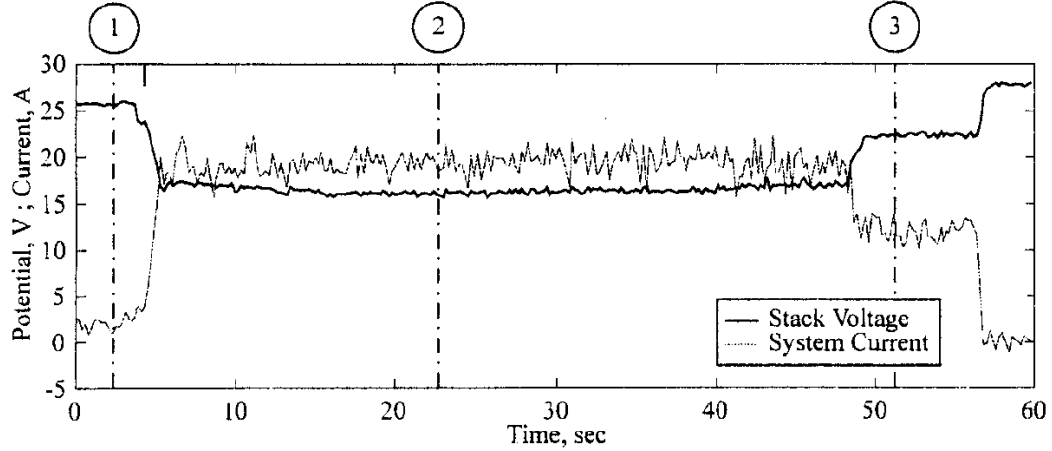


Figure 1.1: Sample data for a straight line flight test of the 500 W Proton Exchange Membrane (PEM) fuel cell powered demonstrator UAV detailed in [7]. Figure used with permission of author. ©American Institute of Aeronautics and Astronautics.

off and climbing. Around the 48 second mark, region three begins. Current draw is reduced and the aircraft assumes steady flight for about 8 seconds before descending and landing. The steady flight region is very short in this test flight. However, for a long endurance UAV deployed in a real world application, this is the region of primary operation. This is the region of propulsion system operation that should be optimized. It should be noted however that final propulsion system design must be able to provide adequate power for all three regions of operation. From Figure 1.1 we see that for UAV steady flight, the operation of the propulsion system remains relatively constant and thus can be accurately described using steady-state models of its components.

Thesis Organization

This thesis considers the steady-state modeling, design, and component selection for a fuel cell powered electric propulsion system. Chapter two discusses in depth

the major components of the propulsion system along with first-order mathematical models used to describe their operation. In addition, information is provided for the corresponding components used in the experimental validation part of the thesis. In chapter three, the simulation program comprised of these models is explained, and a graphical solution approach that allows easy assessment of design choices, e.g. changing stack specifications, is presented. Chapters four and five describe the wind tunnel testing procedure aimed at verifying the individual component models and the results of the tests, respectively. The thesis concludes in chapter six with discussion of the project's successes, necessary improvements, and recommendations for further work.

SYSTEM MODEL

Figure 2.1 depicts the propulsion system investigated in this thesis. The system is comprised of an SOFC fuel cell providing electrical power to a Brushless DC (BLDC) motor system that converts the electricity to mechanical power for turning a propeller. The input to the system is the duty cycle, D , which controls the voltage and current applied to the motor, while the output is the thrust, T produced by the propeller. Of particular concern is the optimization of power delivery from the fuel cell terminals to the propeller.

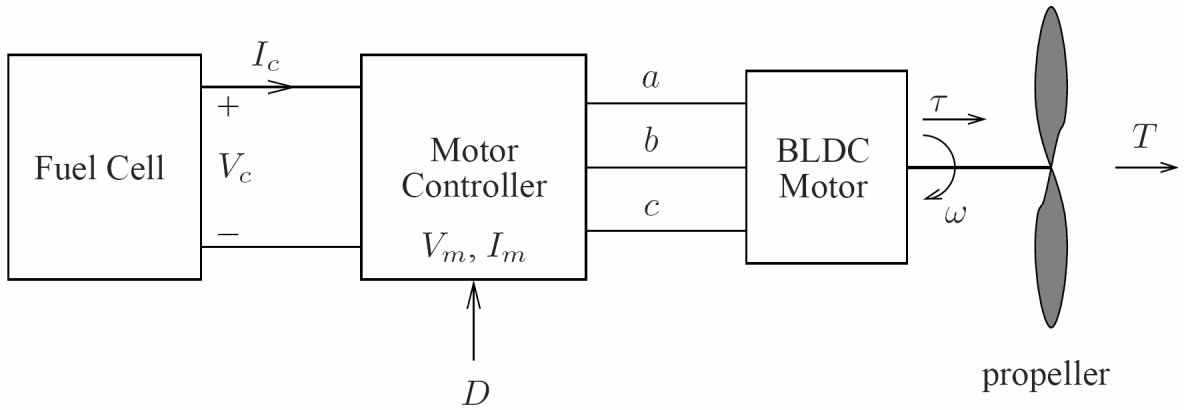


Figure 2.1: The propulsion system considered is comprised of four major components: the SOFC fuel cell stack, the BLDC motor and controller and the propeller. The input to the system is the duty cycle, D and the output is thrust, T [8], ©2009, Institute of Electrical and Electronics Engineers.

The primary purpose of the simulation program, described in further detail in chapter three, is to explore the performance implications of different fuel cell performance characteristics, operating points, and component choices for motor and propeller in the block diagram in Figure 2.1. To accommodate various component models, explicit modularity is maintained in the program codes which is mirrored in the descriptions of components in the following paragraphs. These models are

numerically combined to find an overall solution vector

$$\begin{pmatrix} I_c & V_c & D & I_m & V_m & \omega & \tau & T \end{pmatrix} \quad (2.1)$$

the components of which are detailed in the descriptions of each subsystem, below. The elements of this solution vector can be constrained in the simulation, and the program solved to find the non-constrained elements. Table 2.1 defines these elements.

Table 2.1: Elements contained in the solution vector of equation 2.1

Symbol	Quantity	Units
I_c	Current at fuel cell terminals	A
V_c	Voltage at fuel cell terminals	V
D	Motor controller duty cycle	-
I_m	Effective motor current	A
V_m	Effective motor voltage	V
ω	Motor speed	rad/s
τ	Motor torque	N-m
T	Propeller thrust	N

The following sections describe the operation of the individual components of the propulsion system in Figure 2.1, their first-order steady-state mathematical models, and the corresponding physical components used in the test stand.

Solid Oxide Fuel Cell

Fuel cells are electrochemical devices that convert chemical energy, stored in hydro-carbon fuel, into electrical energy. The basic structure of a fuel cell consists of three layers: the anode (negative electrode), the cathode (positive electrode), and a thin electrolyte layer separating the two. Fuel is supplied to the anode while an oxidant is fed to the cathode. The electrochemical reaction occurring at the boundaries

between the electrodes and the electrolyte produces an electric current through the electrolyte that is returned through a complimentary external load [9].

Fuel cell types are typically distinguished by their electrolyte technology, which dictates the type of ionic conduction through the electrolyte [9, 10, 11]. For example, PEM fuel cells employ a proton conducting polymeric ion exchange membrane, while the electrolyte in an alkaline fuel cell (AFC) is an hydroxide ion (OH^-) conducting aqueous alkaline solution. SOFCs have a solid metal oxide electrolyte and operate at high temperatures, usually between 600 °C and 1000 °C, where the ionic conduction of oxygen ions (O^{2-}) occur. The high temperature operation and ionic conduction of oxygen in SOFCs hold several advantages over other fuel cells. Most notably for military applications, this combination allows the possibility for internal reformation of heavy hydrocarbon fuels such as JP-8 jet fuel and diesel fuel. Additionally, SOFCs are potentially less susceptible than other fuel cell technologies to poisoning from low level sulfur content in hydrocarbon fuels, and carbon-monoxide (CO), a potential byproduct of fuel reformation and poisonous to PEM fuel cells, acts as a fuel in SOFCs [9, 10].

Figure 2.2 shows conceptual and actual images of an SOFC. Oxygen acquires electrons from the external circuit in the porous, electrically conductive cathode. The resulting oxygen ions diffuse readily toward the reducing atmosphere at the anode by means of oxygen vacancies in the lattice of the electrolyte. The electrolyte has a low electronic conductivity. Oxygen ions arriving at the anode combine readily with reformed fuel constituents, (H_2 and CO), and give up electrons to the external circuit. The result of this energetically favorable process is direct conversion of chemical to electrical energy, without the efficiency implications of a heat engine.

The Scanning Electron Micrograph (SEM) image in Figure 2.2(b) of an anode supported cell provides some indication of the actual scale of a fuel cell structure.

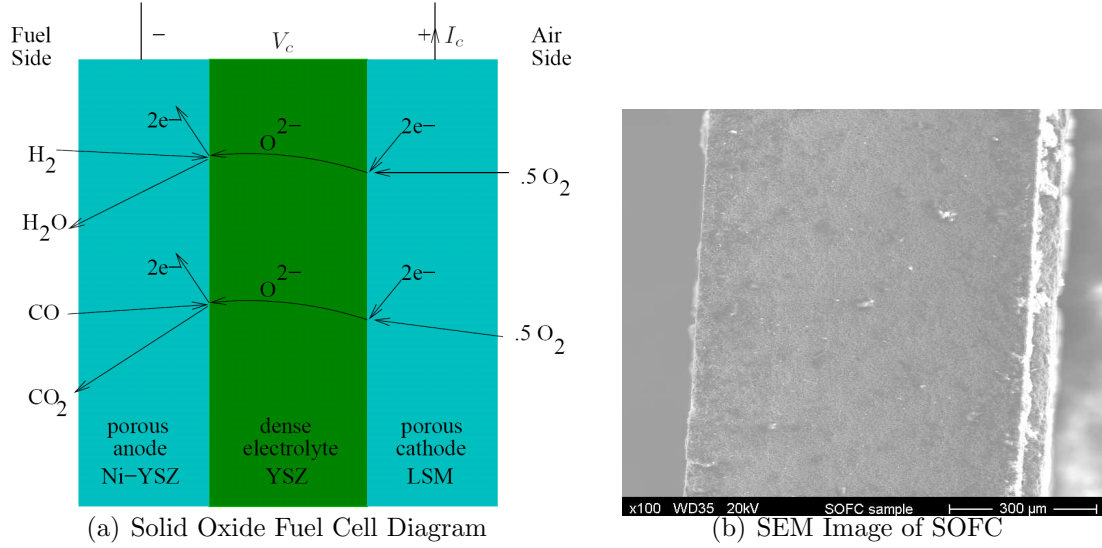


Figure 2.2: (a) Cross-sectional conceptual diagram and (b) scanning electron micrograph of a solid oxide fuel cell [8], ©2009, Institute of Electrical and Electronics Engineers.

The anode appears on the left of the SEM image. The thickness of the anode provides structural support. The electrolyte and cathode appear on the right margin above the scale bar.

Fig. 2.3 shows measured data representing the current voltage relationship of a typical anode supported fuel cell. The data in Fig. 2.3 is for an InDEC anode-supported cell with an active area of 18 cm^2 , at 750°C , operating on oxygen and hydrogen. The output voltage of an SOFC can be characterized as

$$V_{cell} = E_{cell} - V_{cell,act} - V_{cell,ohm} - V_{cell,con} \quad (2.2)$$

E_{cell} , represents the ideal performance of the fuel cell and is dependent on the operating temperature of the cell and the reactants involved. $V_{cell,act}$, $V_{cell,ohm}$, and $V_{cell,con}$ are voltage losses due to an electrochemical activation process, ohmic resistances in the cell components, and finite mass transport rates, respectively [9, 12]. In equation 2.2, contributions of the anode and cathode are lumped. These losses dominate dif-

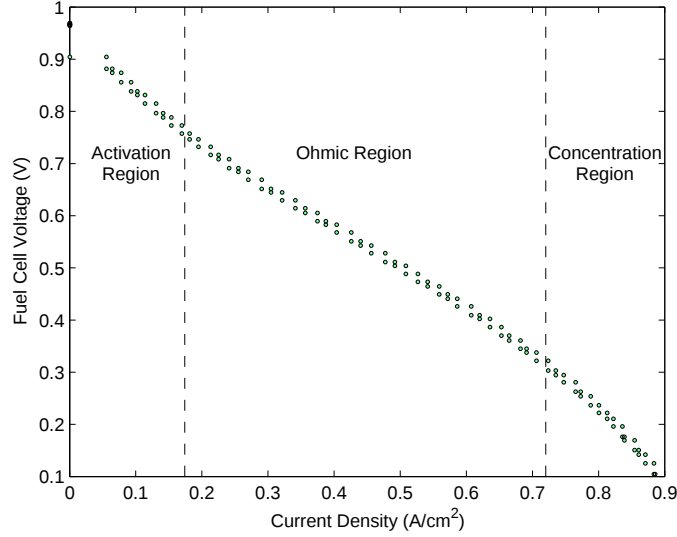


Figure 2.3: Measured current-voltage relationship of a typical InDEC anode supported SOFC [8], ©2009, Institute of Electrical and Electronics Engineers.

ferent regions of the polarization curve as depicted in Figure 2.3. Individual cells are typically “stacked”, or connected in series, to form a power source with convenient output voltages. Fuel cell stack operation is derived from the individual cell operation by

$$V_c = N_c V_{cell} \quad (2.3)$$

where N_c is the number of series connected cells [12]. In the UAV application, it is reasonable to assume that the stack will be designed under a weight constraint so that the nominal operating point is near the peak power point in the ohmic region of the fuel cell curve. In the ohmic region, the fuel cell can be approximated by a Thevenin circuit equivalent, i.e.

$$V_c = V_{oc} - I_c R_{th}, \quad (2.4)$$

where V_{oc} is the zero-current voltage intercept of the linear approximation of the ohmic part of the response, and R_{th} is the slope.

Table 2.2 lists the characteristics for the six fuel stacks involved in this study. Research and design of the fuel cell stacks took place at the Pacific Northwest National Laboratory (PNNL) in Richland, Washington. The specified operating voltages, V_c correspond to optimal voltage levels for producing around 2 kW of electric power as dictated by PNNL.

Table 2.2: Physical and modeling parameters of the SOFC stacks investigated

Fuel Cell	N_c	V_{cell} (V)	V_{oc} (V)	R_{th} (Ω)	V_c (V)
Model 8	67	0.7	70.1	0.55	46.9
Model 9	60	0.7	67.3	0.55	42
Model 10	60	0.625	66.4	0.55	37.6
Model 11	67	0.625	67.8	0.55	41.9
Model 12	73	0.625	57.8	0.28	45.6
Model 13	73	0.7	62.0	0.28	51.1

SOFC Emulation

Because operating a multi-kW SOFC stack is expensive and requires significant infrastructure, an SOFC emulator was built to mimic steady-state stack operation for testing purposes. A 10 kW Sorenson DCR 160-62T power supply in combination with a resistor built from a variable-length of 6.4 mm diameter 316 stainless steel tube was used to recreate fuel cell Ohmic Region polarization characteristics at power levels in the laboratory. A Miller Coolmate 4 welding torch cooling system rated for 4.4 kW was used to stabilize the temperature (and therefore the resistance) of the stainless steel by circulating a low-conductivity coolant through the tubing.

Brushless DC Motor System

Brushless DC (BLDC) motors feature high efficiency, ease of control, and astonishingly high power density at reasonable shaft speeds [13]. In general, BLDC motors outperform conventional permanent DC motors with better speed and torque characteristics, efficiency, longer operating lives, and increased reliability [14, 15]. These features make BLDC motors a natural choice for electric propulsion of small craft.

BLDC motors are permanent magnet synchronous motors, which from a modeling standpoint are similar to conventional permanent magnet DC motors [16]. The salient difference is that the BLDC motor is commutated externally by power electronic switches rather than by the brushes and commutator built into a standard DC motor. This introduces some electronic complexity, as an external controller is required to switch three phases of windings according to a real-time estimate of the rotor position.

Figure 2.4(a) shows the topology of a typical sensorless three-phase BLDC motor system. The inverter used in the motor controller is the same as a conventional three-phase inverter, however because the permanent magnet motor used has trapezoidal shaped back emfs, rectangular stator currents are required to produce constant torque [13, 17]. This operation is illustrated in Figure 2.4(b).

BLDC Motor

For steady-state modeling purposes, the modeling complexity of the BLDC controller is ignored so that the motor and controller is treated “as commutated”, i.e. the controller estimates the rotor position and commutates the motor efficiently in the steady-state. Under this assumption, the system can now be treated as an ideal DC machine with current I_m , voltage V_m , and resistance $2R_m$. The equations describing

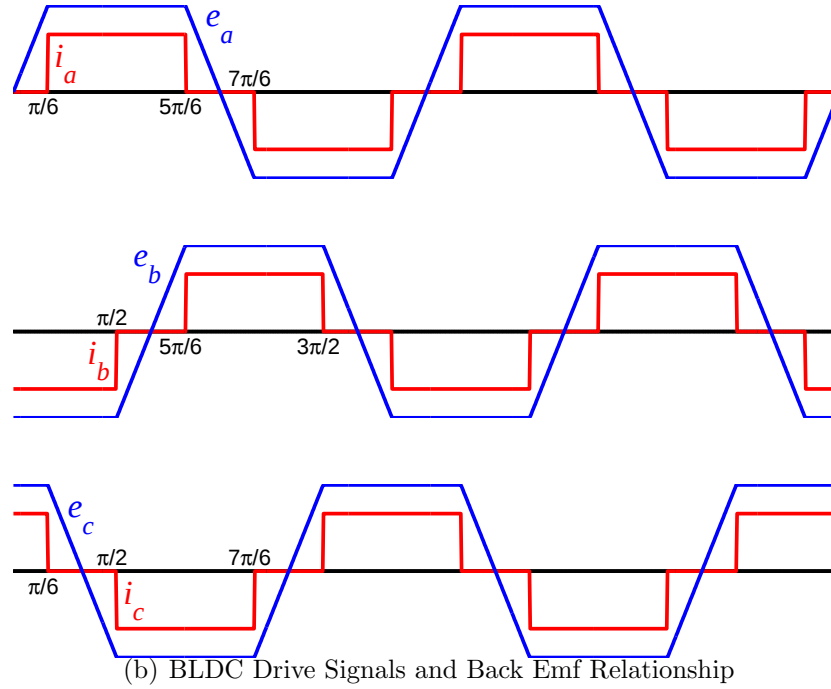
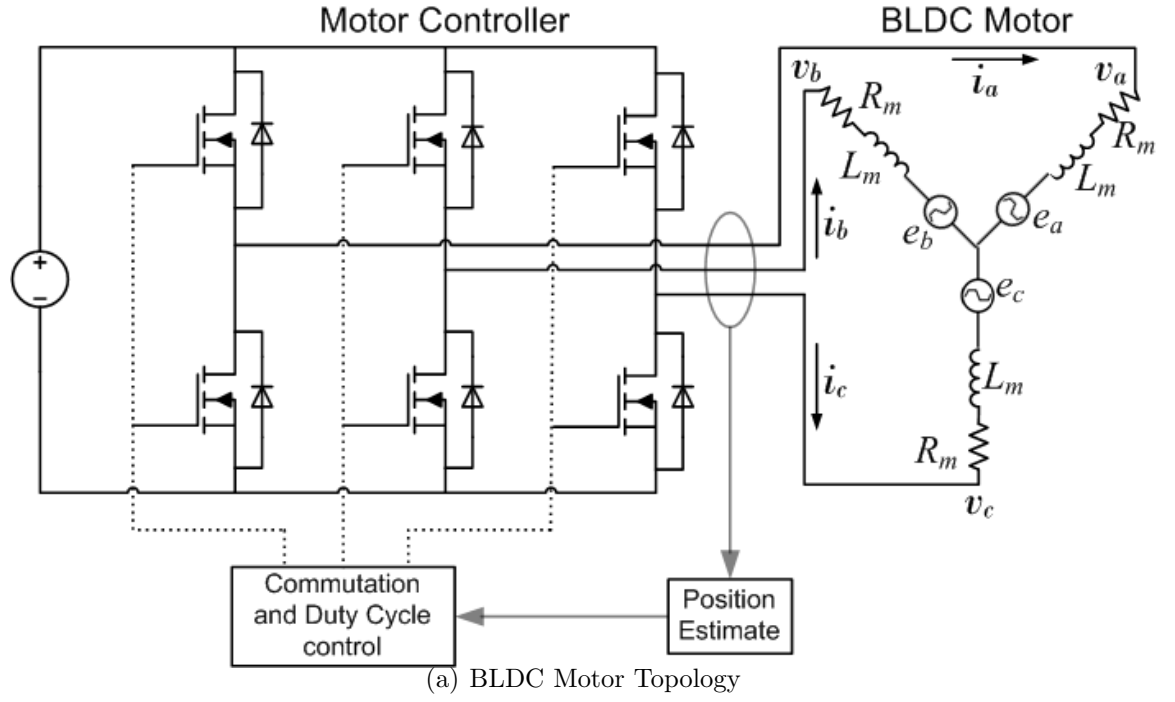


Figure 2.4: Brushless DC (BLDC) motor system topology 2.4(a) and required controller operation 2.4(b)

the motor are then

$$V_m = K\omega + 2R_m I_m \quad (2.5)$$

$$\tau_e = K I_m, \quad (2.6)$$

where K is the motor speed constant, ω is the shaft speed, τ_e is the torque of electric origin, and R_m is the winding resistance. Values for K and R_m are typically supplied by the manufacturer. Note that R_m appears with a factor of two in this equation because resistance is specified per winding and two windings are in series for each commutating sequence.

Motor manufacturers also typically provide current I_0 and voltage V_0 data under “no-load” conditions to indicate the amount of core, friction and windage losses during steady-state motor operation [9]. These losses are lumped together as a windage loss by calculating a drag coefficient

$$\beta = \frac{K^2 I_0}{V_0 - 2I_0 R_m}, \quad (2.7)$$

which modifies the output torque τ to ensure that the motor model passes through the specified no-load operating point, i.e.

$$\tau = \tau_e - \beta\omega. \quad (2.8)$$

The net mechanical output is torque τ at speed ω .

Several motors made by AXI Model Motors were selected for evaluation in the test stand. These motors advertise efficiencies in excess of 90% at the power levels required and have speed constants in a range which does not require a gear box between motor and propeller. Parameters for the motors are listed in Table 2.3. The values for I_0 correspond to $V_0 = 30\text{V}$. For an indication of motor size, the first two numbers in the motor name give the rotor diameter (mm), and the second two give

Table 2.3: Modeling parameters of the AXI motors investigated [8], ©2009, Institute of Electrical and Electronics Engineers.

Motor	K (Vs rad ⁻¹)	R_m (Ω)	I_0 (A)
AXI Double 5330/20	0.041	0.012	4.8
AXI 5345/14	0.042	0.014	2.6
AXI 5345/18	0.056	0.021	1.6
AXI 5360/20	0.080	0.034	1.8



Figure 2.5: AXI 5345/14 BLDC Motor

the stator length (mm). The AXI 5345/14 motor is shown in Figure 2.5. The AXI Double 5330/20 motor is two 5330/20 motors sharing a common rotor.

Motor Controller

In addition to switching the output transistors with rotor position, which is lumped with the model motor, the motor controller can introduce a duty cycle D in the pulses applied to the motor windings. The duty cycle is the input to the propulsion system allowing flight control to change power delivered to the prop. From the power electronics perspective, the average motor voltage over a commutating se-

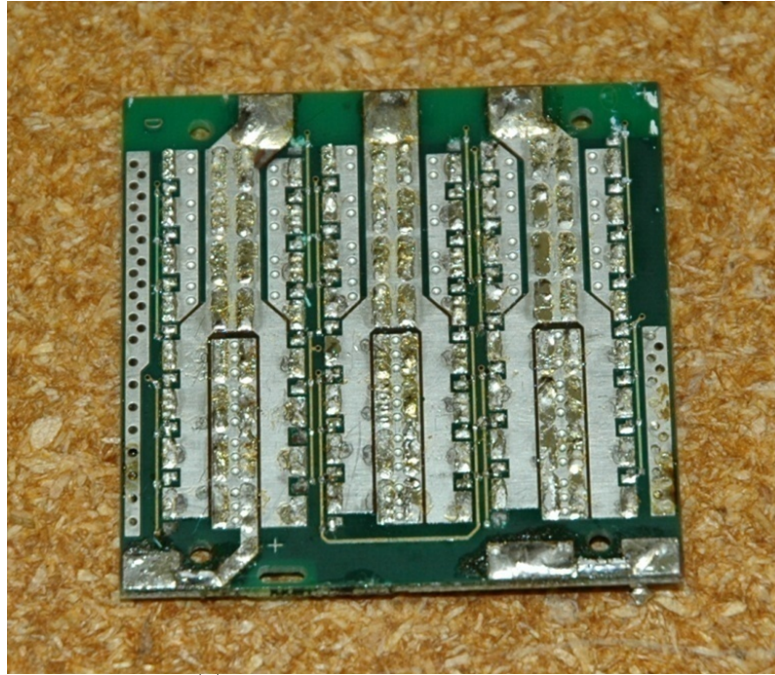
quence is modulated by D , so the duty cycle effectively introduces an integrated buck converter. Assuming the converter is lossless, the equivalent voltage V_m and current I_m at the motor terminals are given by

$$V_m = DV_c \quad (2.9)$$

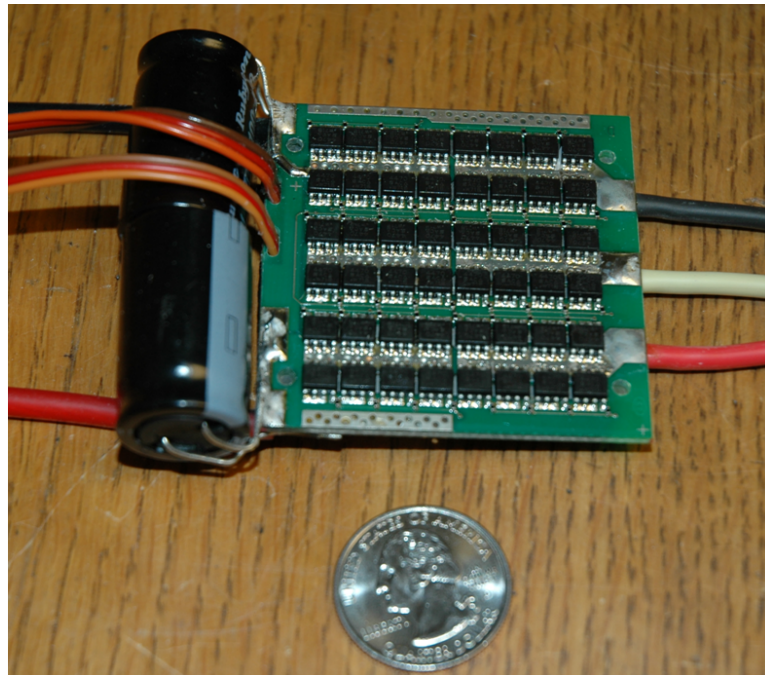
$$I_m = \frac{1}{D}I_c, \quad (2.10)$$

where D is the duty cycle and V_c , I_c are the fuel cell voltage and current. Losses in the motor controller are neglected because they are estimated to be on the order of 10 W while the motor is drawing in excess of 1 kW.

For all laboratory tests, Jeti Spin99 motor controllers were used. These controllers are designed for the appropriate power levels, but are intended for use with NiMH or Li based batteries that have low series resistance compared to the fuel cell. As a result, the no-load voltages in the fuel cell systems exceed the voltage rating of the parts used in these controllers. The Spin99 controllers were disassembled and the power MOSFETS and capacitors were replaced with higher voltage rated parts. Figure 2.6 depicts the process. An Agilent 33220A function generator replaced the radio controlled transmitter and receiver associated with the motor controller allowing precise control of duty cycle.



(a) Disassembled Motor Controller



(b) Modified Motor Controller

Figure 2.6: Components of the Jeti Spin99 motor controller were replaced with components that matched the voltage requirements of the fuel cell systems studied. 2.6(a) shows the completely disassembled controller, and 2.6(b) shows the modified controller

Propeller

The propeller determines the relationship between motor speed and load torque, and therefore ultimately determines the operating point of the propulsion system. Typically, propeller performance is expressed using dimensionless thrust coefficient C_T and power coefficient C_P . The coefficients are functions of the relative speed of the craft and the prop, or the advance ratio

$$J = \frac{S}{n_p L}, \quad (2.11)$$

where S is the air speed, $n_p = \frac{\omega}{2\pi}$ is the rotational speed of the prop in revolutions per second, and L is the prop diameter [18]. Given C_P at a particular advance ratio, the shaft power required is

$$P = C_P \rho L^5 n_p^3, \quad (2.12)$$

where ρ is the local air density. Setting the propeller power requirement equal to the mechanical power at the shaft, i.e. $\tau\omega = P$, yields the desired relationship between motor speed and torque

$$\tau = C_P \rho L^5 \frac{\omega^2}{(2\pi)^3} \quad (2.13)$$

Similarly, given C_T , the thrust produced by the propeller is

$$T = C_T \rho L^4 n_p^2 \quad (2.14)$$

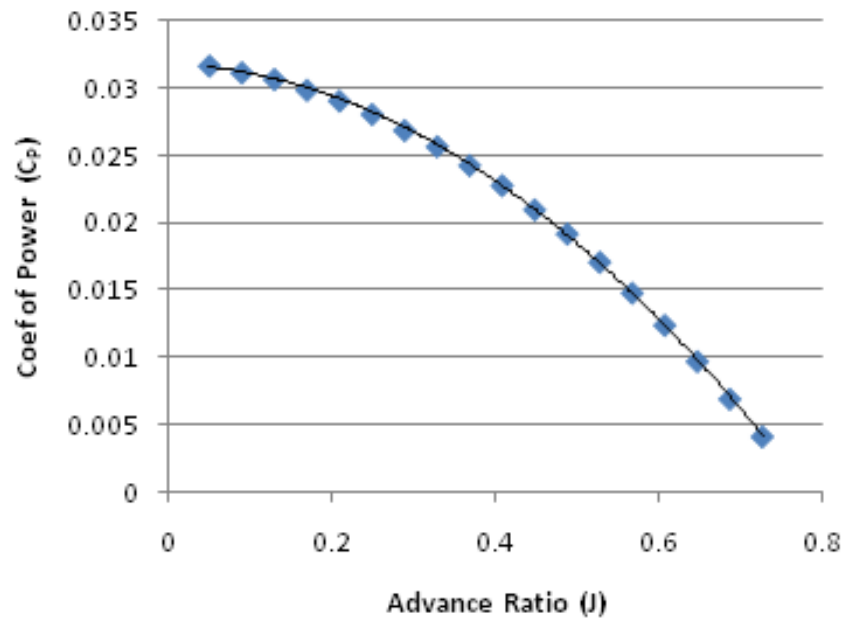
For steady flight, the thrust and lift produced by the propulsion system and wings, respectively, must be sufficient to overcome the aircraft's drag and weight. The relationship between these forces acting on an aircraft and the craft's air speed is complex, and requires an understanding of the aerodynamic properties of the vehicle and the flight profile. The simulation program simply calculates the available thrust

Table 2.4: APC brand propellers used in wind tunnel testing and the 2nd order models used to describe their operation [8], ©2009, Institute of Electrical and Electronics Engineers

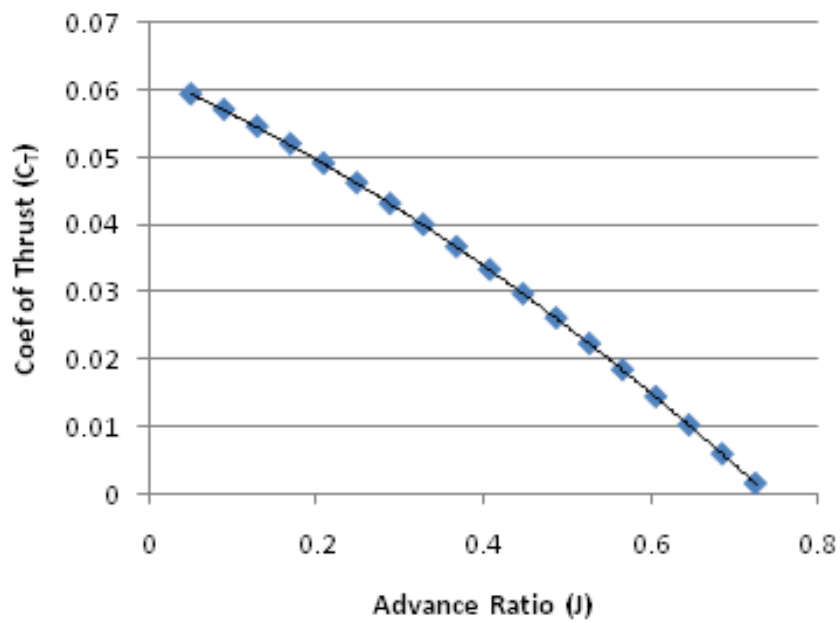
Propeller	Coefficients
APC 22x12	$C_T = -0.039J^2 - 0.055J + 0.062$
	$C_P = -0.049J^2 - 0.001J + 0.031$
APC 24x12	$C_T = -0.038J^2 - 0.055J + 0.057$
	$C_P = -0.045J^2 - 0.005J + 0.028$
APC 26x15	$C_T = -0.040J^2 - 0.053J + 0.067$
	$C_P = -0.053J^2 - 0.002J + 0.042$
APC 27x13	$C_T = -0.037J^2 - 0.055J + 0.054$
	$C_P = -0.044J^2 - 0.005J + 0.026$

at a target airspeed. If this number is in excess of the thrust requirement anticipated by the airframe designer, the craft is predicted to fly.

Four lightweight APC composite propellers were selected for testing in the wind tunnel. For each propeller, APC provided estimated values of C_P and C_T for discrete values of J . Figure 2.7 shows an example of these relationships along with second order polynomial trendlines fit to the data using the least-squares method. These polynomials capture C_T and C_P as continuous functions of J for use in the simulation program. Table 2.4 show these functions for the four propellers selected. The first number in the propeller specification is the diameter in inches, while the second number is the pitch in inches. The pitch of a propeller defines the distance the propeller would travel in one revolution if there were no slip.



(a) Coefficient of Power



(b) Coefficient of Thrust

Figure 2.7: Power and Thrust coefficient plots for the APC 22 x 12 in. propeller.

SIMULATION PROGRAM

The simulation program is comprised of four analysis functions corresponding to the mathematical models presented in chapter two. Parameters of the individual component models (Tables 2.2, 2.3 and 2.4) are stored in global variables and serve as inputs to the analysis functions. With a user-specified controller duty cycle, D , aircraft flight speed, S and local air density, ρ , the combined analysis functions can be solved with standard techniques to find the system operation point, defined in equation 2.1. While this solution is valuable information, it does not provide design insight needed to understand trade-offs in fuel cell output characteristics, control opportunities, or the relative merit of different propeller and motor combinations. Rather than solving for a single operating point found from a single input variable, it is more useful to solve for a collection of operating points that can be presented in a graphical format. The most intuitive independent variable for this purpose appears to be the fuel cell stack terminal current I_c . Numerically, I_c is constrained to a succession of values from a vector, and the matlab command `fsolve()` is used to determine every other variable as a function of current. The outputs are then reflected to the fuel cell terminals where they can be interpreted on one plot in conjunction with the fuel cell response.

Figure 3.1 shows a sample output. This two dimensional voltage/current space represents the design space of the fuel cell stack. The line labeled “linearized FC curve” is simply a plot of the output characteristic of one specific fuel cell stack. In this example, SOFC PNNL Model 12 with an open circuit voltage of 57.8 V and a Thevenin equivalent resistance of 0.28 Ω is used. The red box, labeled “propeller and motor operation region”, represents a family of voltage/current curves for the motor and propeller combination at the specified airspeed. The lower margin of this box

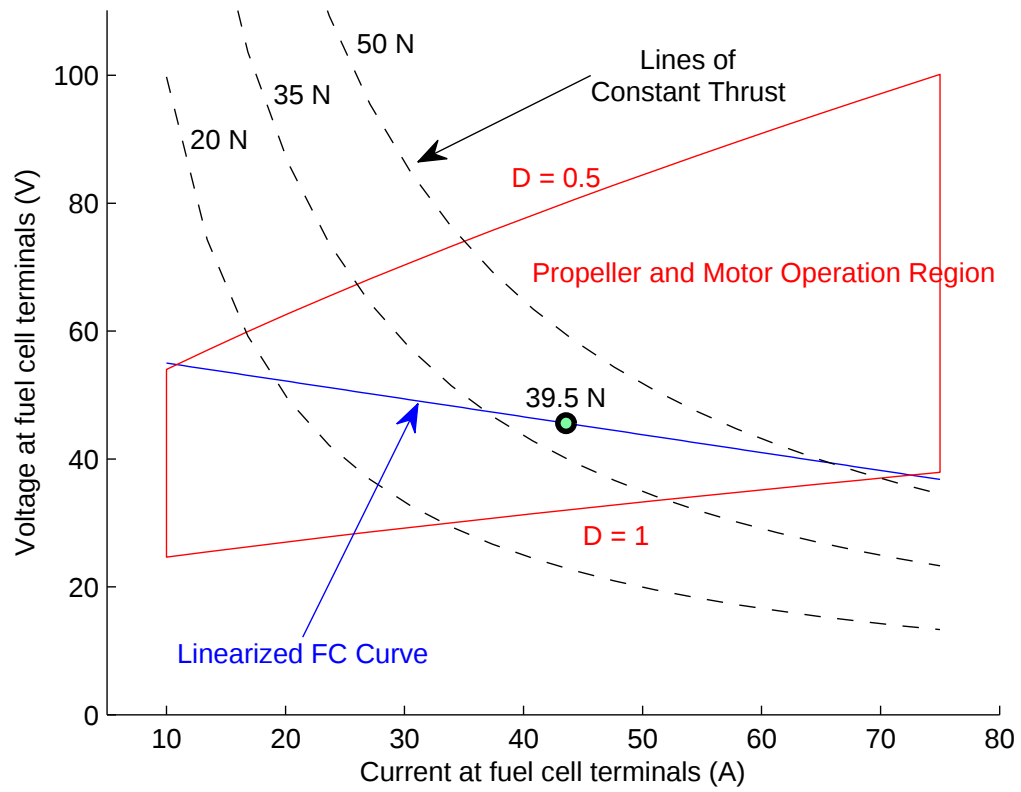


Figure 3.1: Predicted performance of the PNNL Model 12 SOFC, AXI 5345/18 motor, Jeti Spin 99 controller and APC 27x13 in. propeller. The simulation was performed assuming a cruising velocity of 31.3 m/s (70 mph) and air density of 1.2 kg/m^3 .

shows the relationship between current and voltage for the motor and propeller with duty cycle $D = 1$. The upper margin of the box is the curve corresponding to $D = 0.5$. The operating point of the propulsion system is determined by the intersection of the motor/propeller curve at a specified duty ratio and the fuel cell curve. Thus, the interpretation of the graph is that any point on the fuel cell curve within the box is an achievable operating point at a reasonable steady-state duty ratio between 0.5 and 1.

The other variables of equation 2.1 can also be constrained to provide interpretation of the achievable operating points. Contours of constant thrust are added to the plot by constraining thrust, T , to specific values and repeating the solution process. These are the dashed lines labeled with thrust values. These curves provide current/voltage relationships required for the motor and propeller to produce the thrusts specified.

The operating point as specified by the PNNL defined optimal fuel cell output voltage is found by constraining V_c to the V_{op} value of 45.6 V. This is indicated by a large point in Figure 3.1 and shows the estimated thrust to be 39.5 N at a duty ratio of roughly 0.75. With relatively high estimated thrust and an operation point well within the duty cycle limits of the propeller and motor operation region, Figure 3.1 represents a good propulsion system design.

In contrast, Figure 3.2 shows a poor combination of components, the AXI 5360/20 motor and APC 22 x 12 propeller, for the same fuel cell parameters. In this case, it is not possible to select a duty ratio where the motor and propeller are even able to use the power that the fuel cell is capable of delivering. The nominal fuel cell operating point is outside of the propeller curve box, demonstrating that this system is also incapable of producing the thrust achieved by the system in Figure 3.1. At the maximum duty ratio of 1.0, this system would only produce slightly more than

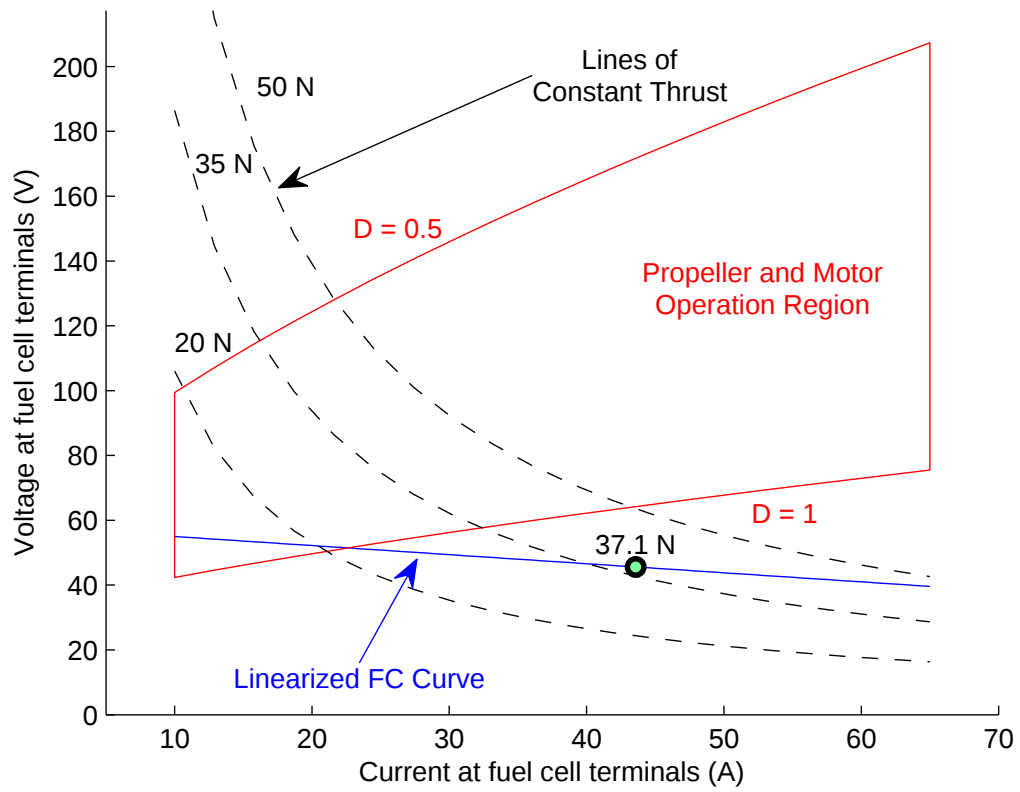


Figure 3.2: Predicted performance of the PNNL Model 12 SOFC, AXI 5360 motor, Jeti Spin 99 controller and APC 22x12 in. propeller. The simulation was performed assuming a cruising velocity of 31.3 m/s (70 mph) and air density of 1.2 kg/m^3 .

20 N of thrust. Furthermore, even if it were possible to command the necessary duty cycle, Figure 3.2 is predicted to produce less thrust at the same power level.

Graphs of these kind immediately connect the quantities of interest to the fuel cell stack designer, i.e. current and voltage at the stack terminals, to the ability to command thrust, which is of interest to the airframe designer. Additionally, the graphs lend themselves to understanding how the current/voltage characteristics of a fuel cell might be modified with an auxiliary source, e.g. photovoltaics or battery, and the effect that the new current/voltage characteristic might have on flight performance. As a specific example, the inherently sloping fuel cell curves tend to become parallel to lines of constant thrust at higher currents. Even if the fuel cell is subjected to severe high-current loading, very little additional thrust is possible. On the other hand, an alternate source with a flat current voltage characteristic could be used to temporarily cross several thrust curves and substantially increase the flight envelope. This idea is illustrated in Figure 3.3 with the dotted line indicating the polarization curve of an second power source with a flat current voltage relationship. The 3 kW operating point shown would still draw only 2 kW from the fuel cell with the remaining 1 kW of power being provided by the secondary source.

Appendix A contains the full set of simulation results for all combinations of propulsion system components.

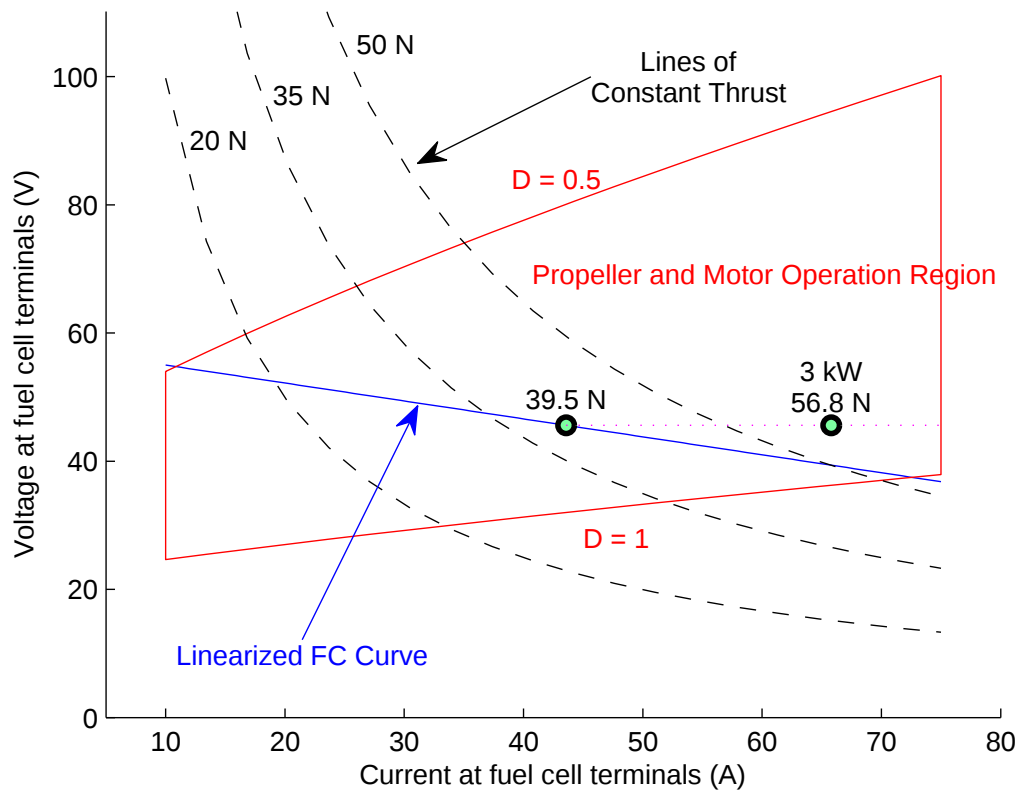


Figure 3.3: Predicted performance of the propulsion system of Figure 3.1 with an added second power source. The simulation was performed assuming a cruising velocity of 31.3 m/s (70 mph) and air density of 1.2 kg/m^3 .

EXPERIMENTAL SETUP

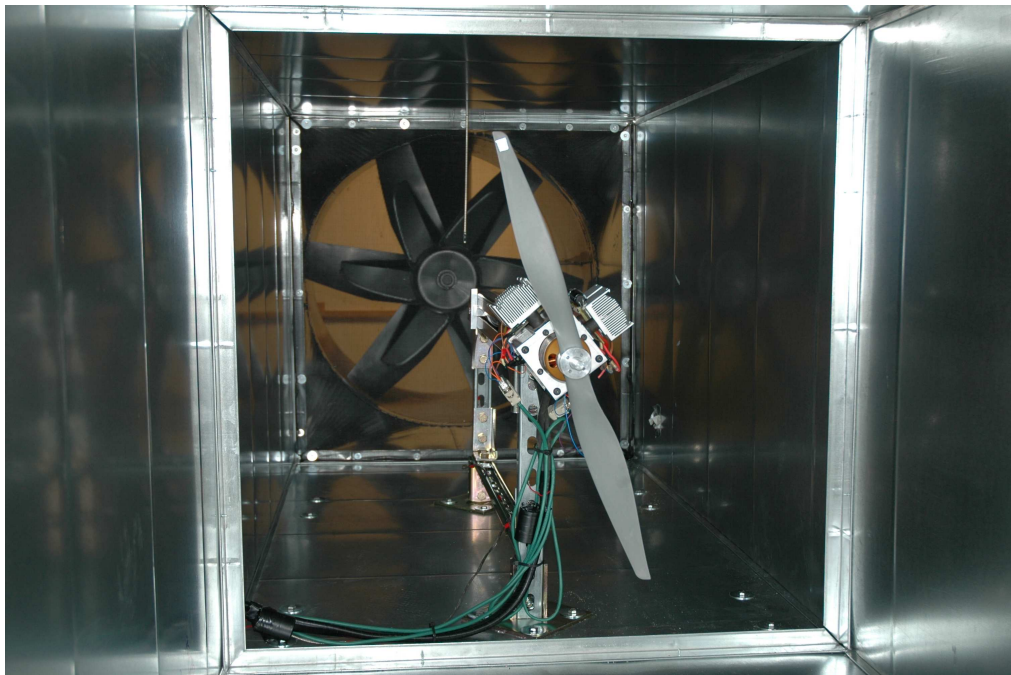
As indicated in chapter two, the propeller models relate thrust, T , and torque, τ , to the advance ratio, J (equations 2.11, 2.13 and 2.14). These models assume a non-zero free-stream velocity, S , up stream of the propeller. Thus, static propeller tests are inadequate for verifying propeller models. An open circuit wind tunnel, Figure 4.1(a), was constructed for the purpose of testing propulsion systems under flight conditions. The working section of the wind tunnel is 91 cm x 91 cm and 3 m in length. Ideally, the wind tunnel would be capable of an air flow velocity equivalent to the 30 m/s desired aircraft velocity. However, this would require a significantly large and expensive excitation fan that would exceed our available lab space and budget. Instead, the wind tunnel is excited by a 3.7kW, 91cm diameter Dayton tube-axial duct fan upstream of the propeller capable of wind tunnel velocities around 40% aircraft velocities. Data achieved at these lower wind tunnel velocities can be extrapolated to predict performance at actual flight speeds.

A test stand was mounted in the working section of the wind tunnel 4.1(b). The test stand consists of an interchangeable motor mounting plate fixed to a steel rod. The rod is supported at its center of gravity on a pillow block, so that it is free to translate and rotate. The rod is constrained by only a torque/force load cell which provides direct measurement of motor torque and developed thrust. In addition to torque and thrust, we measure atmospheric conditions, air speed, propeller speed, fuel cell current and voltage, and duty cycle on the controller. This allows a comparison of simulation variables with lab measurements. The propeller is mounted in a pusher configuration.

As recommended in [19], both a screen and a honeycomb section were installed in an effort to normalize the air flow through the wind tunnel. Screens have the



(a) Wind Tunnel



(b) Test Stand

Figure 4.1: The open circuit wind tunnel 4.1(a) and test stand 4.1(b) constructed for testing propulsion system components [8], ©2009, Institute of Electrical and Electronics Engineers.

benefit of creating a more uniform flow velocity through the wind tunnel as well as reducing turbulence intensity. Honeycombs reduce swirl and also have a minor turbulence reduction effect. The screen was made of heavy duty nylon construction. The honeycomb was constructed of 396 pieces of 1.5 inch PVC pipe 6 inch in length, 18 pieces to a row and 22 rows. To measure the effectiveness of these components, the test stand was removed from the wind tunnel and a grid was constructed from kite string along the cross section of the tunnel corresponding to the propeller location. The grid consisted of 25 measurement locations as indicated by Figure 4.2. Velocity measurements were taken using a Kestrel 3500 Weather Meter at each location with the screen installed, the honeycomb installed and with neither installed. The installation point for both the screen and the honeycomb was 3 feet downstream of the axial fan and 5 feet upstream of the propeller location.

With no normalizing device installed, the wind tunnel had an average wind speed of 13.7 m/s and a maximum deviation from the average of 29%. Unexpectedly, both screen and honeycomb had adverse affects on air flow. The screen caused a reduction in average velocity to 9.7 m/s, and an increase in flow variation to 61%. The honeycomb reduced the average velocity to 12.2 m/s and increased the maximum variation in velocity to 43% from the average. Thus, it was determined that wind tunnel testing should procede without either component installed. The effects of the screen and the honeycomb on wind tunnel swirl were not measured.

Instruments

The instruments used to measure system operation for comparison with simulated variables are described below.

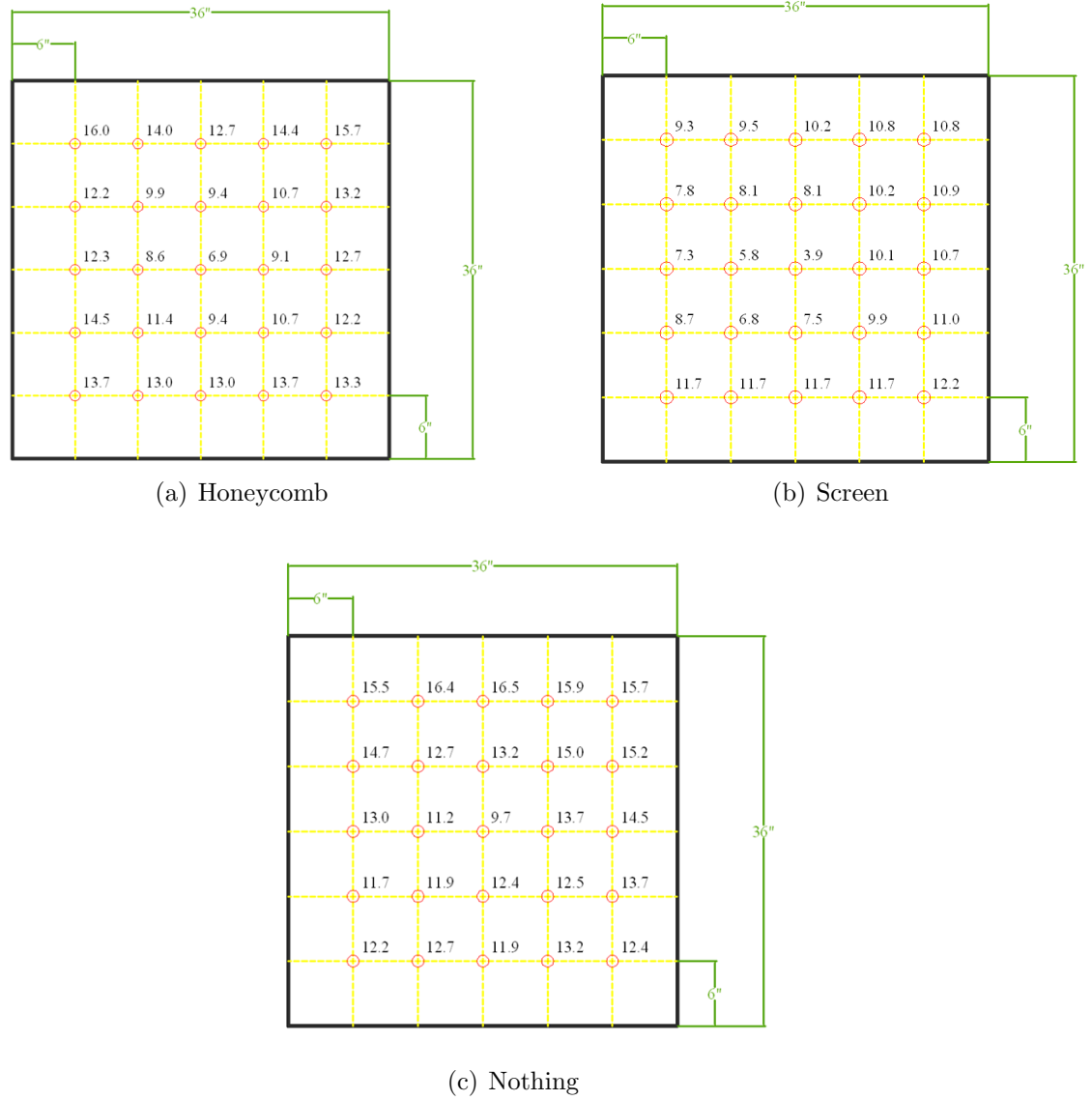


Figure 4.2: Both a honeycomb and a screen were installed in the wind tunnel in an attempt to normalize air flow. The velocities measured are shown in m/s.

Fuel Cell Emulator Voltage and Current

As described in chapter two, a Sorenson DCR 160-62T in series with a stainless steel resistor was used to simulate the steady-state performance of the fuel cell stacks. The current delivered from the power supply, I_c was recorded off the power supply ammeter which has an accuracy of 0.1%. Voltage at the emulated fuel cell terminals, V_c was measured using a B&K Test Bench 389A digital multimeter. The 389A has an accuracy of 0.25% for DC voltage readings.

Duty Cycle

Duty cycle D was recorded using a Tektronix P5205 high voltage probe in conjunction with a DPO 4054 Tektronix Oscilloscope. The P5205 has a maximum voltage rating of 1300 V and bandwidth of 100 MHz.

Motor Torque and Propeller Thrust

Propeller torque τ and thrust T were measured using a Cooper LXT-920 force / torque load transducer. The linearity, hysteresis and repeatability ratings for thrust are ± 1.8 N, ± 0.9 N and ± 0.4 N, respectively. These ratings for torque are ± 0.045 N-m, ± 0.023 N-m and ± 0.011 N-m.

Propeller Rotational Speed

A CheckLine DT-205L non-contact tachometer was used to access the propeller's rotational speed ω . The DT-205L has a maximum measurement rating of 10,470 rad/s and an accuracy of 0.1 rad/s for the range of speeds observed.

Wind Tunnel Velocity and Air Density

The simulated craft velocity S and the atmospheric conditions used to calculate air density ρ were measured using a Kestrel 3500 Weather Meter. For velocity, the Kestrel has an operating range of 0.4 to 60 m/s, and 3% accuracy. Atmospheric pressure, temperature and dew point are required for estimating air density. The Kestrel's accuracy for these measurements are ± 1.5 hPa (hectopascals), ± 1 °C and ± 2 °C respectively.

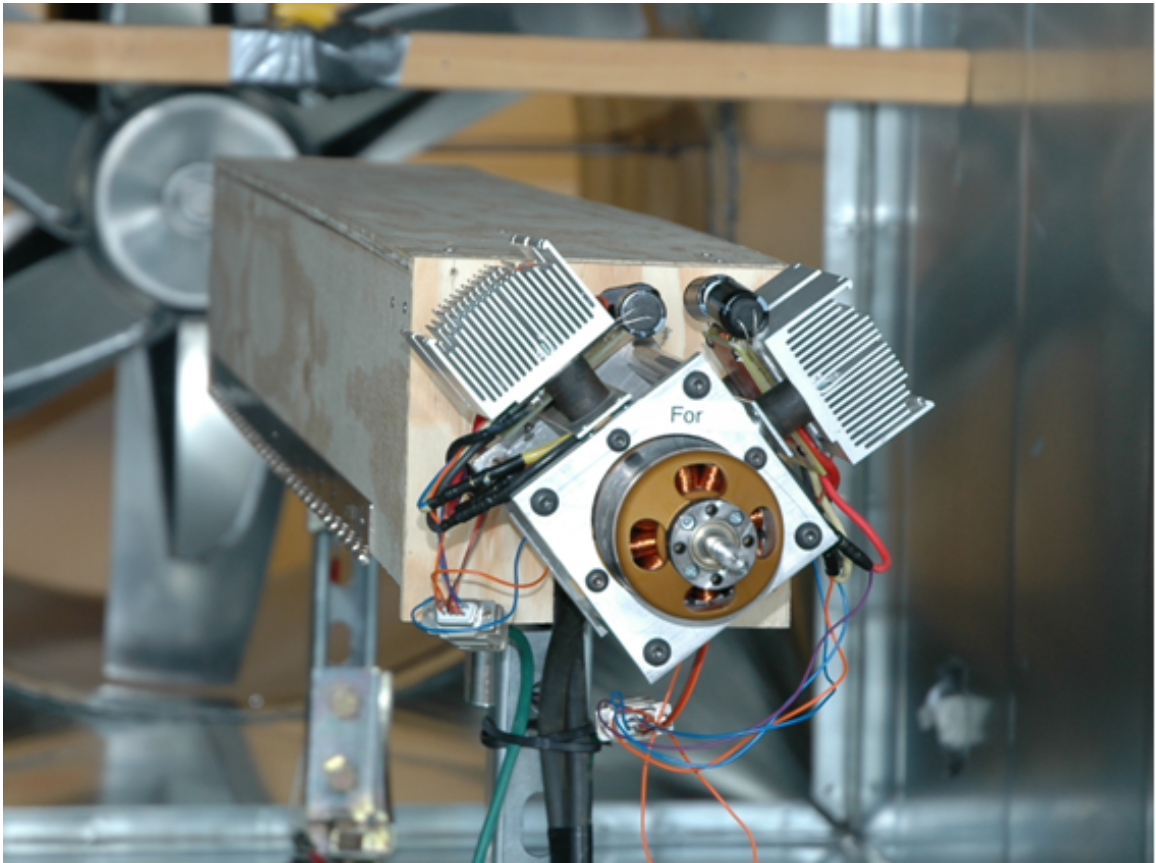


Figure 4.3: A mock fuselage, 6 in. x 6.5 in. and 3 feet in length was constructed for installation on the test stand. This allowed testing of propeller performance with partial occlusion by the aircraft fuselage.

Test Schedule

With six fuel cell models, four BLDC motors and four propellers considered, a complete study would involve 96 combinations of components. Additionally, a mock aircraft fuselage was constructed for installation on the test stand (figure 4.3). With the mock fuselage installed, tests could be repeated to determine if the UAV fuselage would occlude the propeller enough to invalidate the propeller models used in the simulation. To limit the number of tests required, an experiment schedule was constructed so that each motor/propeller combination was tested at least once, and that each fuel cell model was tested with each motor and each propeller at least once. This allowed a comprehensive study of the possible components while reducing the required testing to 25% of the total combinations. This schedule is displayed in Table 4.1. The results of these experiments are discussed in the next chapter, and presented in full in Appendix B.

Test Procedure

Each experiment consists of two runs through the test procedure; the first with the mock fuselage installed and the second without. First, the resistor is calibrated to the desired fuel cell output resistance using a precise meter. The resistor cooling system and wind tunnel excitation fan are then turned on. Atmospheric conditions and any instrumentation offsets are then recorded. The power supply simulating the fuel cell is then adjusted to the required open circuit Thevenin equivalent voltage. Then the duty cycle command is adjusted until the desired operating point is achieved. All variables are recorded, and the process is repeated for several duty cycle controlled operating points.

Table 4.1: 24 of the 96 possible combinations of components were tested in the wind tunnel. Each motor/propeller combination was tested at least once and each fuel cell model was tested with each motor and each propeller at least once. Results of these tests are described in chapter five and listed in Appendix B.

Test	FC Model	Motor	Prop
Test 1	PNNL Model 08	AXI DBL 5330/20	APC 22 x 12
Test 2	PNNL Model 08	AXI 5345/14	APC 27 x 13
Test 3	PNNL Model 08	AXI 5345/18	APC 24 x 12
Test 4	PNNL Model 08	AXI 5360/20	APC 26 x 15
Test 5	PNNL Model 09	AXI DBL 5330/20	APC 27 x 13
Test 6	PNNL Model 09	AXI5345/14	APC 26 x 15
Test 7	PNNL Model 09	AXI5345/18	APC 22 x 12
Test 8	PNNL Model 09	AXI5360/20	APC 24 x 12
Test 9	PNNL Model 10	AXI DBL 5330/20	APC 22 x 12
Test 10	PNNL Model 10	AXI5345/14	APC 27 x 13
Test 11	PNNL Model 10	AXI5345/18	APC 24 x 12
Test 12	PNNL Model 10	AXI5360/20	APC 26 x 15
Test 13	PNNL Model 11	AXI DBL 5330/20	APC 24 x 12
Test 14	PNNL Model 11	AXI5345/14	APC 22 x 12
Test 15	PNNL Model 11	AXI5345/18	APC 26 x 15
Test 16	PNNL Model 11	AXI5360/20	APC 27 x 13
Test 17	PNNL Model 12	AXI DBL 5330/20	APC 26 x 15
Test 18	PNNL Model 12	AXI5345/14	APC 24 x 12
Test 19	PNNL Model 12	AXI5345/18	APC 27 x 13
Test 20	PNNL Model 12	AXI5360/20	APC 22 x 12
Test 21	PNNL Model 13	AXI DBL 5330/20	APC 27 x 13
Test 22	PNNL Model 13	AXI5345/14	APC 26 x 15
Test 23	PNNL Model 13	AXI5345/18	APC 22 x 12
Test 24	PNNL Model 13	AXI5360/20	APC 24 x 12

EXPERIMENTAL RESULTS

As outlined in chapter four, each test listed in Table 4.1 was conducted twice; once with the mock fuselage installed and once without. These combinations of components were assembled on the test stand in our wind tunnel and tested at a variety of operating points. Using these operating points as inputs along with the measured air density and wind tunnel velocity, the simulation program was run to solve for individual component models.

Fuel Cell Modeling Results

Figures 5.1 - 5.6 show the experimental results for the six fuel cell models. Each fuel cell model was tested with four different motor/propeller loads which are indicated in the accompanying figure legend. The blue line in each figure is the simulated ohmic region of the fuel cell. While this is somewhat of a trivial result since the fuel cell emulator is simply a voltage source with a resistor in series, an accurately sloping voltage/current power source is required for characterizing motor performance with a fuel cell power source. Additionally, with an emulator current of 60 A, and resistance set to $0.55\ \Omega$, the variable resistor dissipates around 2 kW of power. These tests prove the cooling systems effectiveness in regulating resistor temperature and maintaining constant resistance values for a wide range of emulated fuel cell currents.

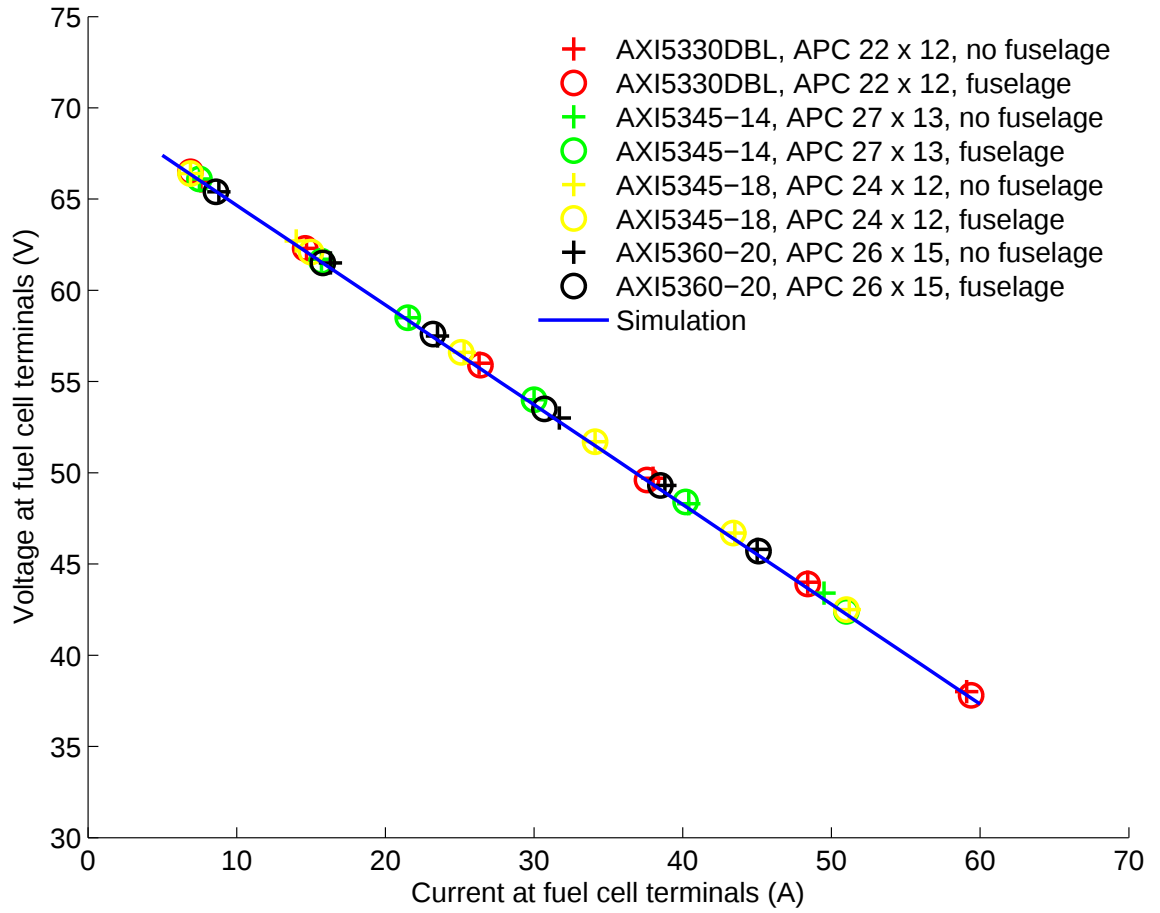


Figure 5.1: Comparison of simulated polarization curve to experimental values for the steady-state SOFC PNNL Model 08 emulator assuming operation in the ohmic region

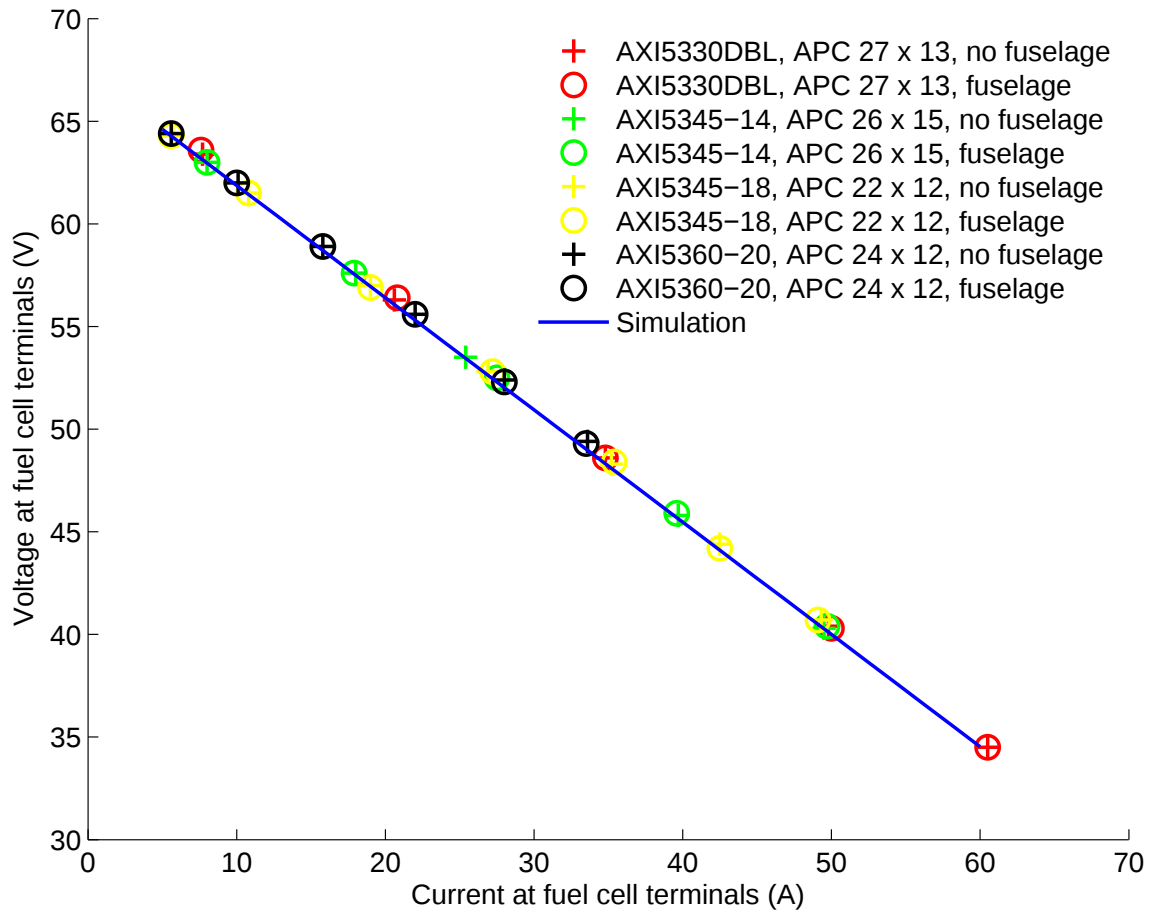


Figure 5.2: Comparison of simulated polarization curve to experimental values for the steady-state SOFC PNNL Model 09 emulator assuming operation in the ohmic region

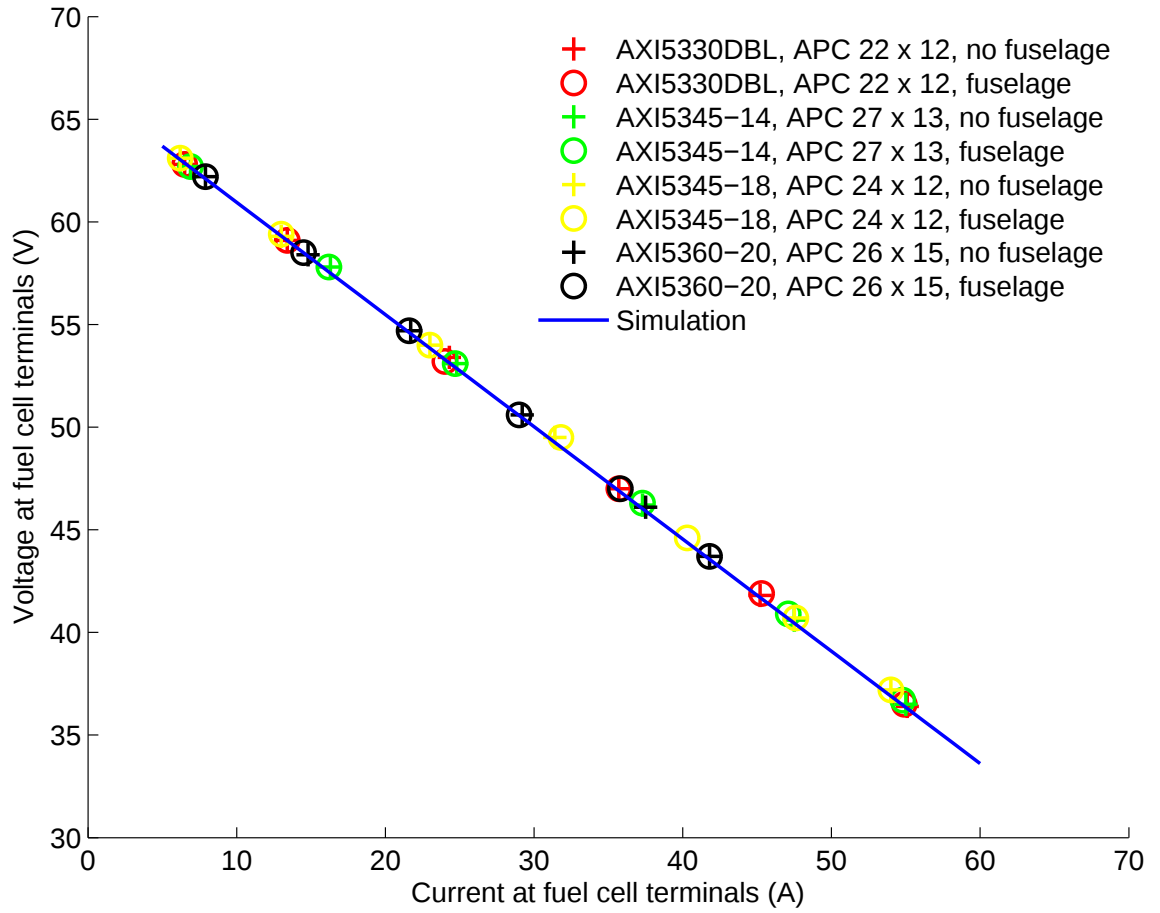


Figure 5.3: Comparison of simulated polarization curve to experimental values for the steady-state SOFC PNNL Model 10 emulator assuming operation in the ohmic region

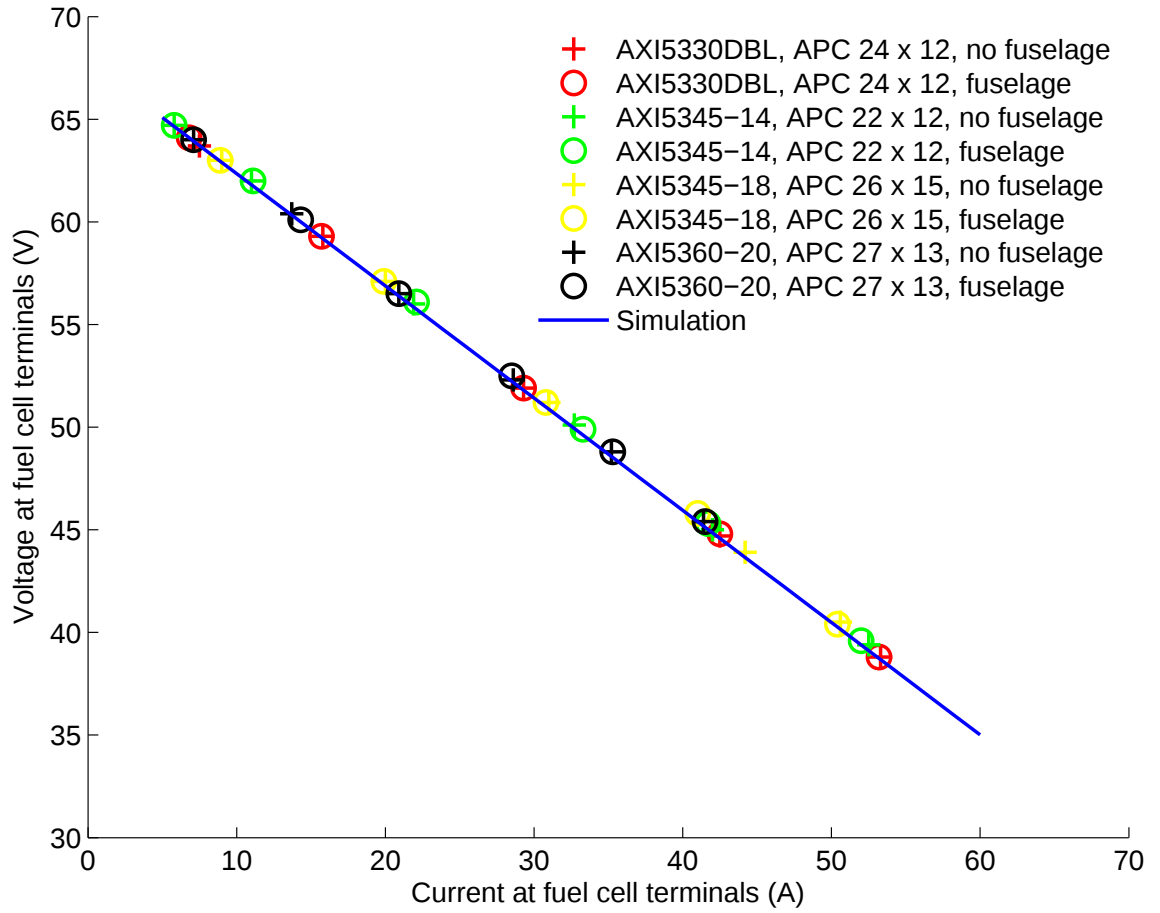


Figure 5.4: Comparison of simulated polarization curve to experimental values for the steady-state SOFC PNNL Model 11 emulator assuming operation in the ohmic region

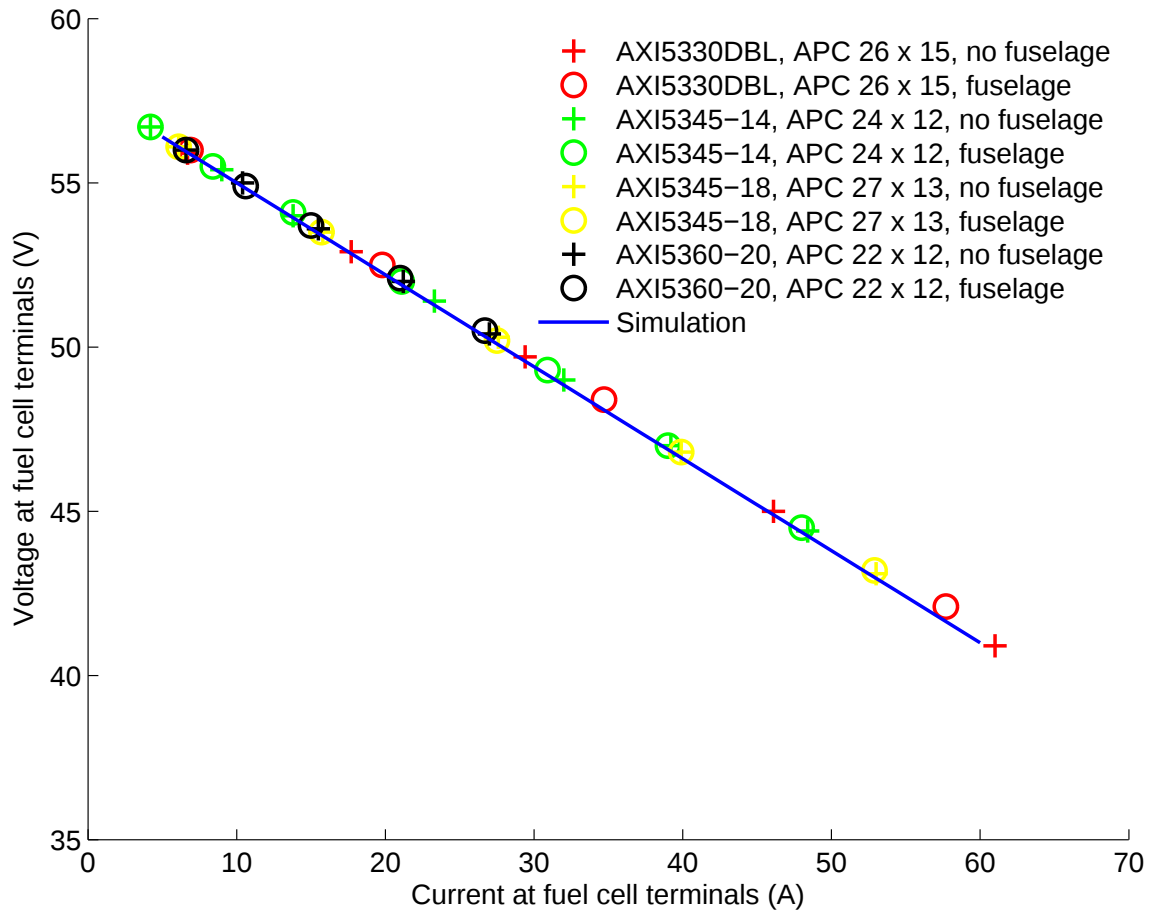


Figure 5.5: Comparison of simulated polarization curve to experimental values for the steady-state SOFC PNNL Model 12 emulator assuming operation in the ohmic region

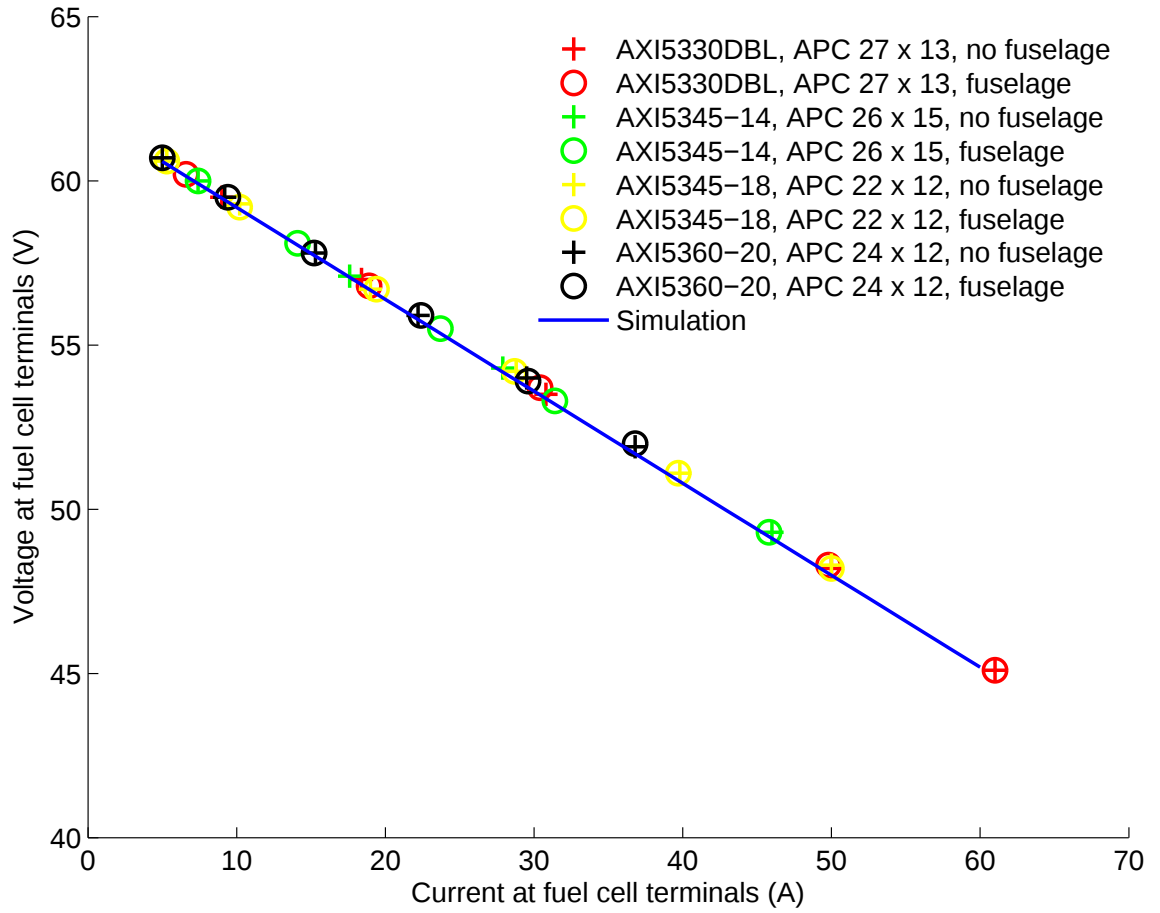


Figure 5.6: Comparison of simulated polarization curve to experimental values for the steady-state SOFC PNNL Model 13 emulator assuming operation in the ohmic region

BLDC Motor Modeling Results

The propeller determines the relationship between motor speed and load torque. If the propeller models used in the simulation program do not accurately describe the propeller performance in the wind tunnel, comparison between simulated motor performance and wind tunnel motor performance is not effective. To eliminate discrepancies between simulated and wind tunnel motor performance caused by inaccuracies in the propeller models, a second order polynomial was fit to the recorded torque and propeller speed values for each test. As indicated in equation 2.13, torque is a function of air density, the propeller's coefficient of power, propeller diameter and propeller speed. Table 2.4 and Figure 2.7(a) show that this coefficient is accurately described as a second order function of the advance ratio, the ratio of velocity and propeller speed (equation 2.11). Assuming constant velocity, C_P becomes a function of propeller speed with the form

$$C_P = \frac{\alpha_2}{n_p^2} + \frac{\alpha_1}{n_p} + \alpha_0 \quad (5.1)$$

Combining this with equation 2.13, and assuming constant ρ , the relationship between τ and ω takes the form

$$\tau = \alpha'_0 \omega^2 + \alpha'_1 \omega + \alpha'_2 \quad (5.2)$$

Thus, fitting simulated models to measured results simply shifts the 2nd order propeller model to match experimental data. Similarly, a 1st order polynomial is fit to the emulator's voltage and current data. This removes any differences in emulator open circuit voltage and resistance from simulated models. For all polynomial fits, the coefficient of determination, R^2 , values were greater than 0.99.

Figures 5.7 through 5.14 show experimental results for each BLDC motor system. Each motor was tested with six combinations of fuel cell models and propellers. The solid lines indicate the simulated relationships between fuel cell voltage and propeller speed, and fuel cell current and motor torque using the method described above. Since simulation variables V_m and I_m are not directly measurable, performance of the controller and motor are lumped together.

Wind tunnel tests show very good correlation to motor models. These tests encompass a variety of power source characteristics and load profiles with the simulation program predicting motor performance in every test reasonably well.

The AXI double 5330/20, AXI 5345/14 and AXI 5345/18 motor models slightly over-predict motor performance. That is, for a given fuel cell current, the simulation program predicts a higher motor torque than is measured. Similarly, for a given motor speed, the fuel cell emulator voltage is lower than the simulated fuel cell voltage. This indicates a lower motor operating efficiency than predicted in simulation and tends to be more predominant for low power operation and with the larger APC propellers. The reduced efficiencies for low power operation is expected as all motors advertise maximum efficiencies when current is in excess of 20 A. Additionally, the low power levels correspond to low duty cycle numbers where switching losses in the motor controller represent a higher percentage of total system losses. The simulation model assumes a lossless controller.

The higher operating efficiencies with the APC 22 x 12 and 24 x 12 propellers was also expected for the AXI 5345/14 and 5345/18 motors. These motors are smaller than the 5360/20 and only rated for use with 22 in. and 24 in. propellers. However, both the AXI double 5330/20 and the AXI 5360/20 are rated for large propellers so higher operating efficiencies with the smaller props is somewhat surprising.

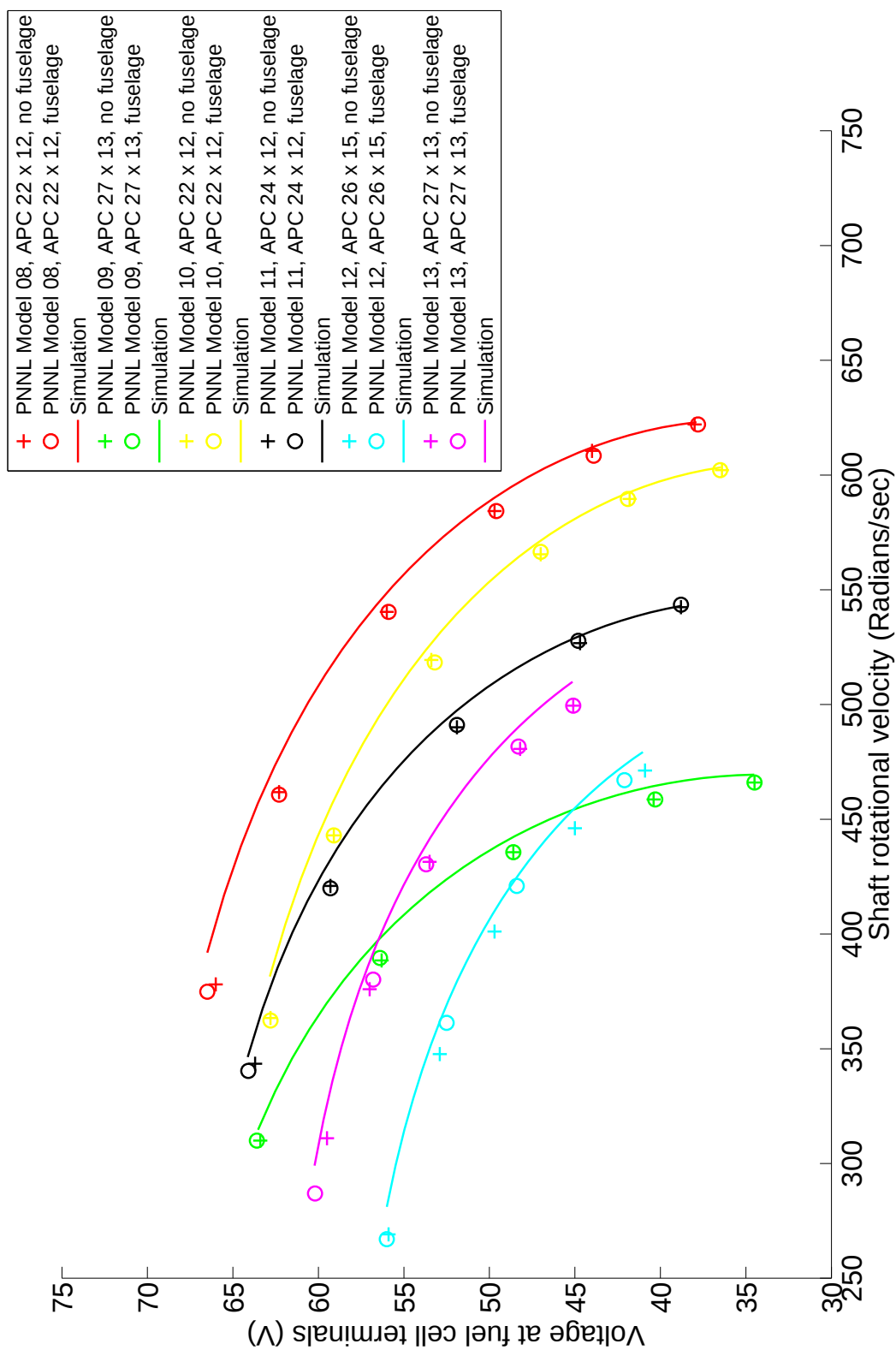


Figure 5.7: Comparison of simulated voltage-speed relationships for the AXI DBL 5330/20 motor to experimental results

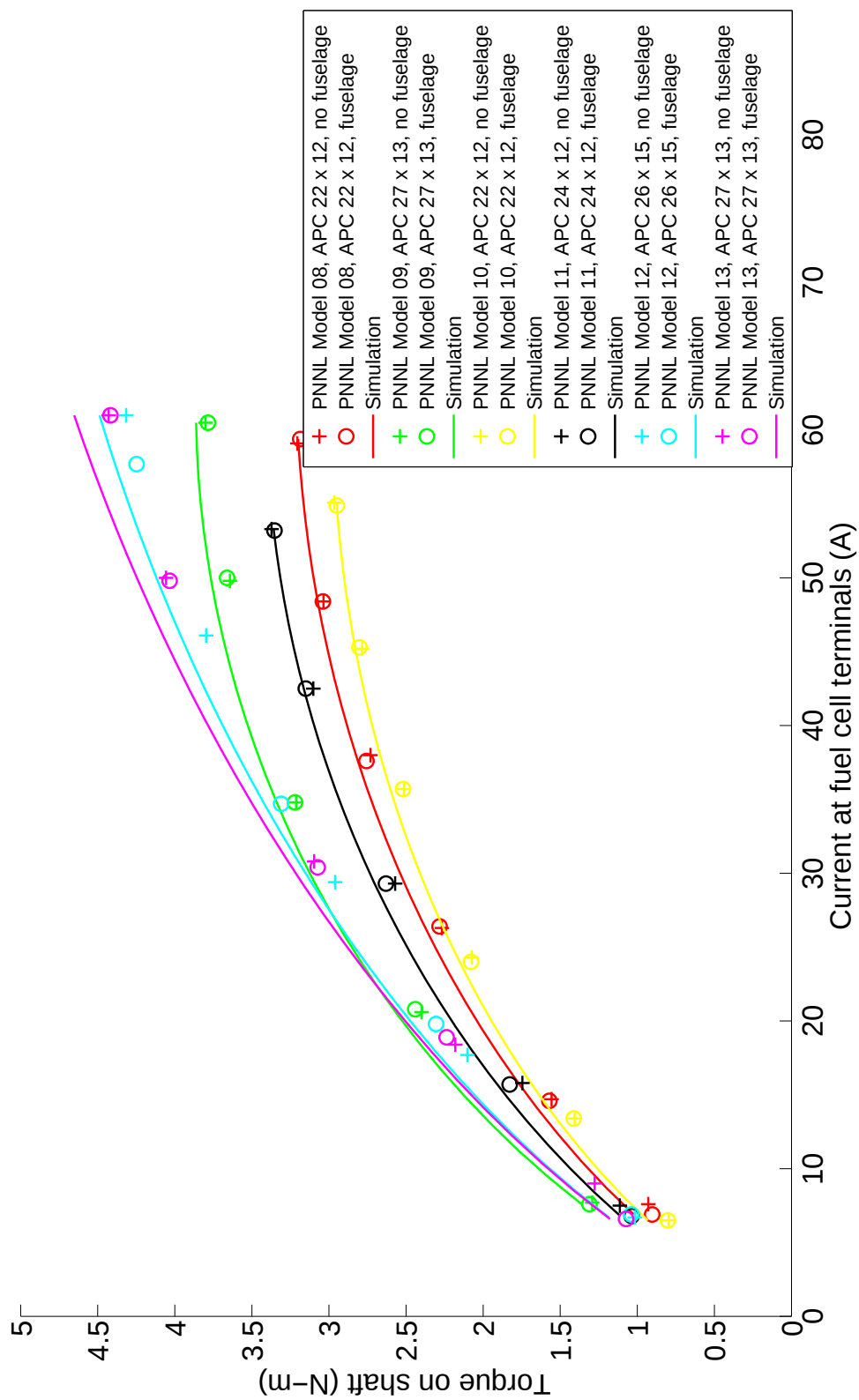


Figure 5.8: Comparison of simulated torque-current relationships for the AXI DBL 5330/20 motor to experimental results

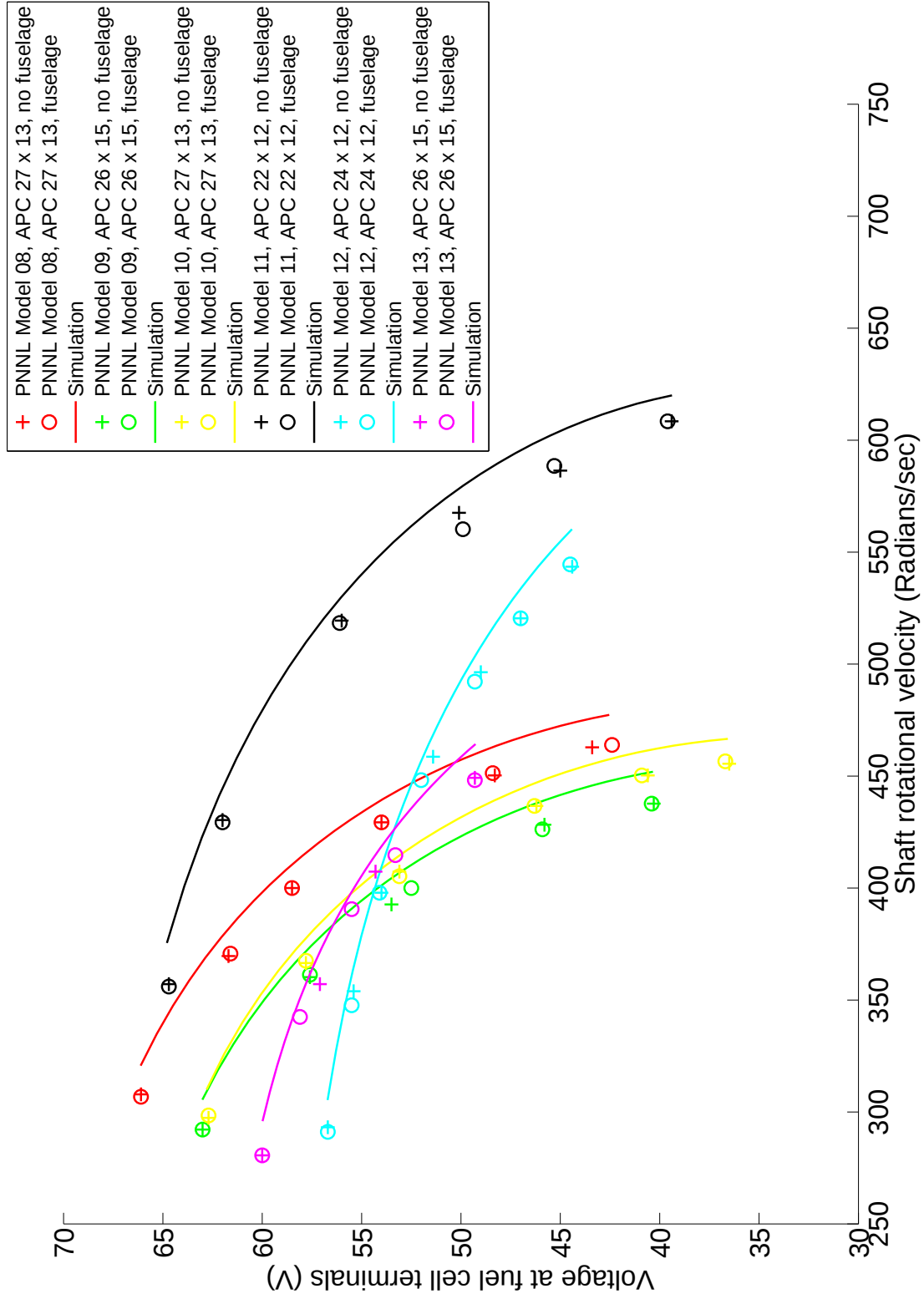


Figure 5.9: Comparison of simulated voltage-speed relationships for the AXI 5345/14 motor to experimental results

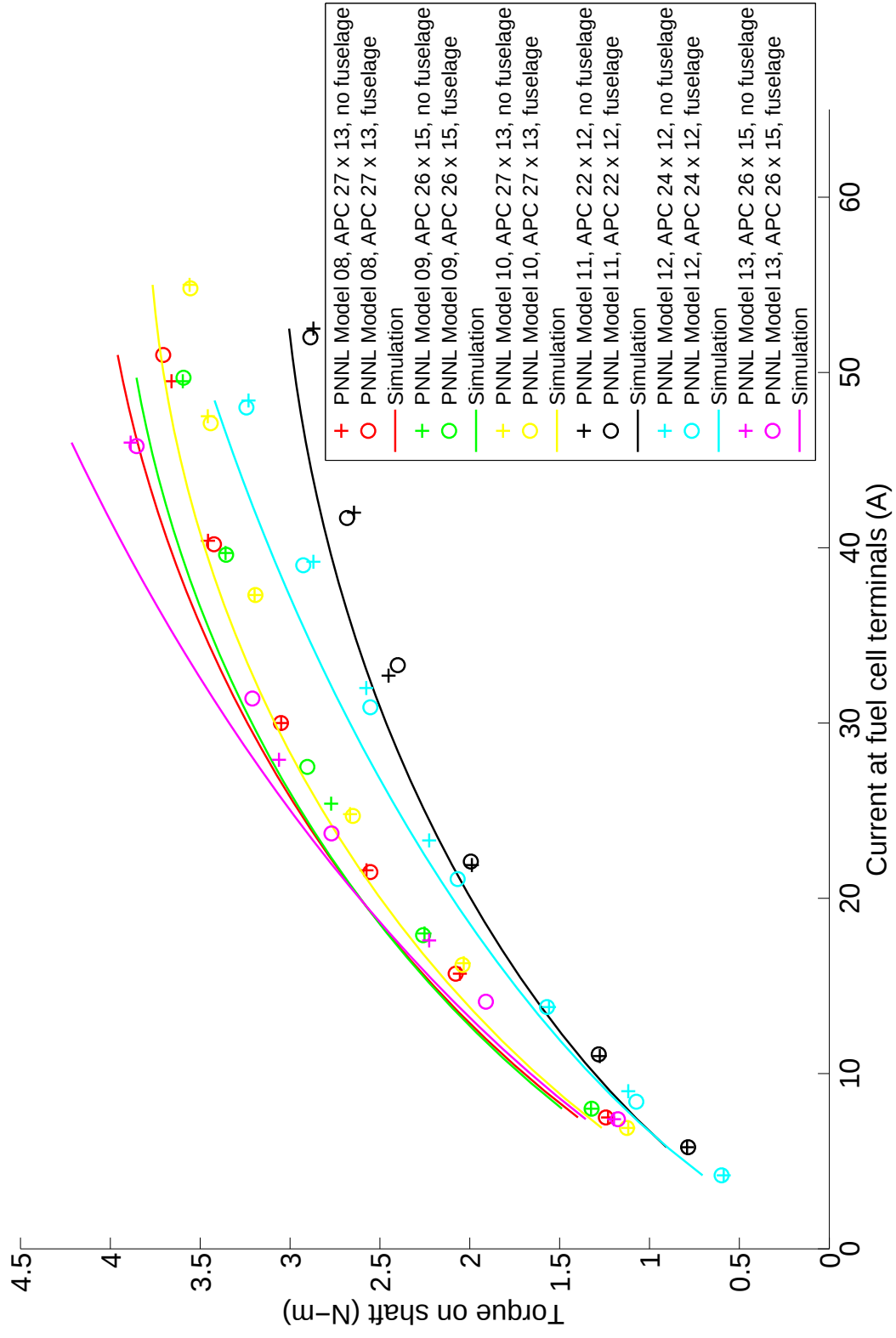


Figure 5.10: Comparison of simulated torque-current relationships for the AXI 5345/14 motor to experimental results

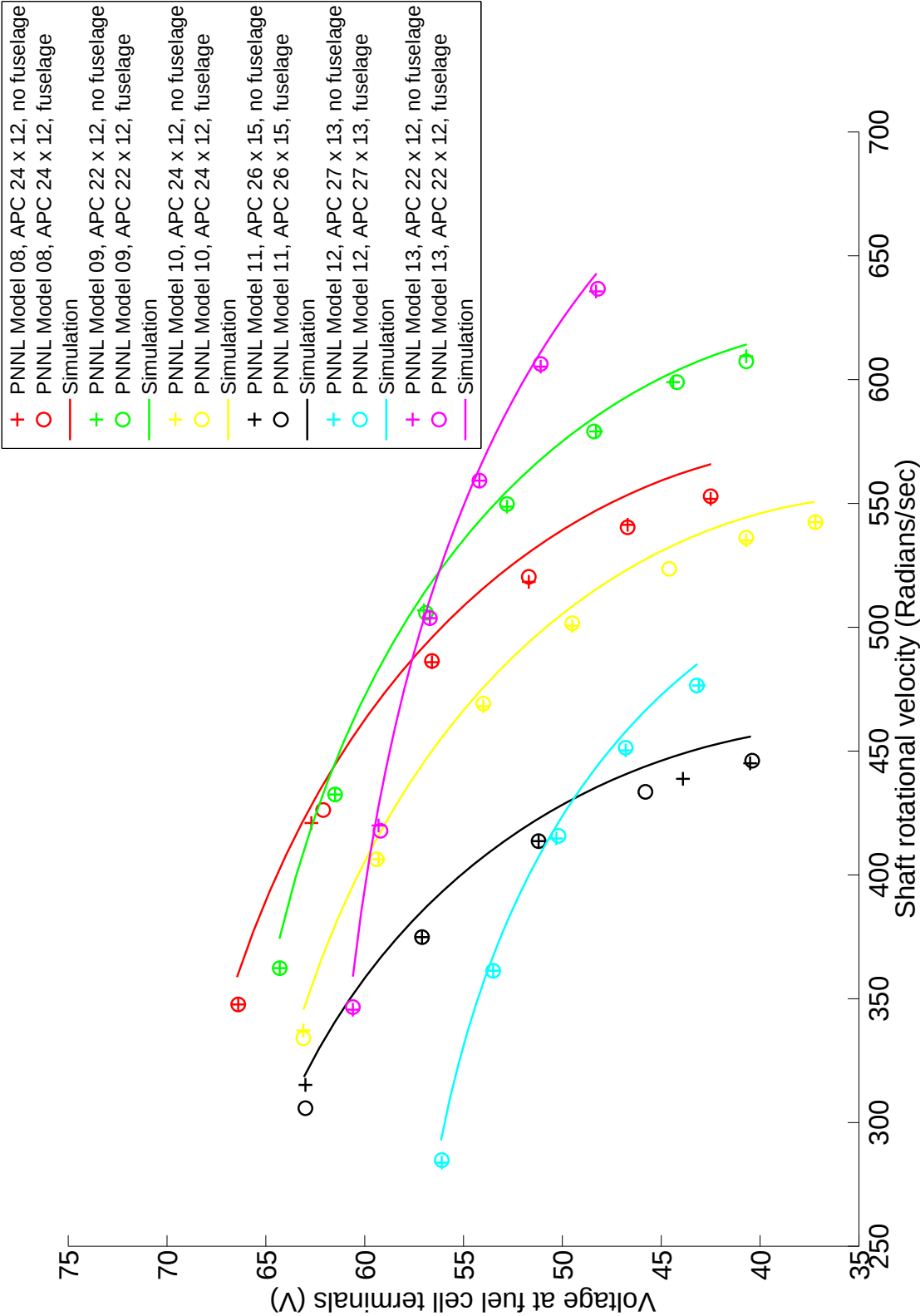


Figure 5.11: Comparison of simulated voltage-speed relationships for the AXI 5345/18 motor to experimental results

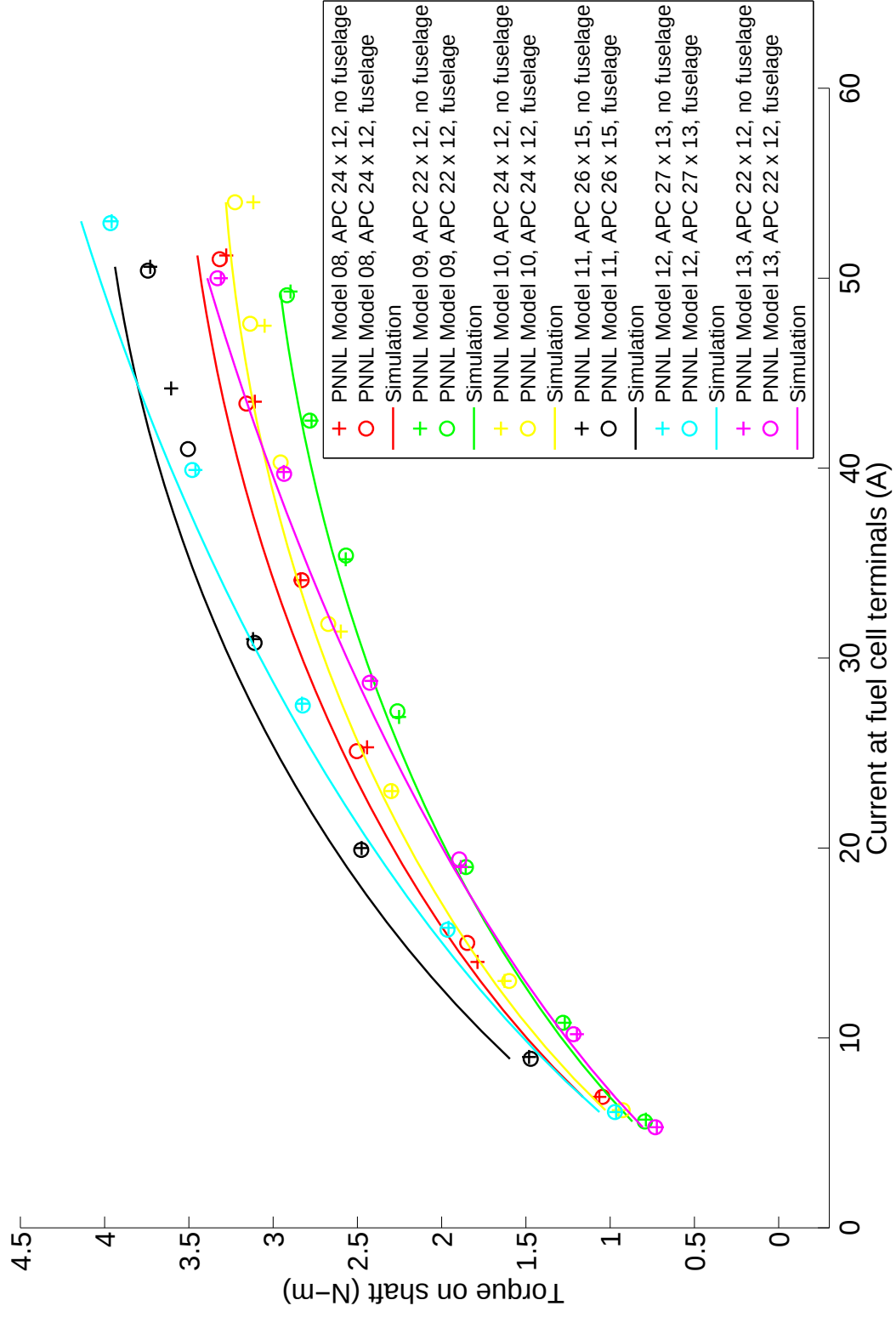


Figure 5.12: Comparison of simulated torque-current relationships for the AXI 5345/18 motor to experimental results

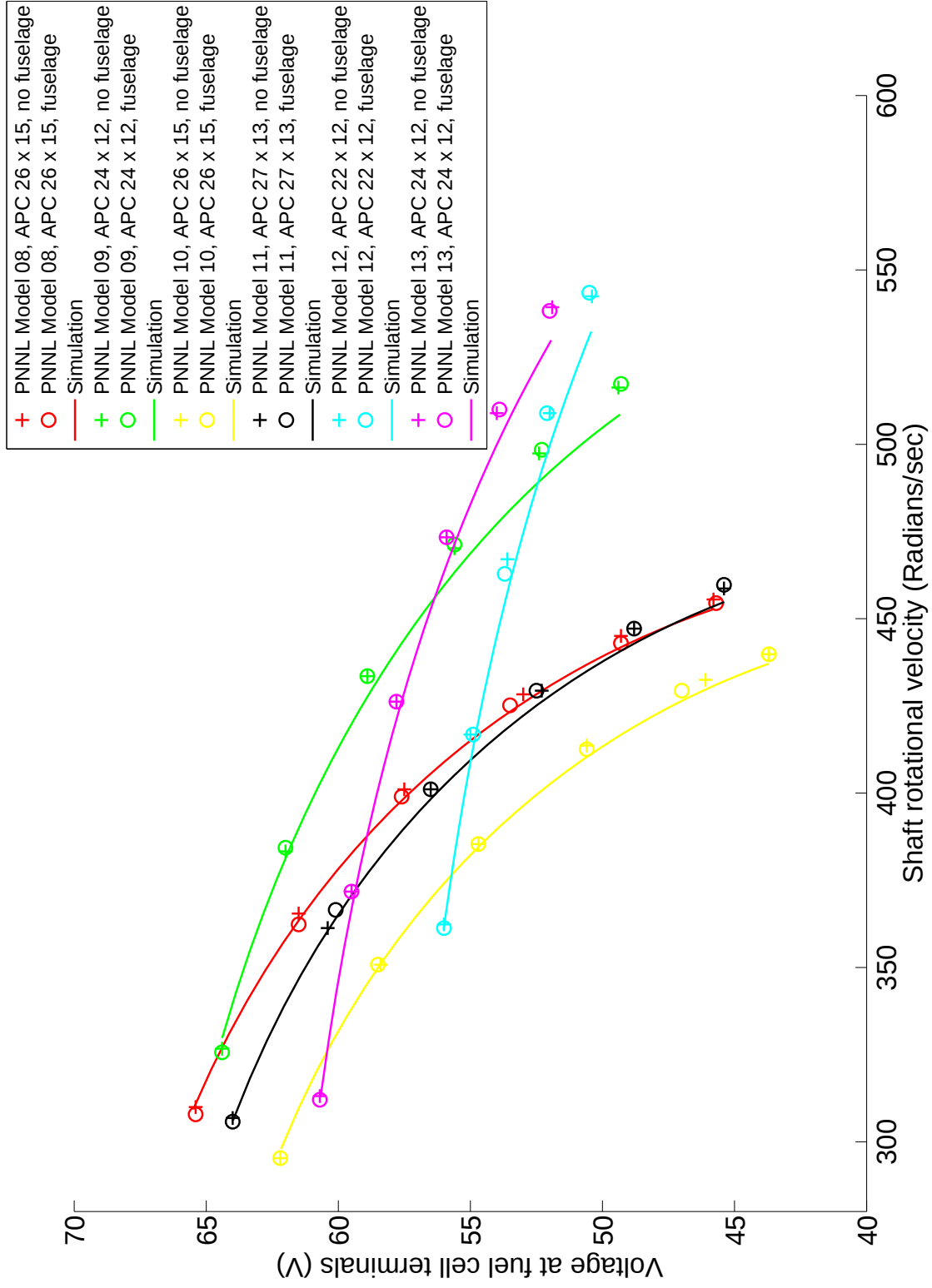


Figure 5.13: Comparison of simulated voltage-speed relationships for the AXI 5360/20 motor to experimental results

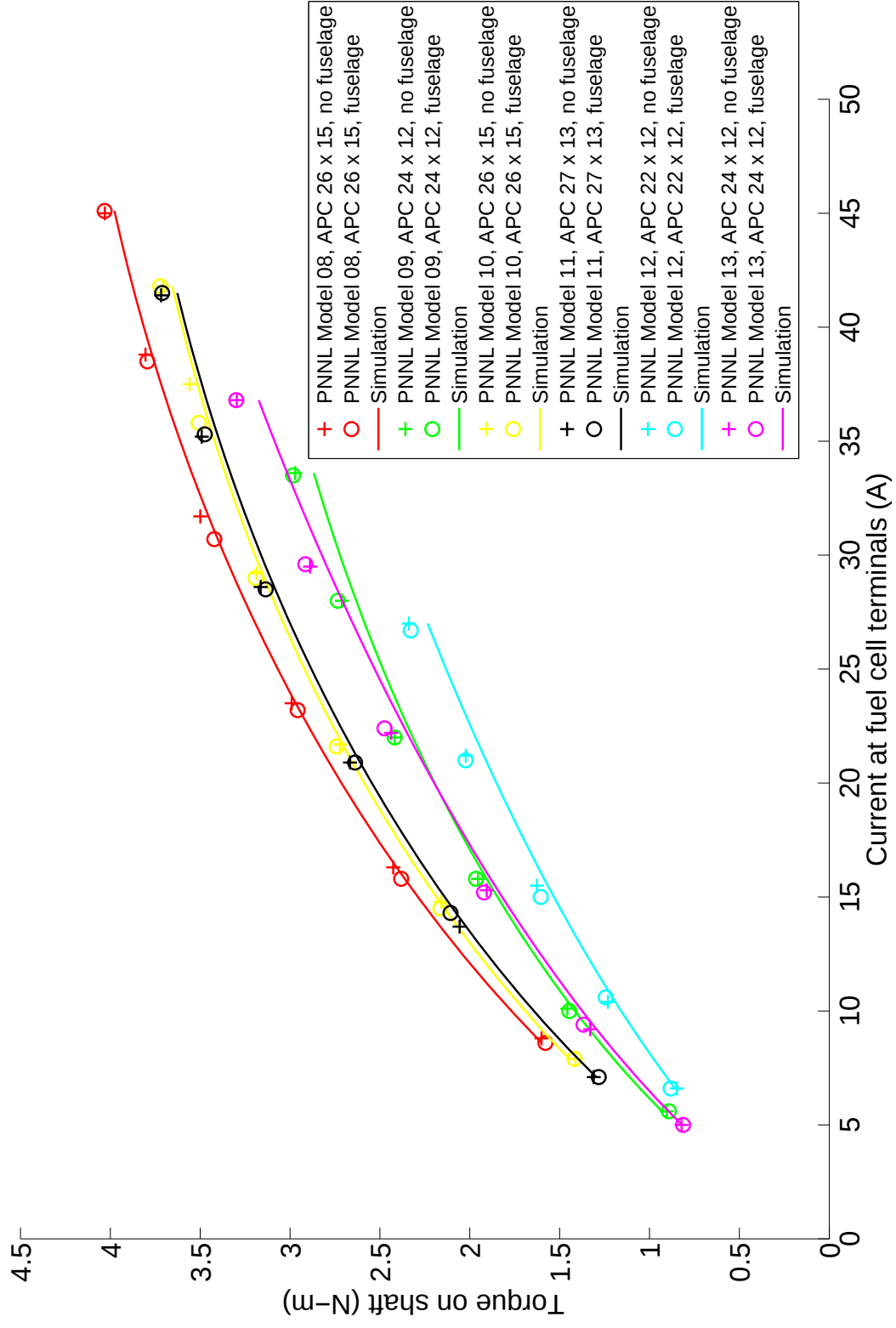


Figure 5.14: Comparison of simulated torque-current relationships for the AXI 5360/20 motor to experimental results

The AXI 5360/20 model under predicts motor operation, though only slightly. It is important to note however, that even with a maximum duty ratio of 1.0, this motor cannot reach the PNNL dictated operation points when operating with any of the studied propellers. Thus, the motor cannot turn the propeller at speeds required for adequate thrust. This is reflected in comparing propeller speeds of the farthest most right measured operating points of Figure 5.13 to those of Figures 5.7, 5.9 and 5.11.

Propeller Modeling Results

Equations, 2.12, 2.13 and 2.14 show that propeller torque and thrust are functions of air density ρ , their respective dimensionless coefficients (C_P and C_T), propeller diameter L and propeller rotational speed n_p . Coefficients C_P and C_T are functions of advance ratio, J , which itself is a function of simulated craft velocity, S , L and n_p as explained in Table 2.4 and equation 2.11. Both ρ and S can vary between and during propeller tests. Therefore, the most effective method for comparing measured data to propeller models is to calculate J , C_P and C_T for all measured operating points. Figures, 5.15 through 5.18 show these results.

The calculated C_P for the APC 22 x 12, 24 x 12 and 27 x 13 propellers show fairly good correlation to APC provided propeller models. These values tend to be slightly higher than model values, but follow the same trend as a function of J . The calculated C_P values for the APC 26 x 15 propeller differ significantly from the model. C_P can be thought of as a measure of power required to turn a propeller at a specific advance ratio. Compared to measured results, the simulation model grossly over predicts the amount of power required for the APC 26 x 15 to spin. This is why the simulation program predicts much lower thrust values for propulsion systems operating with this propeller (see Appendix A for the full set of simulation results). Because measured C_P

values for the other propellers correlate well with propeller models and the observed C_P values for the 26 x 15 prop are comparable to those of the other propellers, the disparity between measured C_P and the model is thought to be due to model error.

In all cases, the observed values of C_T exceed model values for low J where propeller speeds are high. This is largely due to a wind tunnel blockage effect discussed in [20, 21]. In a limited air space environment such as a wind tunnel, higher static pressures build aft of the propeller than upstream of the propeller. This exaggerates thrust measurements with the effect more prominent at high propeller speeds.

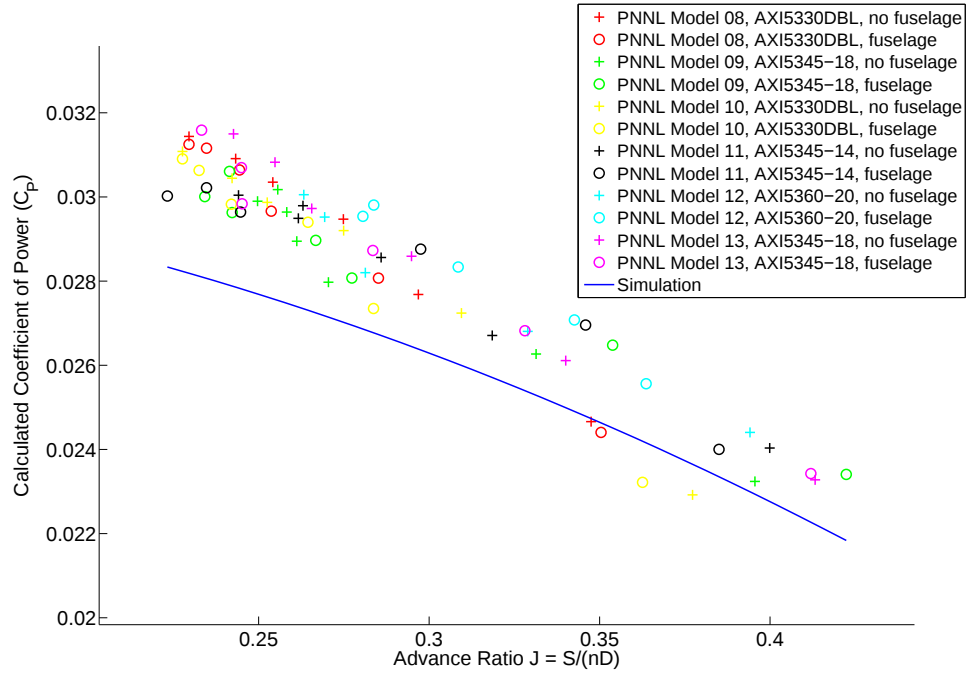
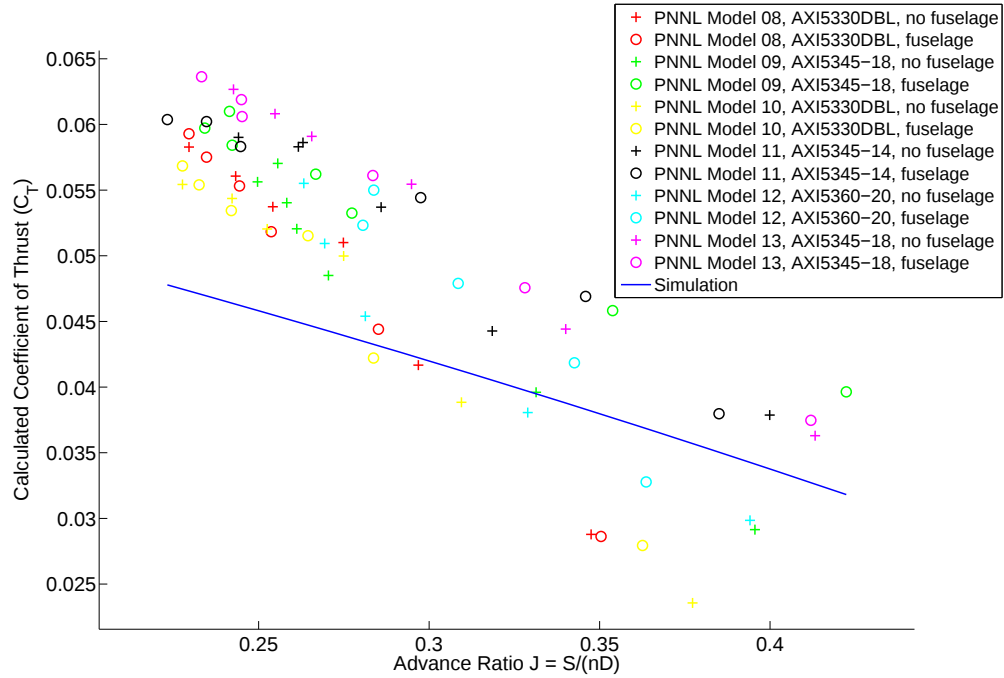
(a) Coefficient of Power (C_P)(b) Coefficient of Power (C_T)

Figure 5.15: Comparison of simulated C_P and C_T values with experimental results for the APC 22 in. x 12 in. propeller

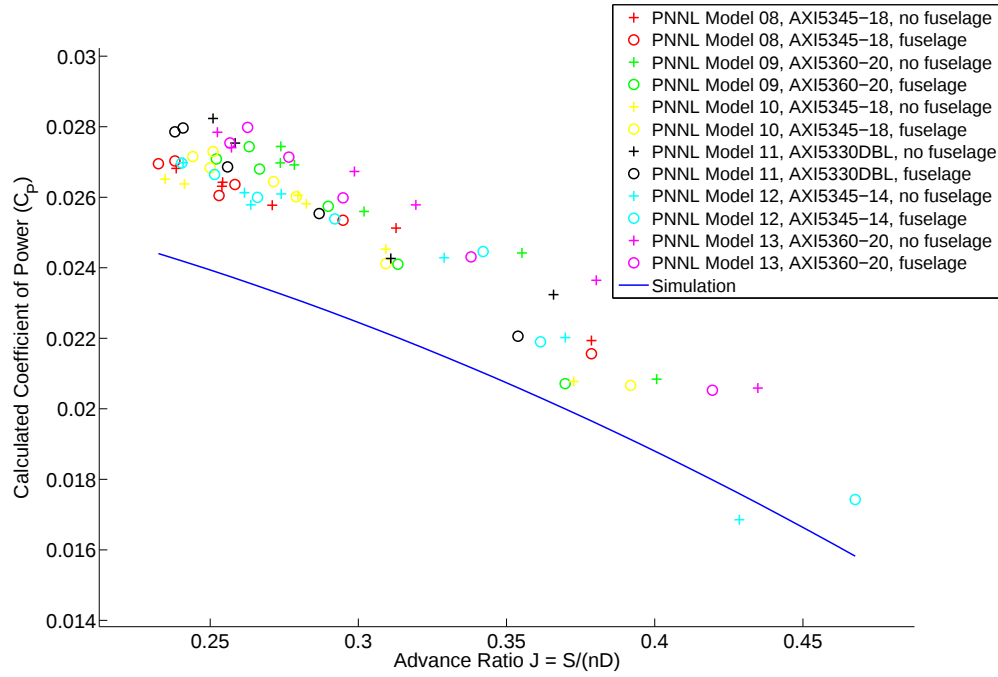
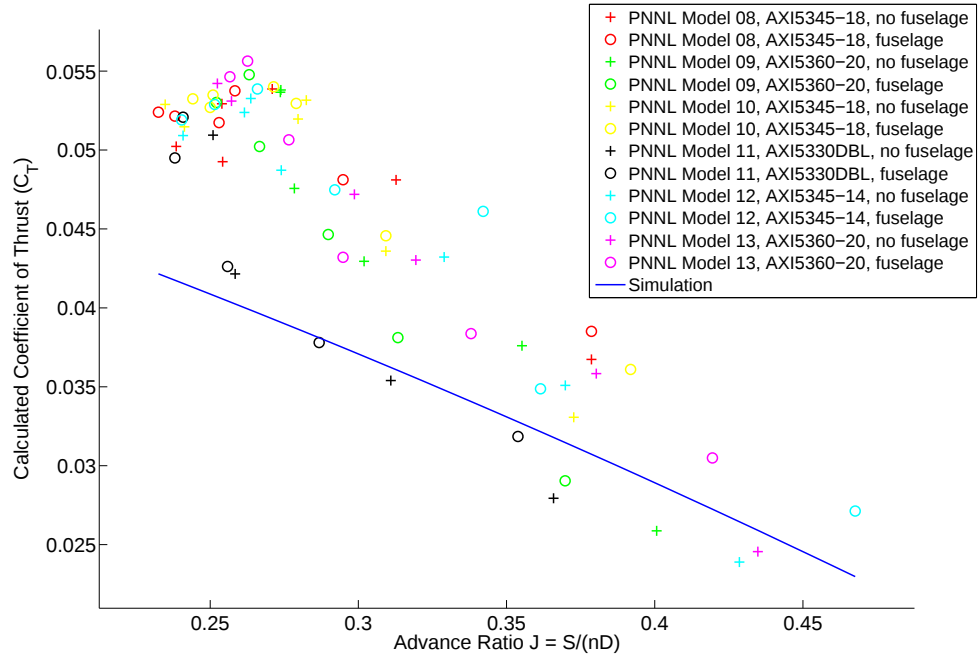
(a) Coefficient of Power (C_P)(b) Coefficient of Power (C_T)

Figure 5.16: Comparison of simulated C_P and C_T values with experimental results for the APC 24 in. x 12 in. propeller

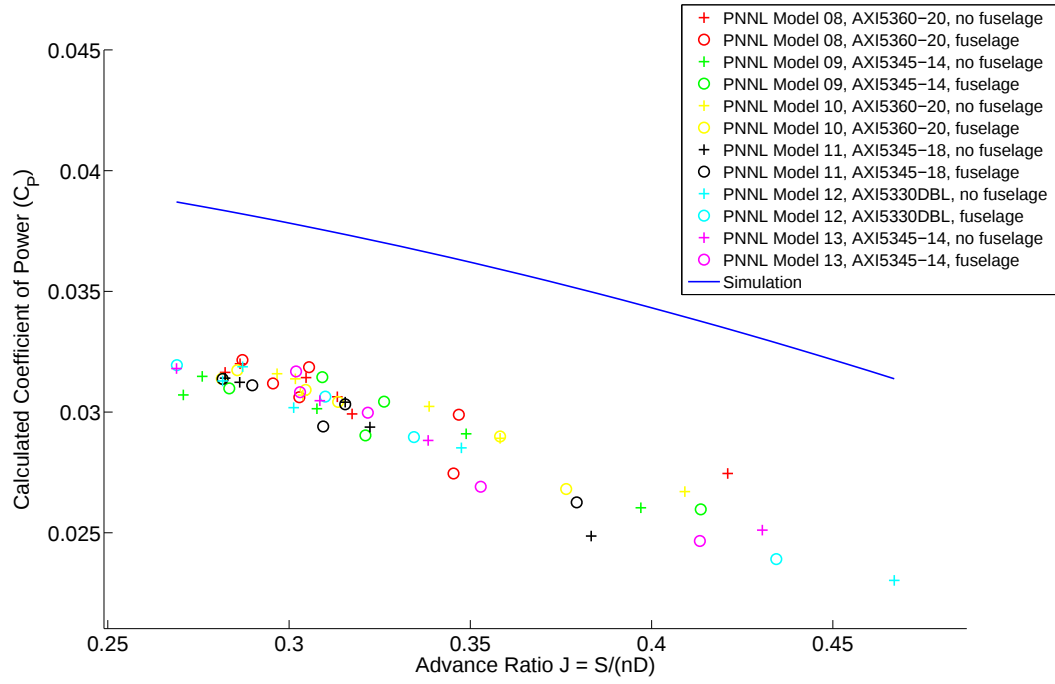
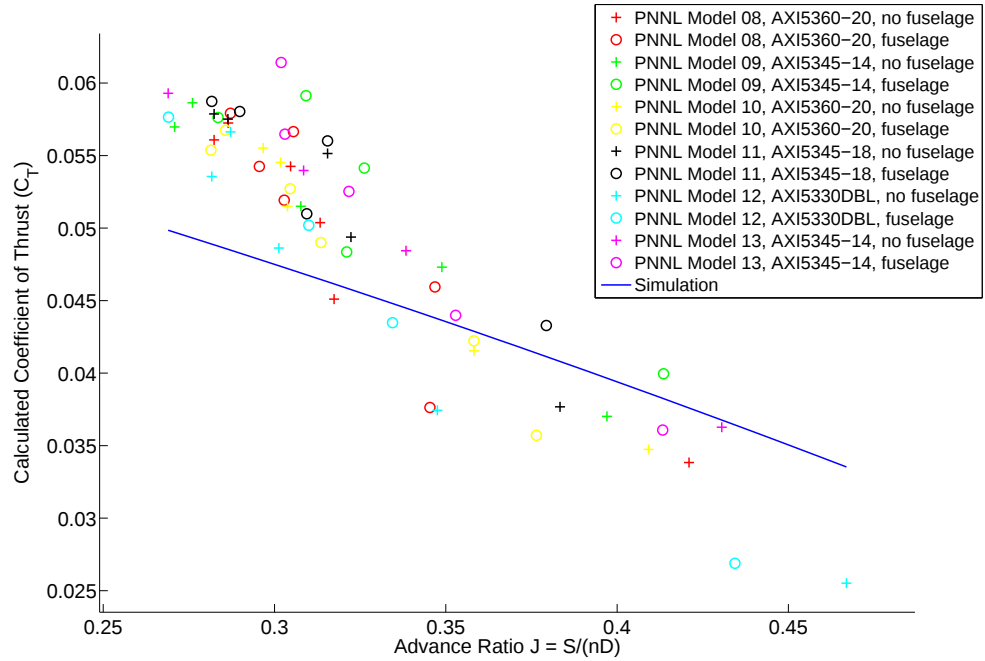
(a) Coefficient of Power (C_P)(b) Coefficient of Power (C_T)

Figure 5.17: Comparison of simulated C_P and C_T values with experimental results for the APC 26 in. x 15 in. propeller

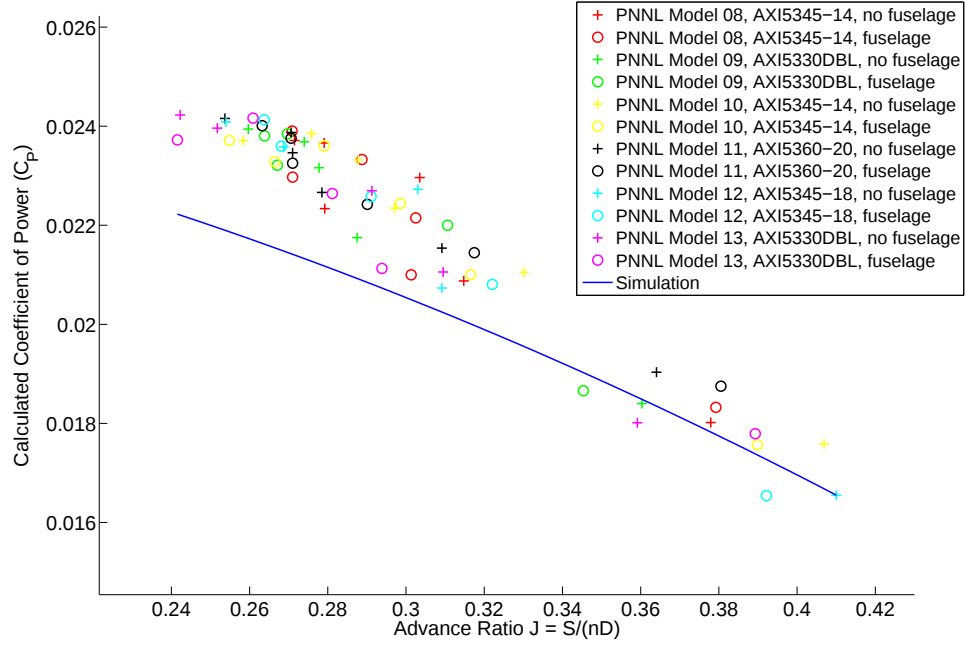
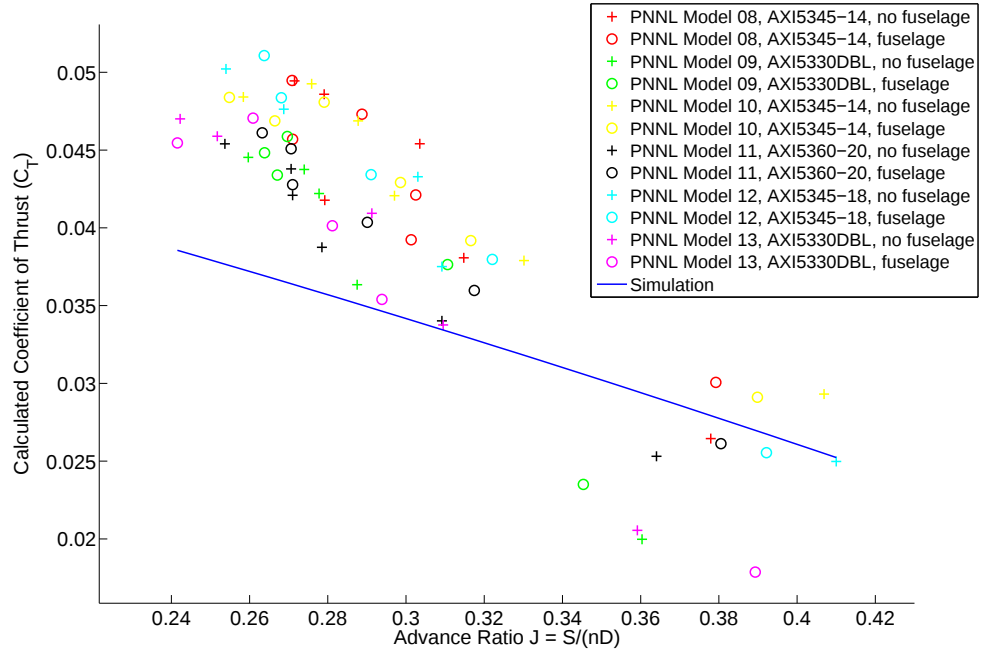
(a) Coefficient of Power (C_P)(b) Coefficient of Power (C_T)

Figure 5.18: Comparison of simulated C_P and C_T values with experimental results for the APC 27 in. x 13 in. propeller

Measurement Uncertainty

In the wind tunnel experiments, there are two primary mechanisms for measurement uncertainty. First, as was mentioned in the Instruments section of the previous chapter, each instrument has an associated amount of measurement uncertainty. Second, the turbulent air flow in the wind tunnel causes stochastic fluctuations in air velocity, which causes stochastic fluctuations in all data measurements. Table 5.1 below gives confidence intervals (i.e. 95% of measurements within the interval) for the directly measurable quantities.

Table 5.1: The uncertainty in measurements is due to a combination of instrument limitations and system noise primarily caused by turbulent air flow through the wind tunnel. This table lists the 95% confidence intervals for each measured quantity.

Measurement	Confidence Interval
Wind Tunnel Air Velocity (S)	± 2 m/s
Fuel Cell Emulator Current (I_c)	± 0.2 A
Fuel Cell Emulator Voltage (V_c)	± 0.3 V
Duty Cycle (D)	± 0.005
Motor/Propeller Speed (ω)	± 1 rad/s
Motor Torque (τ)	± 0.1 N-m
Propeller Thrust (T)	± 3 N

For the fuel cell emulator and BLDC system results, error analyses of collected data are determined directly from the confidence intervals of table 5.1. This is because the data presented in their analyses are all directly measurable quantities. The propeller analysis is more complicated as results are expressed in calculations of C_T and C_P as functions of J . These calculations require two or more measurements each with an associated amount of uncertainty. To determine the total uncertainty in the calculated values of C_T , C_P and J , the uncertainty analysis method presented in [22] is used. In this method, the uncertainty in the calculated result F where F is a

function of independent variables, $x_1, x_2, \dots, x_n$, each with an associated measure of uncertainty, $w_1, w_2, \dots, w_n$, is determined by the formula

$$w_F = \left(\left(\frac{\partial F}{\partial x_1} w_1 \right)^2 + \left(\frac{\partial F}{\partial x_2} w_2 \right)^2 + \dots + \left(\frac{\partial F}{\partial x_n} w_n \right)^2 \right)^{1/2} \quad (5.3)$$

Using the confidence intervals of table 5.1 as the measures of uncertainty, confidence intervals for each calculated value of J , C_P and C_T are found. These results are included in Appendix B along with the calculated values of J , C_P and C_T . Noting these results, we see that the variability in the operation points seen in the propeller results, i.e. figures 5.15 through 5.18 is easily explained. First, primarily due to turbulent air flow, J is found to have confidence intervals ranging from ± 0.04 to ± 0.07 with the larger intervals corresponding to larger J . This indicates that data points shown in figures 5.15 through 5.18 could vary fairly significantly along the horizontal axis, especially for higher values of J . Similarly, C_T and C_P have relatively large confidence intervals also corresponding to higher values of J . This is primarily due to inherent uncertainty in instrument measurements. High values of J correspond to low propeller speeds, and thus, small measurements of thrust and torque. The inherent inaccuracies of the Cooper LXT-920 load cell are significant in magnitude compared to the thrust and torque values recorded for these operation points. Thus, as is reflected in the figures, calculated values of C_T and C_P show large variances especially for high values of J .

Despite these variations, the general trends of C_P and C_T as functions of J match model expectations. Additionally, little appreciable difference in propeller performance is seen between tests with and without the mock fuselage installed. These results give some confidence that component models (with the exception of the C_P values for the APC 26 x 15 propeller) are accurate.

It is important to note that this error analysis only serves to quantify error present in data measurements caused by measurement uncertainty. Other mechanisms of error such as the wind tunnel blockage effect mentioned earlier cause offset deviations in measured quantities from model predictions. Further, this error analysis assumes variable uncertainties to be independent, which is obviously not the case for the stochastic fluctuations in all data measurements caused by turbulent air flow. Still, the results of the error analysis are consistent with the number of significant digits presented in data tables of Appendix B and provides further insight into the variability seen in wind tunnel testing.

CONCLUSION

In this thesis, a physically-based model for design and optimization of a fuel cell powered UAV electric propulsion system comprised of a solid oxide fuel cell providing power, a brushless DC motor and controller, and a propeller was presented. The individual component models were integrated into a simulation program which used the MATLAB command `fsolve()` to numerically find specific propulsion operating points. A graphical procedure using this simulation program was introduced that allows rapid assessment and selection of design choices, including fuel cell characteristics and hybridization with multiple sources. Experimental results from wind tunnel tests provided validation of the component models.

In addition to providing insight into design choices, the graphical presentation of simulation results such as Figure 3.1 proved to be very effective for coordinating the efforts of multiple groups involved in building a fuel cell / electric propulsion system. Stack designers could immediately appreciate the implications of increasing the height of the stack or changing cell thickness, simply by sketching a new fuel cell curve on the plot. Further, the effect of power source hybridization or alternate power electronic topologies can be displayed on the same graph by adding the associated curves to the plot as in Figure 3.3. Finally, the implications of design changes in the fuel cell / electric propulsion are immediately apparent to the air frame design team.

Future Work

There are a couple remaining concerns and important goals for future work in this project. Though wind tunnel test results give some confidence that a UAV utilizing a propulsion system designed with the simulation program will fly, variations

in measured propeller performance from model values exist. Further, wind tunnel air flow velocities measure only around 40% of specified UAV velocity so propulsion system performance at higher velocities must be extrapolated from these experimental results. To alleviate remaining concerns, it is recommended that propeller tests take place in a fully calibrated wind tunnel such as the Kirsten Wind Tunnel at the University of Washington. The working section of this wind tunnel is 2.4 m x 3.7 m in cross-sectional area which should significantly reduce the wind tunnel blockage effect described in chapter five. Additionally, the wind tunnel's low turbulence intensity factor would reduce measurement fluctuations and with maximum velocities of 90 m/s, the wind tunnel easily meets UAV velocity specifications.

For future studies, further design investigations should center around dynamic models, which can be combined with aircraft dynamic models for a fully integrated UAV simulation program. Also, investigation into a hybrid power source is required to increase the operation range of the propulsion system as illustrated in Figure 3.3. In addition to increasing maximum propulsion system thrust, a second power source could also be utilized to protect the fuel cell from exposure to severe high-current loading and load transients.

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APPENDICES

APPENDIX A

SIMULATION RESULTS

Appendix A contains the full set of simulation results for all combinations of propulsion system components used in this study as indicated by Figure 2.1. The SOFC stack models and their associated parameters are listed in Table 2.2, the BLDC motors in Table 2.3, and the propellers in Table 2.4. The blue line in the figures below represent the linearized fuel cell stack, the dashed black lines indicate constant thrust values, and the red box defines a family of voltage/current curves for the motor and propeller combination. The physically based models used in the simulation program and the simulation program itself are described in chapters two and three, respectively. In all cases, the motor controller was treated as a lossless component. Air density was assumed to be 1.2 kg/m^3 and cruising velocity, 31.3 m/s .

Solid Oxide Fuel Cell Model 8

AXI 5330 DBL BLDC Motor

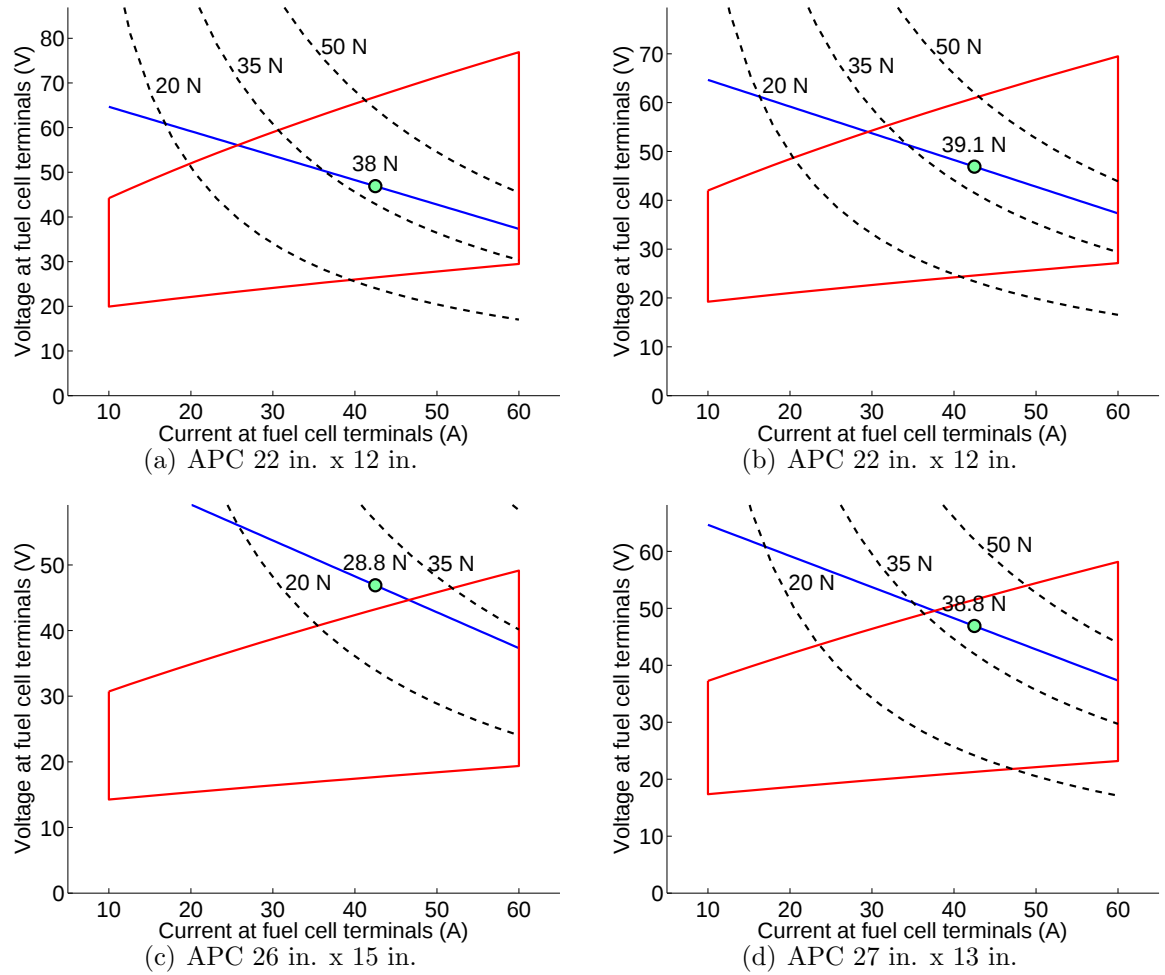


Figure A.1: Simulation results for the propulsion system with components: SOFC Model 8, AXI 5330 DBL Motor, and Jeti Spin 99 Controller. The propeller is indicated below each figure.

AXI Motor 5345-14 BLDC Motor

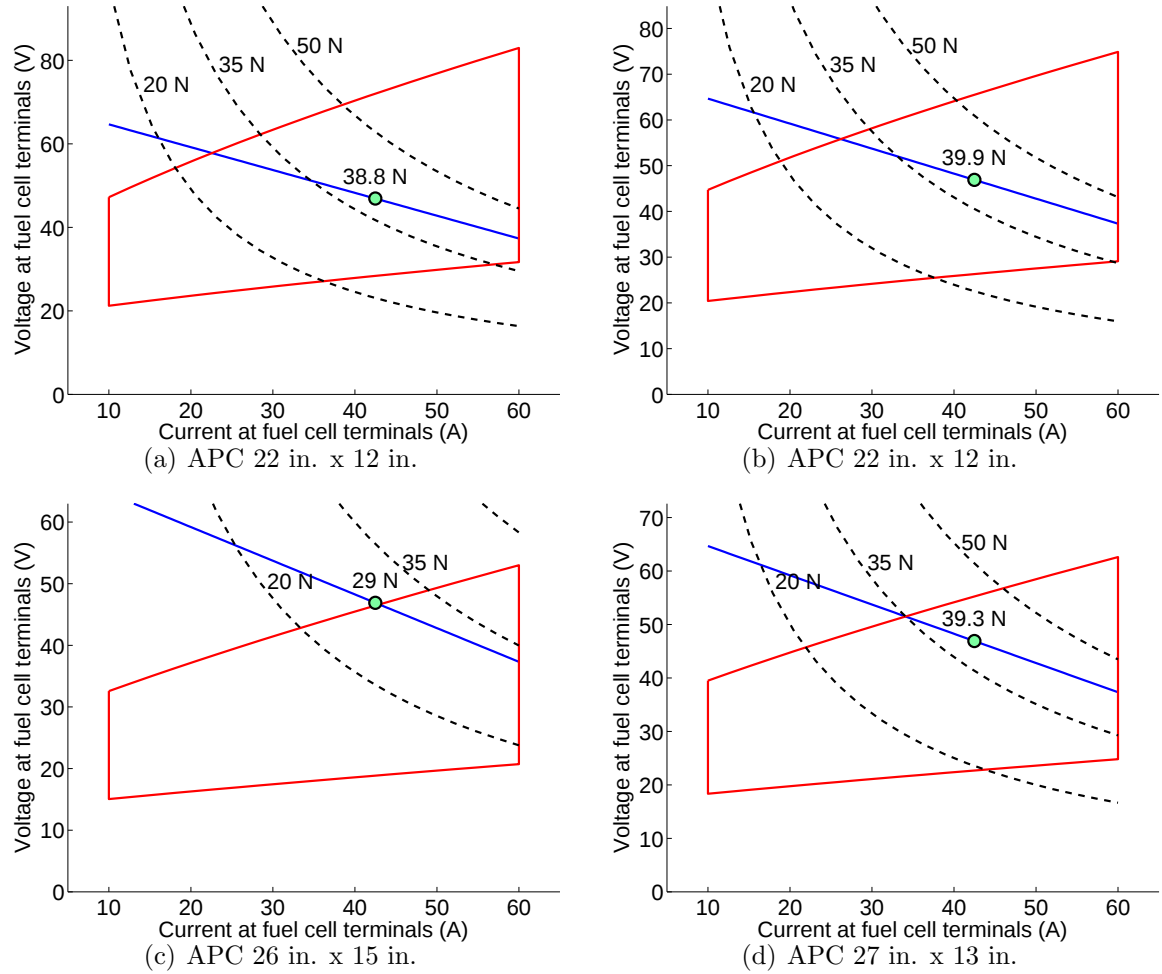


Figure A.2: Simulation results for the propulsion system with components: SOFC Model 8, AXI 5345-14 Motor, and Jeti Spin 99 Controller. The propeller is indicated below each figure.

AXI Motor 5345-18 BLDC Motor

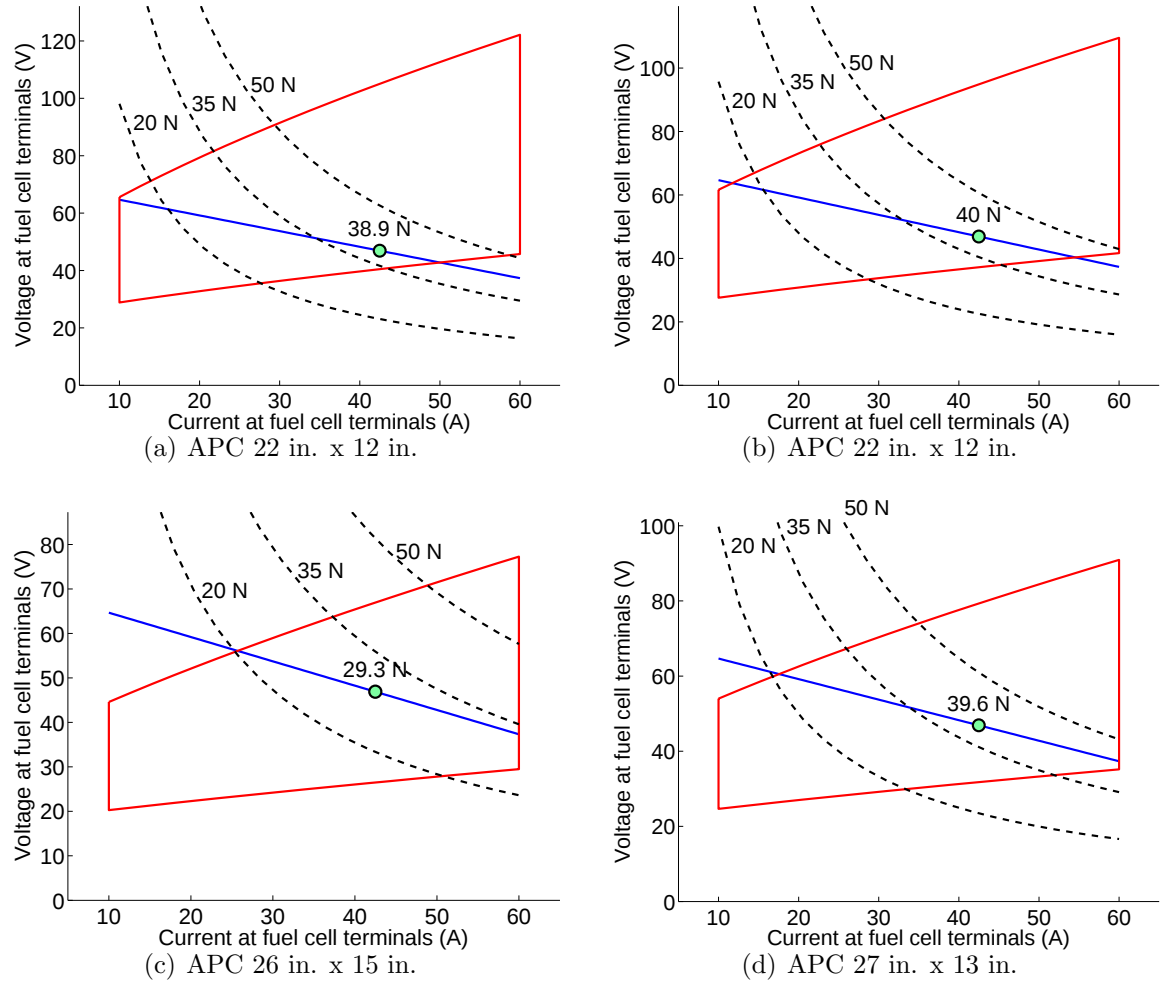


Figure A.3: Simulation results for the propulsion system with components: SOFC Model 8, AXI 5345-18 Motor, and Jeti Spin 99 Controller. The propeller is indicated below each figure.

AXI Motor 5360 BLDC Motor

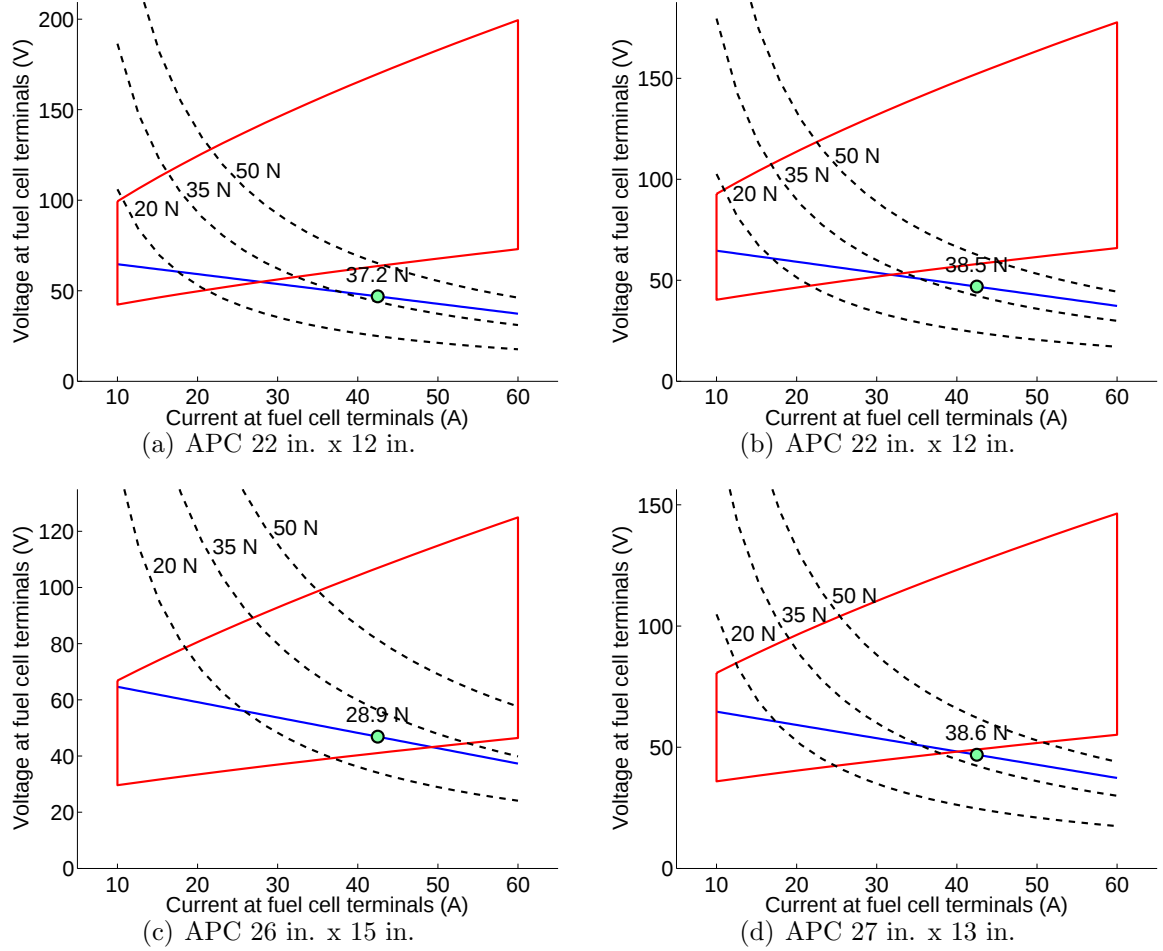


Figure A.4: Simulation results for the propulsion system with components: SOFC Model 8, AXI 5360 Motor, and Jeti Spin 99 Controller. The propeller is indicated below each figure.

Solid Oxide Fuel Cell Model 9

AXI 5330 DBL BLDC Motor

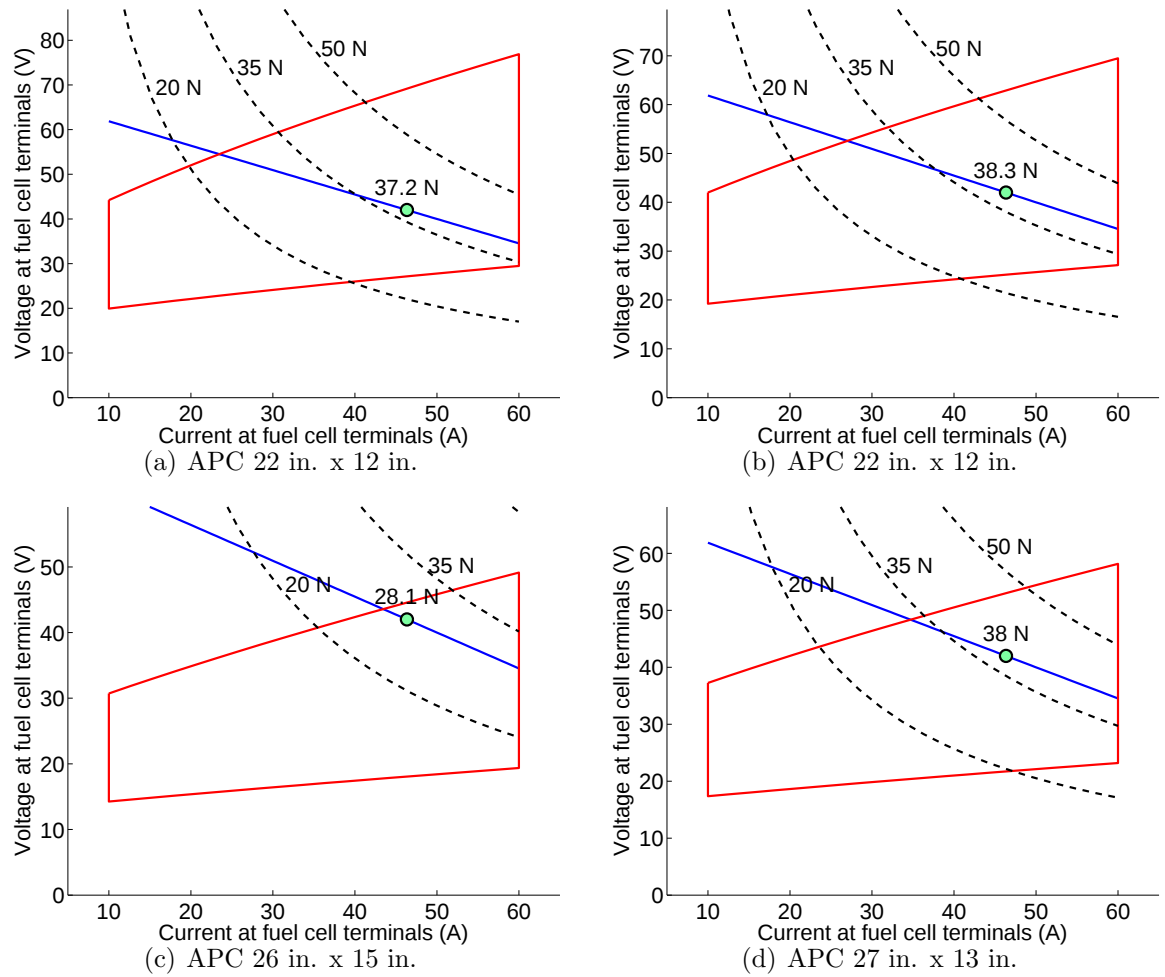


Figure A.5: Simulation results for the propulsion system with components: SOFC Model 9, AXI 5330 DBL Motor, and Jeti Spin 99 Controller. The propeller is indicated below each figure.

AXI Motor 5345-14 BLDC Motor

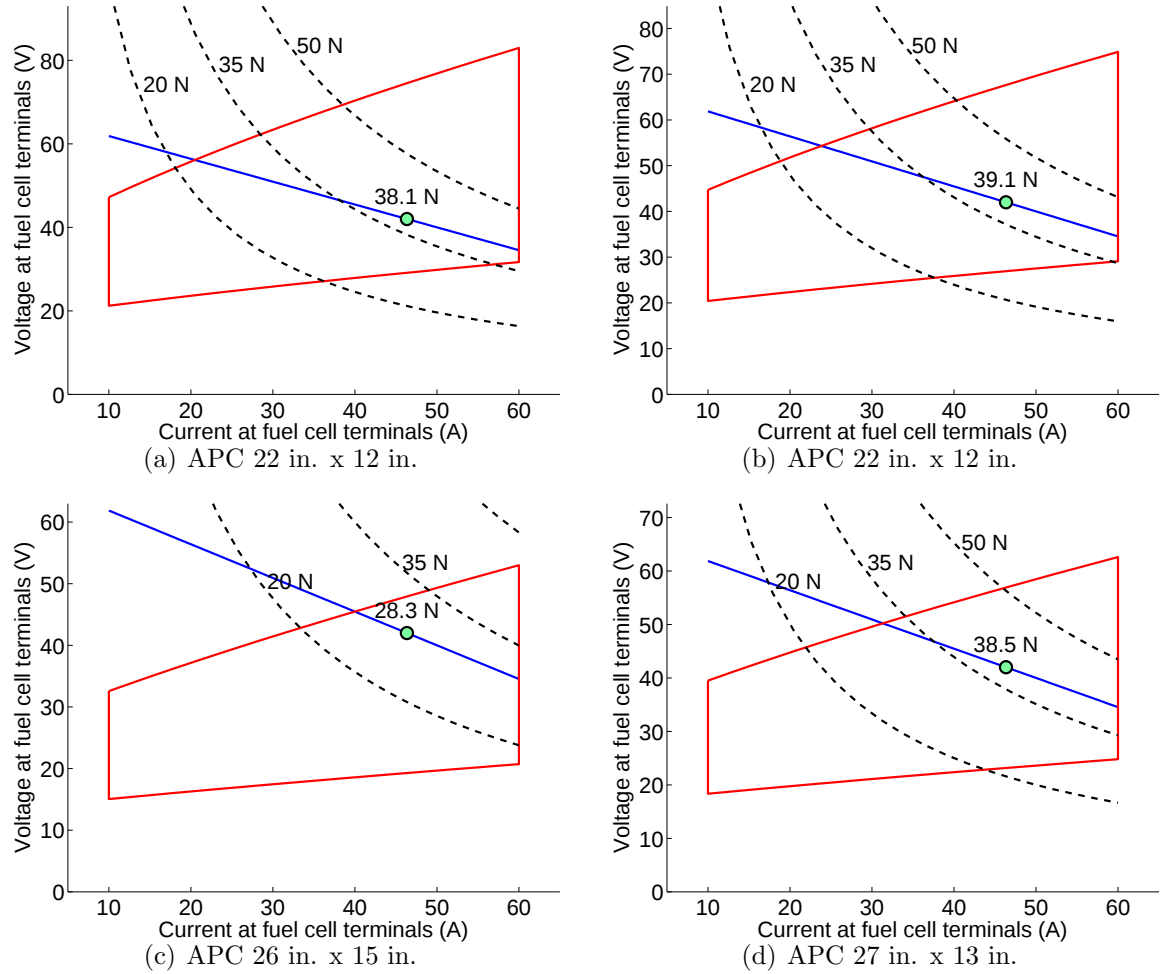


Figure A.6: Simulation results for the propulsion system with components: SOFC Model 9, AXI 5345-14 Motor, and Jeti Spin 99 Controller. The propeller is indicated below each figure.

AXI Motor 5345-18 BLDC Motor

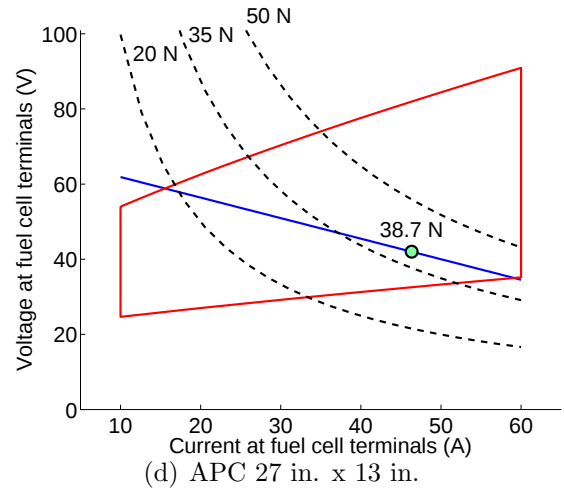
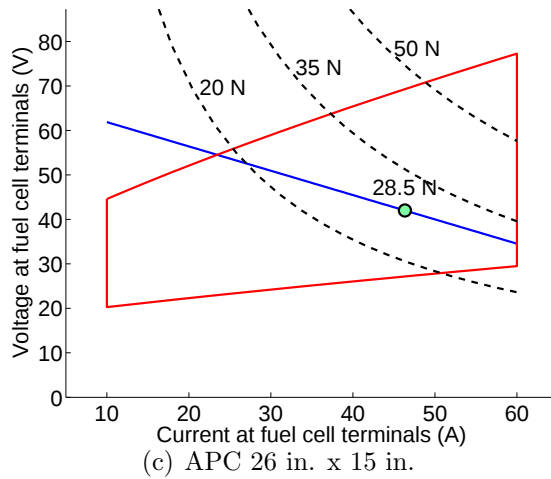
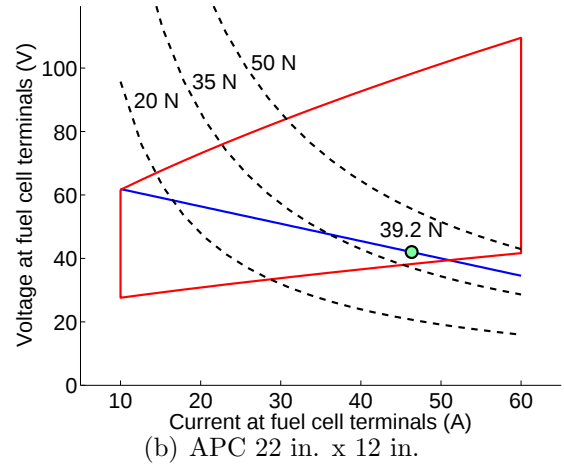
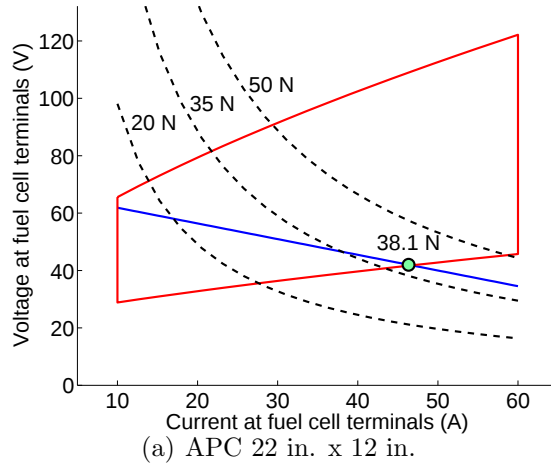
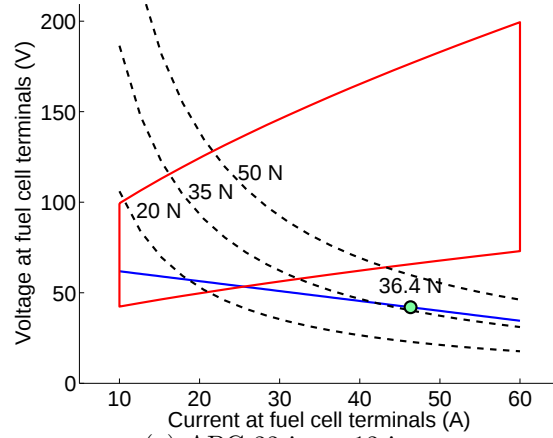
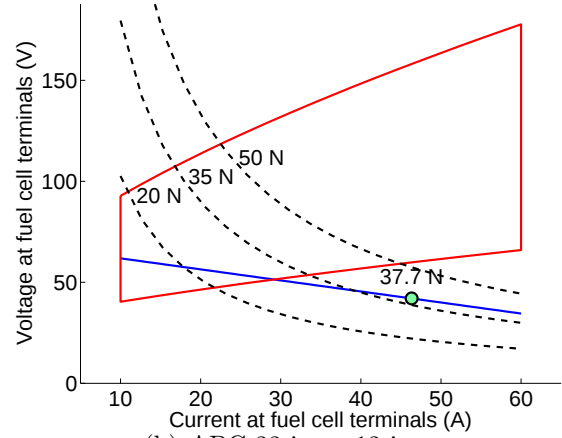


Figure A.7: Simulation results for the propulsion system with components: SOFC Model 9, AXI 5345-18 Motor, and Jeti Spin 99 Controller. The propeller is indicated below each figure.

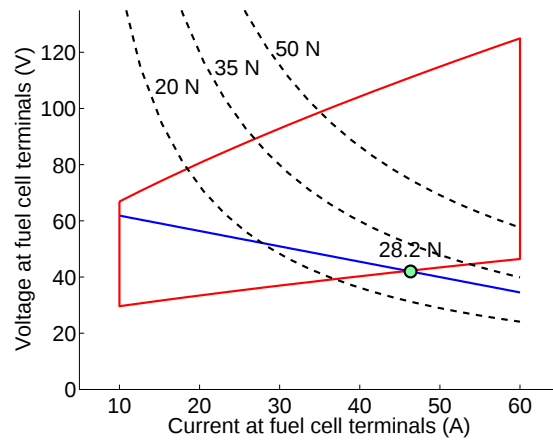
AXI Motor 5360 BLDC Motor



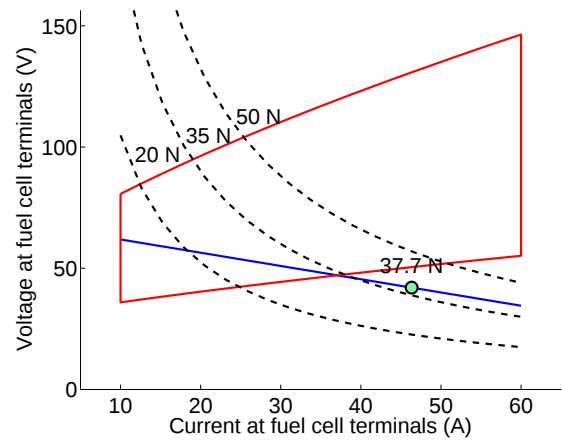
(a) APC 22 in. x 12 in.



(b) APC 22 in. x 12 in.



(c) APC 26 in. x 15 in.



(d) APC 27 in. x 13 in.

Figure A.8: Simulation results for the propulsion system with components: SOFC Model 9, AXI 5360 Motor, and Jeti Spin 99 Controller. The propeller is indicated below each figure.

Solid Oxide Fuel Cell Model 10

AXI 5330 DBL BLDC Motor

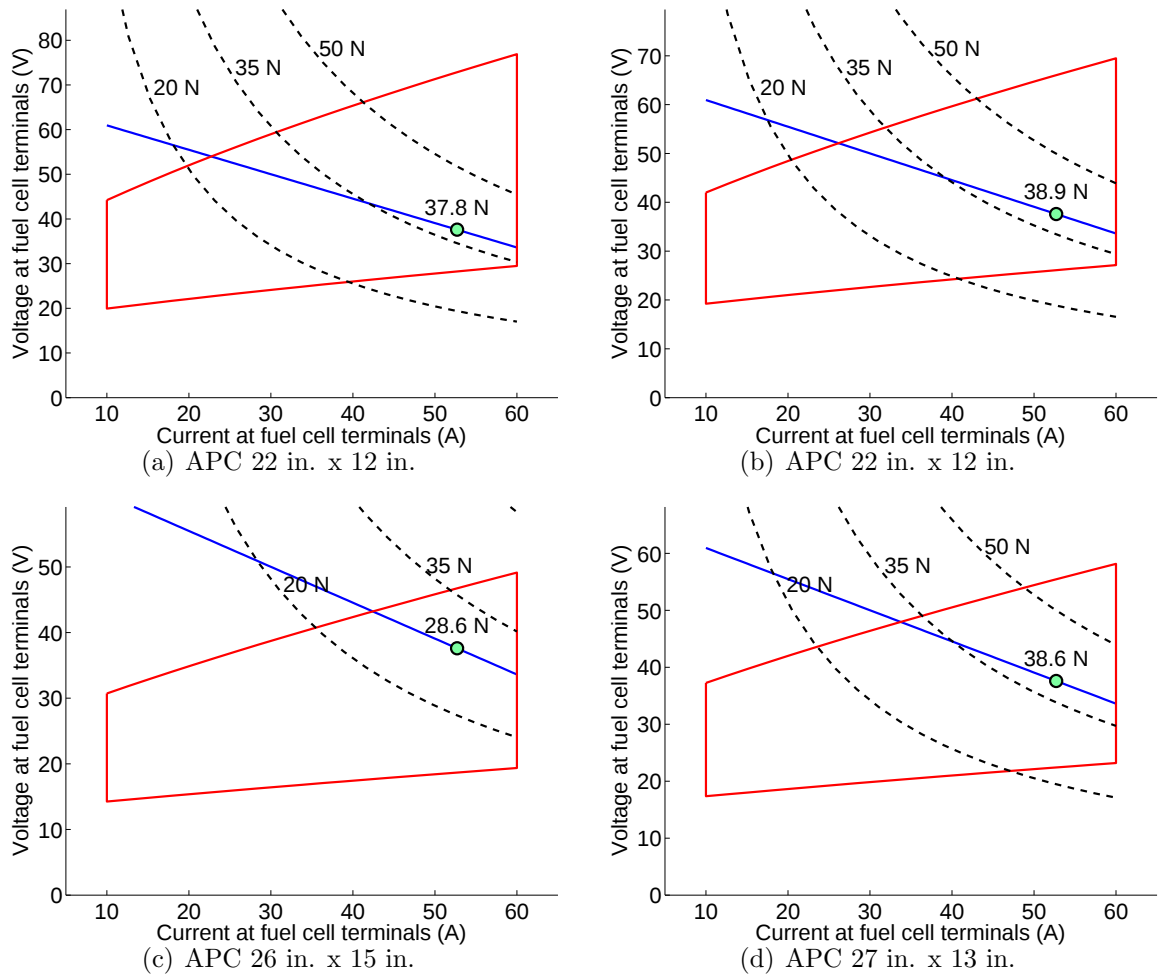
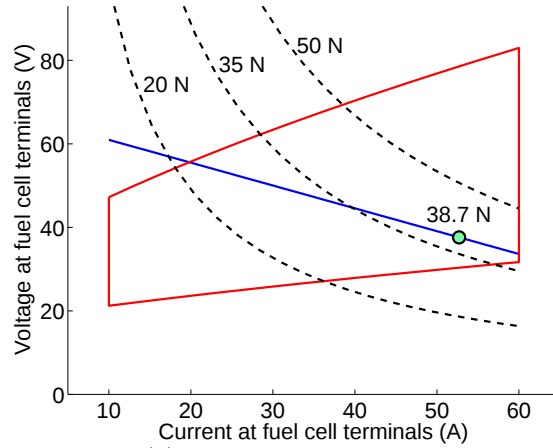
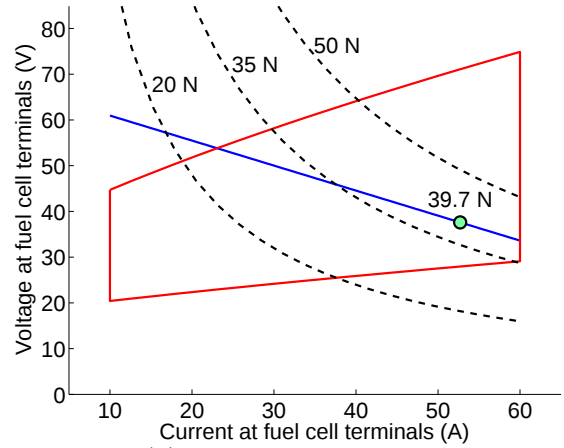


Figure A.9: Simulation results for the propulsion system with components: SOFC Model 10, AXI 5330 DBL Motor, and Jeti Spin 99 Controller. The propeller is indicated below each figure.

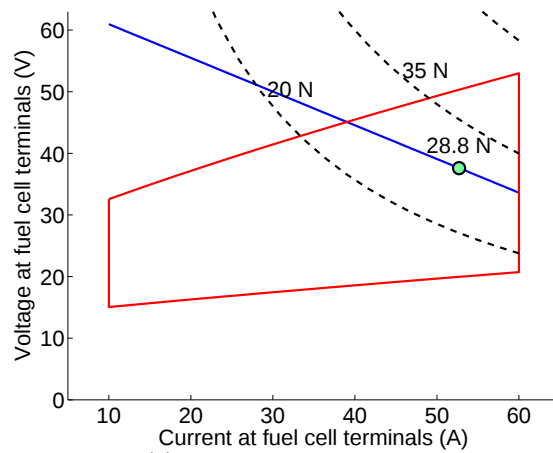
AXI Motor 5345-14 BLDC Motor



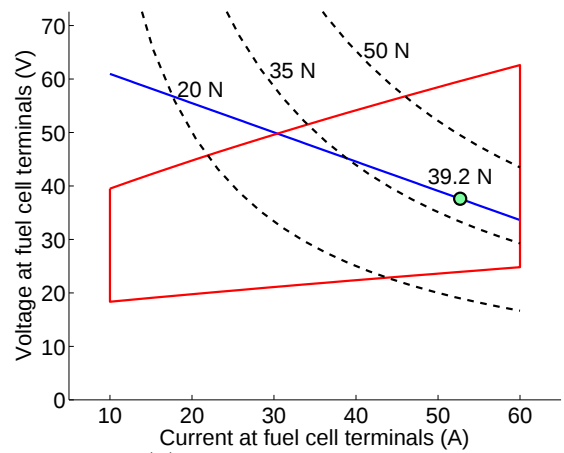
(a) APC 22 in. x 12 in.



(b) APC 22 in. x 12 in.



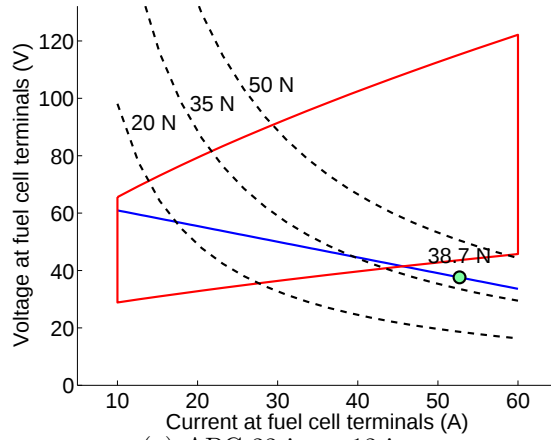
(c) APC 26 in. x 15 in.



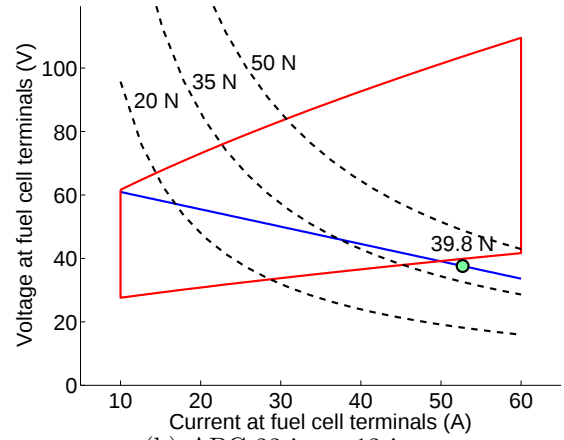
(d) APC 27 in. x 13 in.

Figure A.10: Simulation results for the propulsion system with components: SOFC Model 10, AXI 5345-14 Motor, and Jeti Spin 99 Controller. The propeller is indicated below each figure.

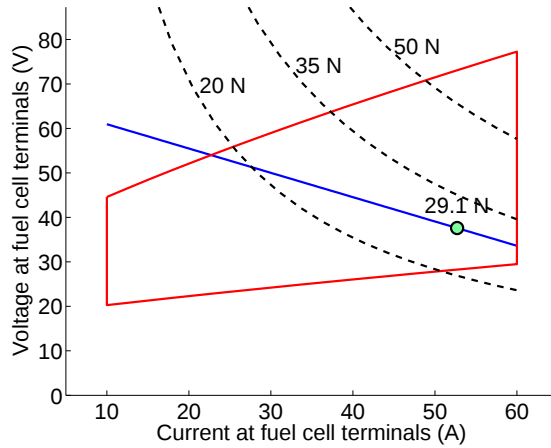
AXI Motor 5345-18 BLDC Motor



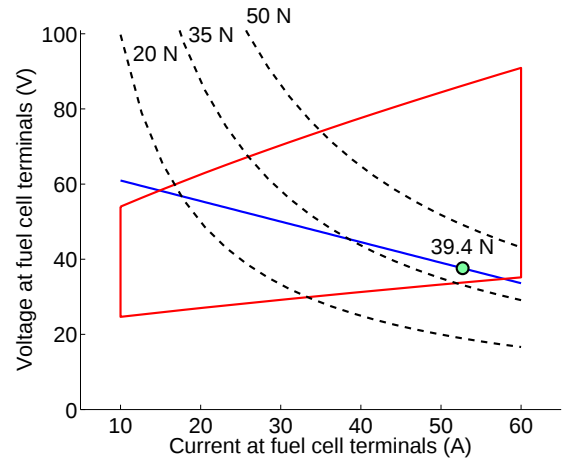
(a) APC 22 in. x 12 in.



(b) APC 22 in. x 12 in.



(c) APC 26 in. x 15 in.



(d) APC 27 in. x 13 in.

Figure A.11: Simulation results for the propulsion system with components: SOFC Model 10, AXI 5345-18 Motor, and Jeti Spin 99 Controller. The propeller is indicated below each figure.

AXI Motor 5360 BLDC Motor

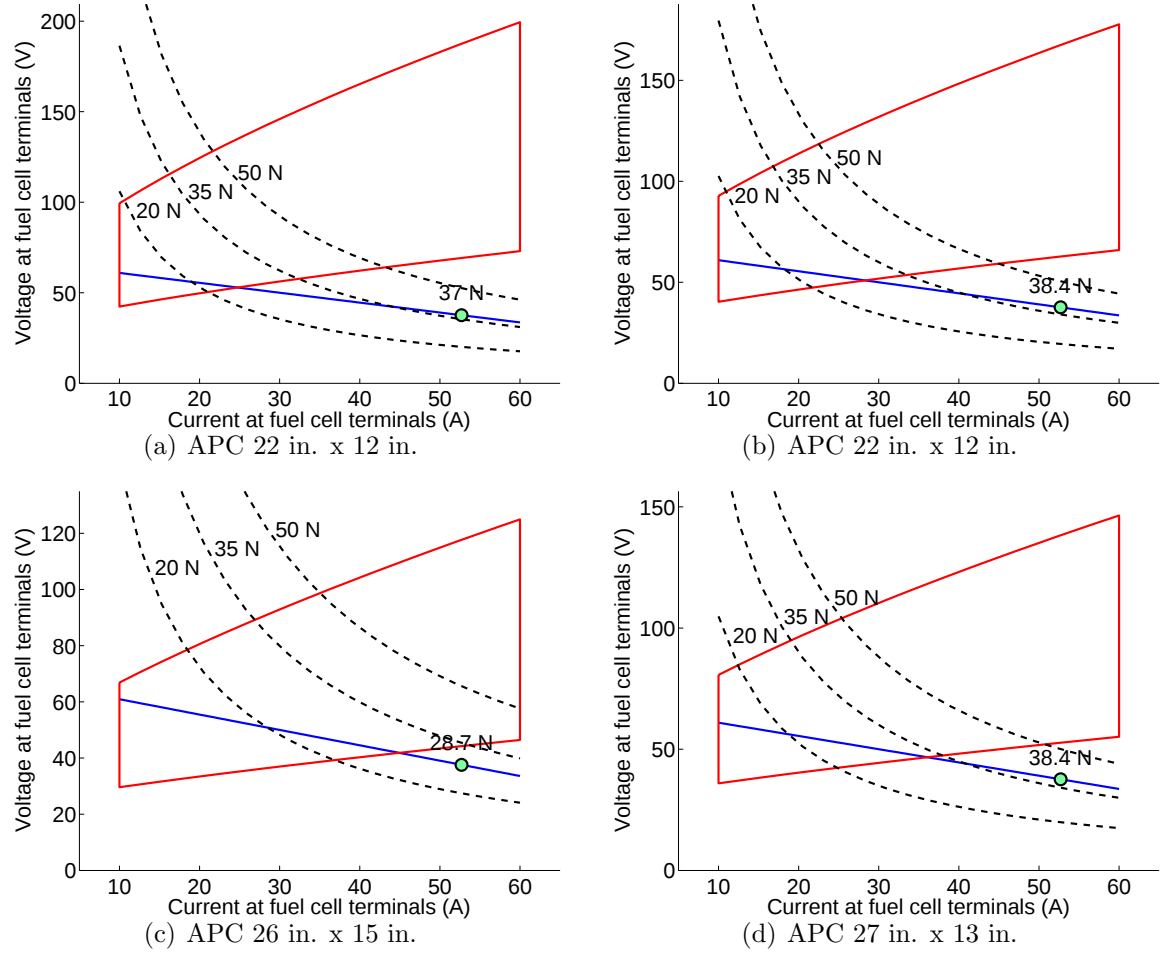


Figure A.12: Simulation results for the propulsion system with components: SOFC Model 10, AXI 5360 Motor, and Jeti Spin 99 Controller. The propeller is indicated below each figure.

Solid Oxide Fuel Cell Model 11

AXI 5330 DBL BLDC Motor

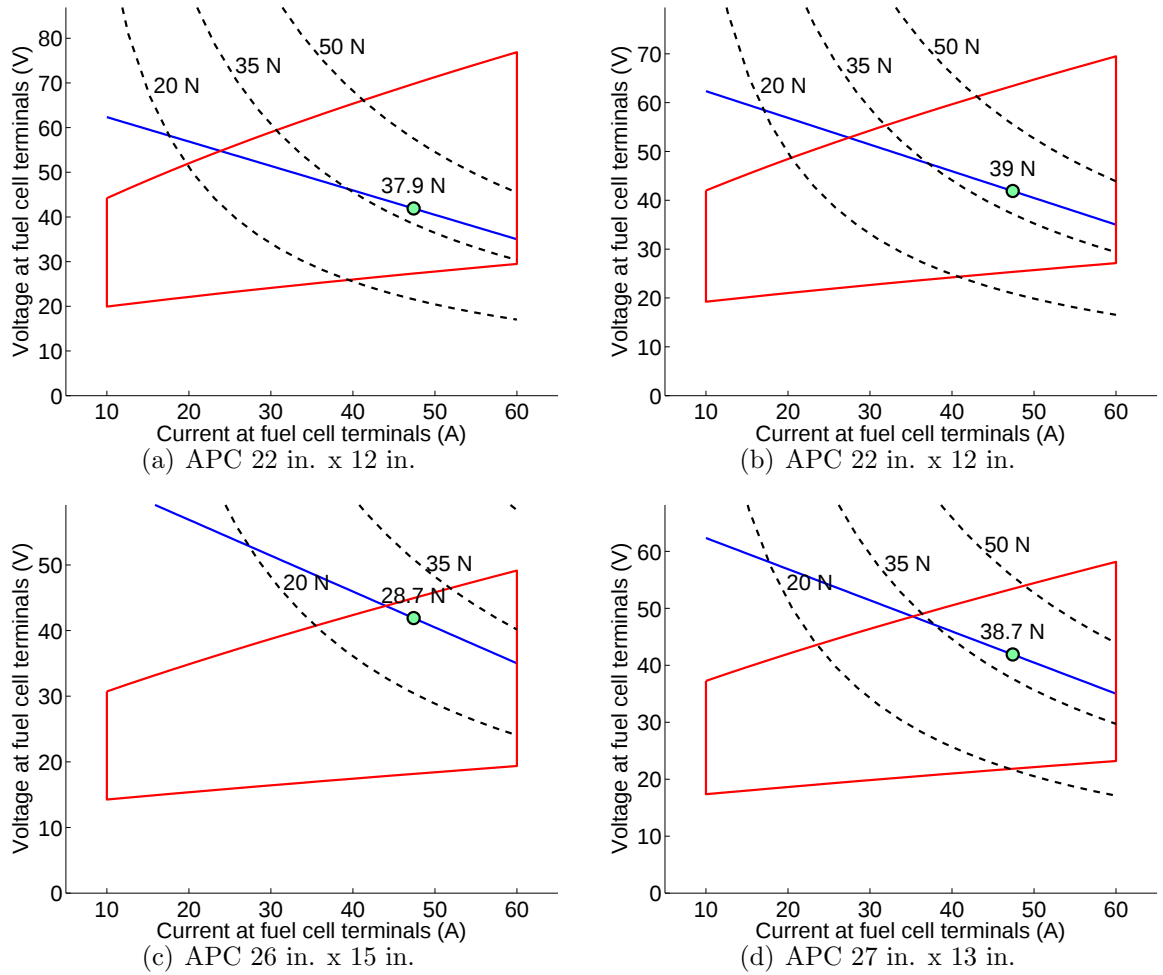


Figure A.13: Simulation results for the propulsion system with components: SOFC Model 11, AXI 5330 DBL Motor, and Jeti Spin 99 Controller. The propeller is indicated below each figure.

AXI Motor 5345-14 BLDC Motor

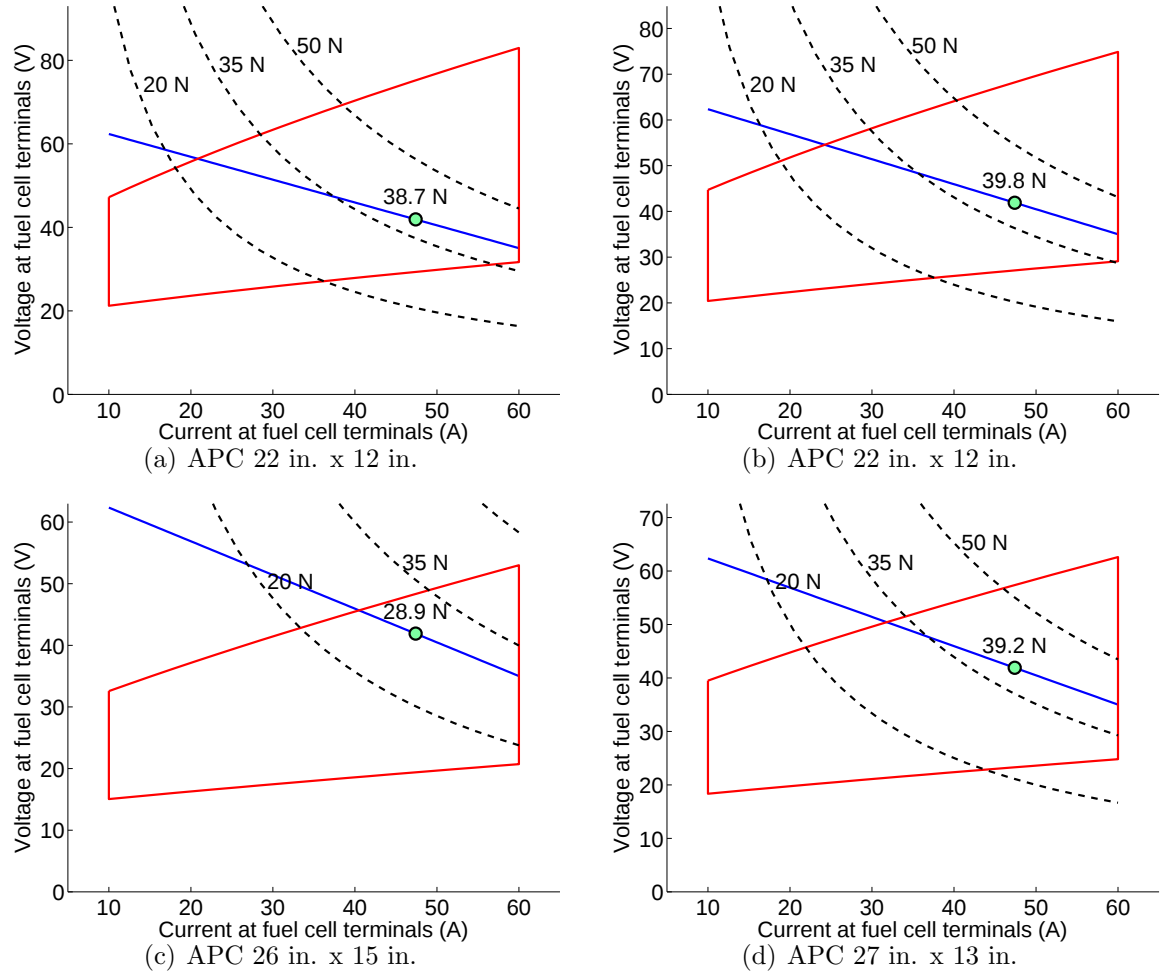


Figure A.14: Simulation results for the propulsion system with components: SOFC Model 11, AXI 5345-14 Motor, and Jeti Spin 99 Controller. The propeller is indicated below each figure.

AXI Motor 5345-18 BLDC Motor

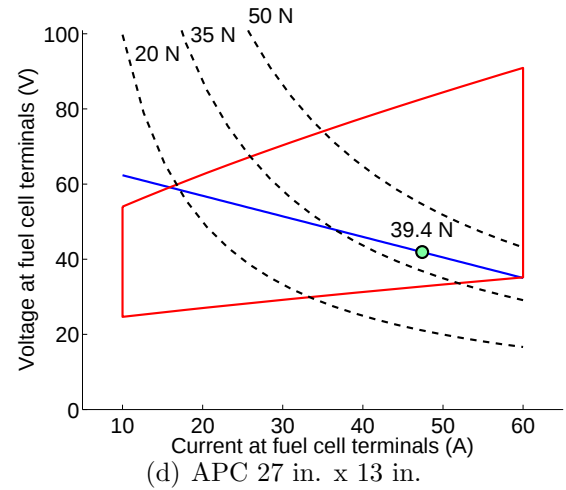
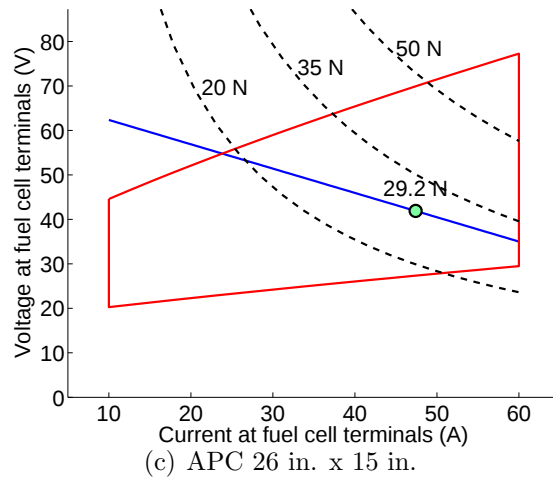
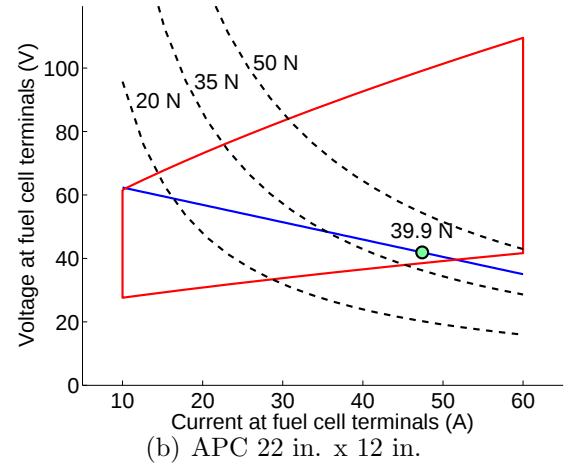
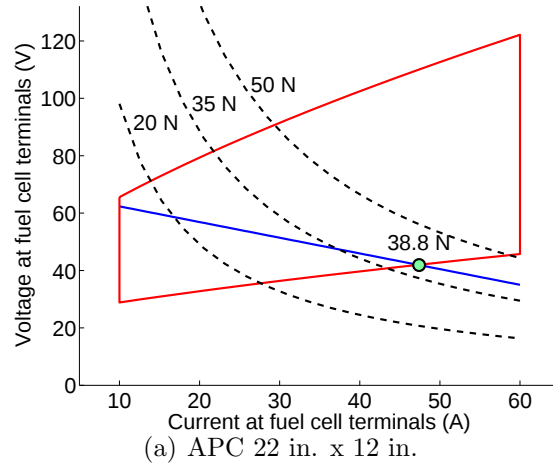


Figure A.15: Simulation results for the propulsion system with components: SOFC Model 11, AXI 5345-18 Motor, and Jeti Spin 99 Controller. The propeller is indicated below each figure.

AXI Motor 5360 BLDC Motor

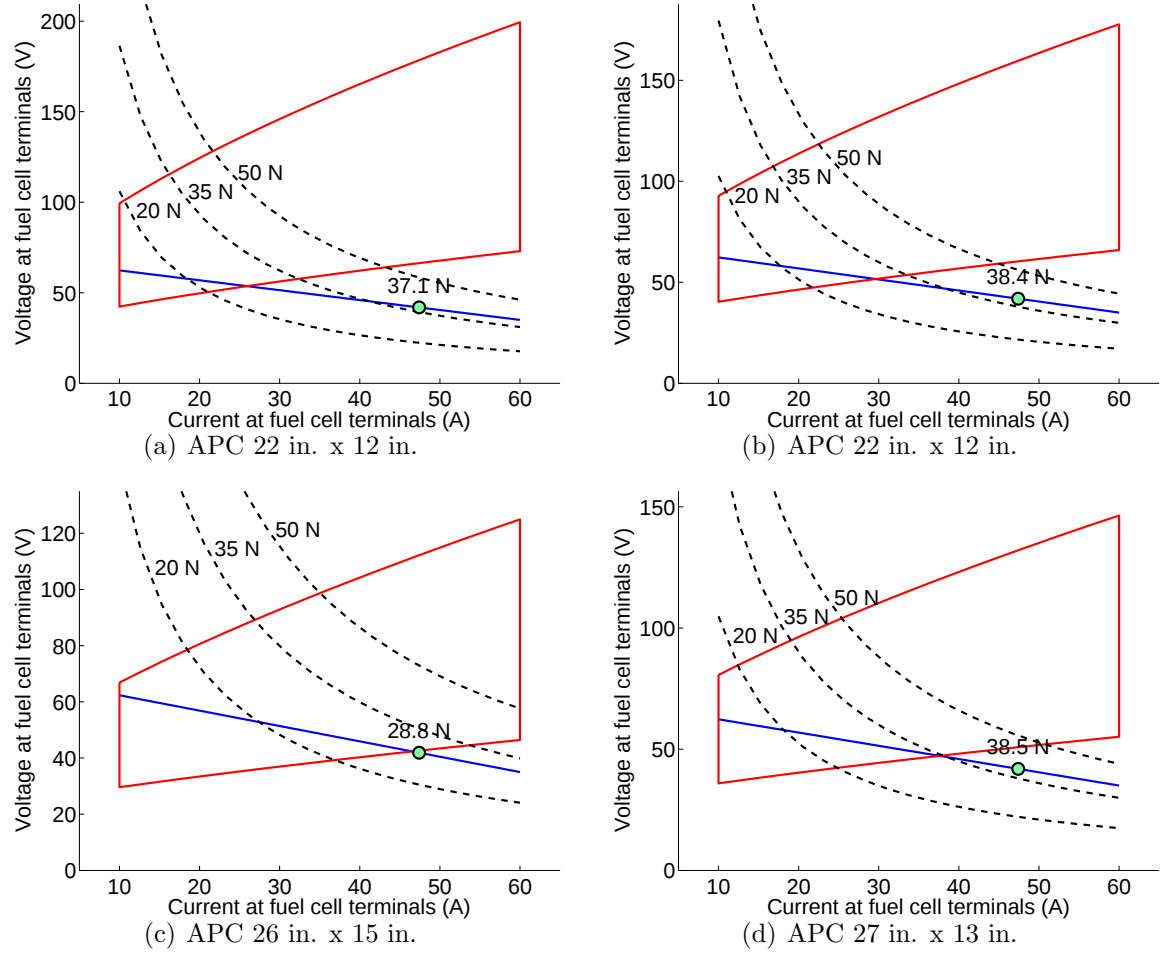


Figure A.16: Simulation results for the propulsion system with components: SOFC Model 11, AXI 5360 Motor, and Jeti Spin 99 Controller. The propeller is indicated below each figure.

Solid Oxide Fuel Cell Model 12

AXI 5330 DBL BLDC Motor

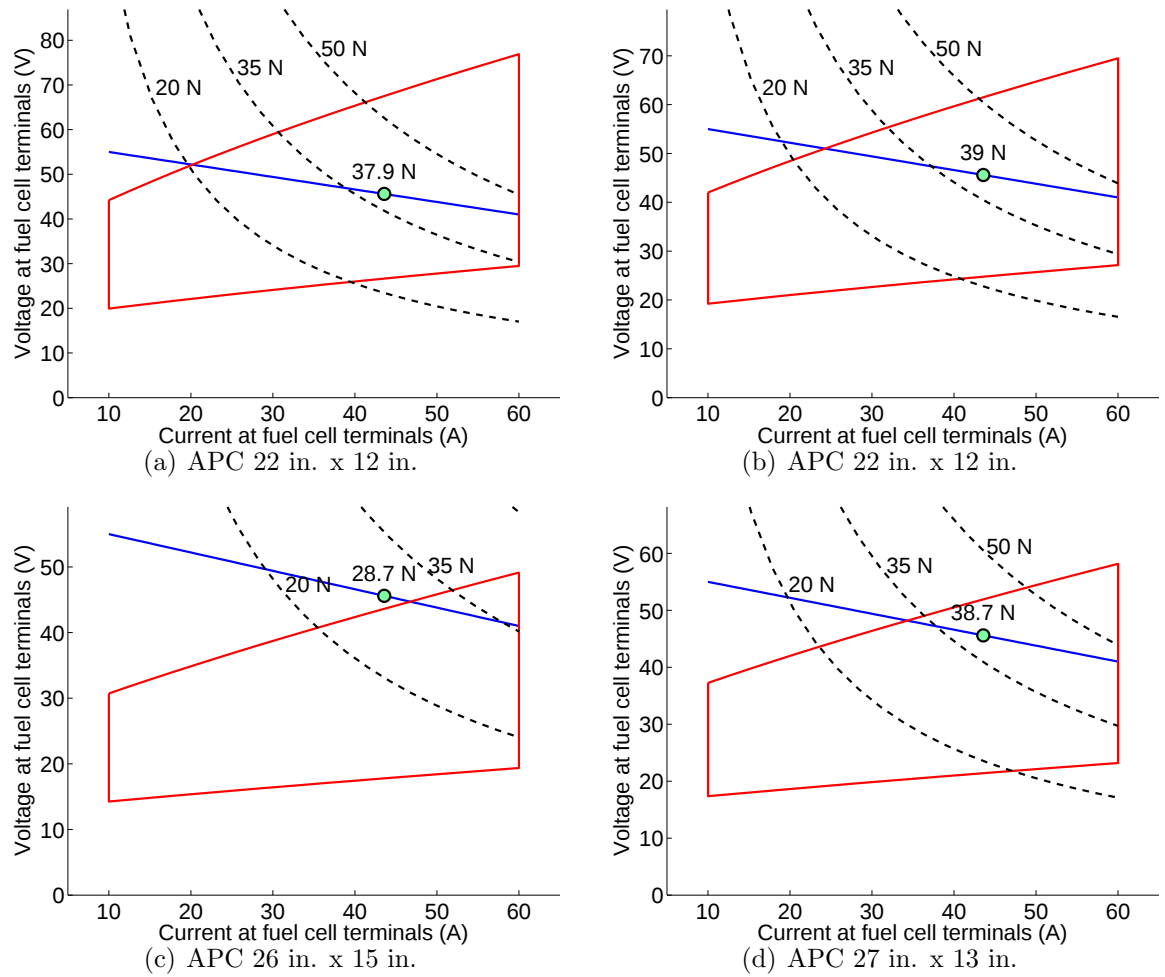


Figure A.17: Simulation results for the propulsion system with components: SOFC Model 12, AXI 5330 DBL Motor, and Jeti Spin 99 Controller. The propeller is indicated below each figure.

AXI Motor 5345-14 BLDC Motor

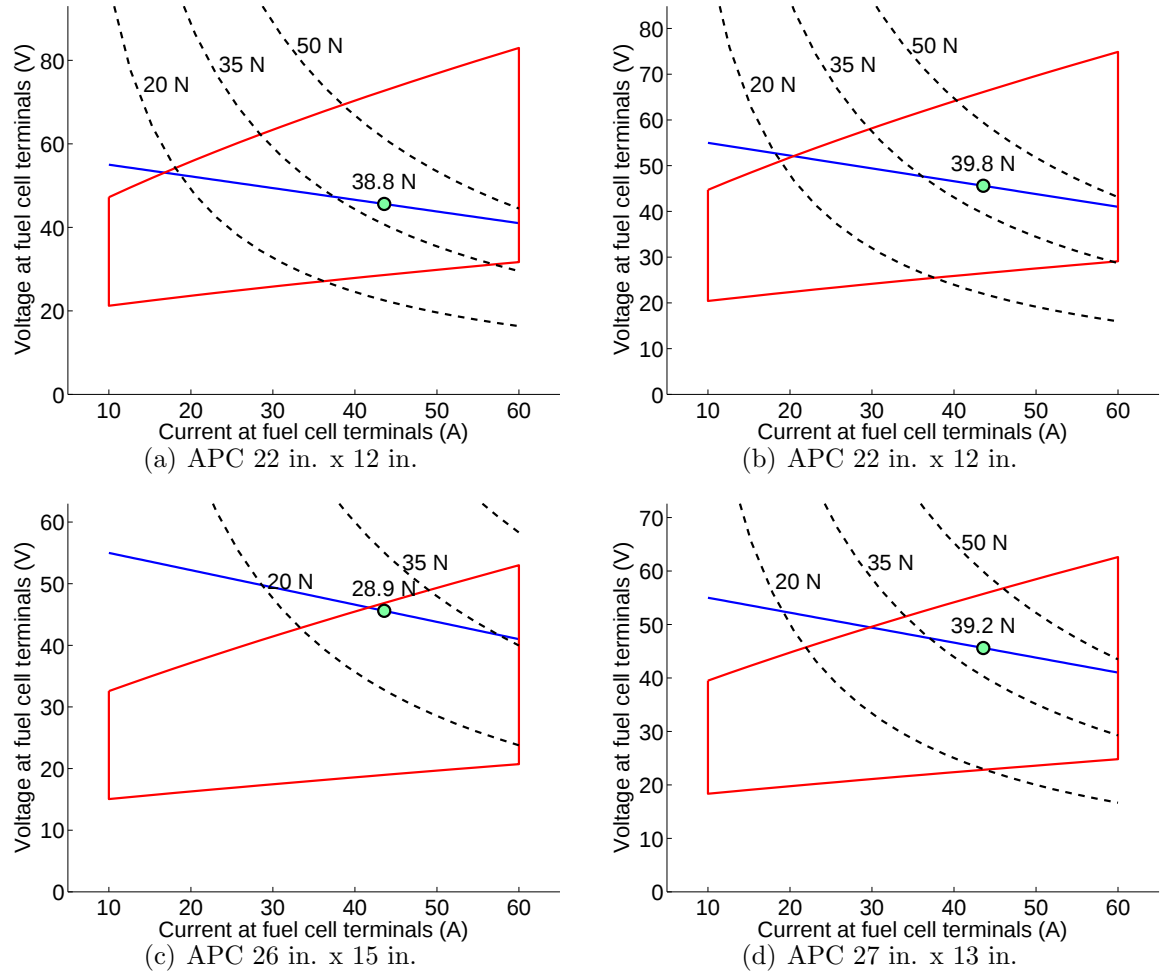


Figure A.18: Simulation results for the propulsion system with components: SOFC Model 12, AXI 5345-14 Motor, and Jeti Spin 99 Controller. The propeller is indicated below each figure.

AXI Motor 5345-18 BLDC Motor

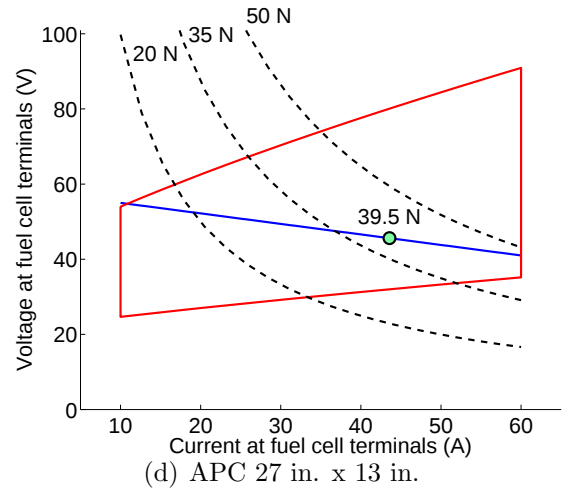
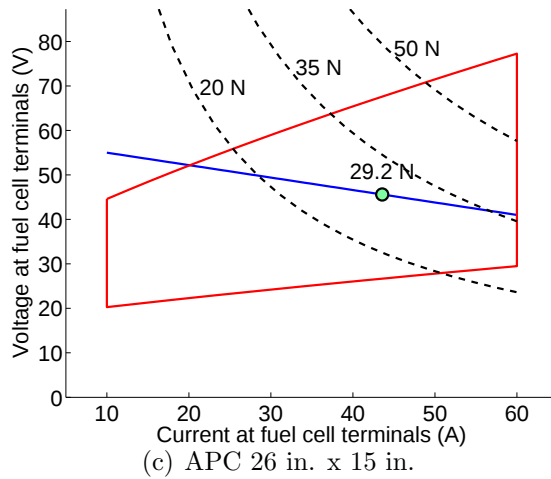
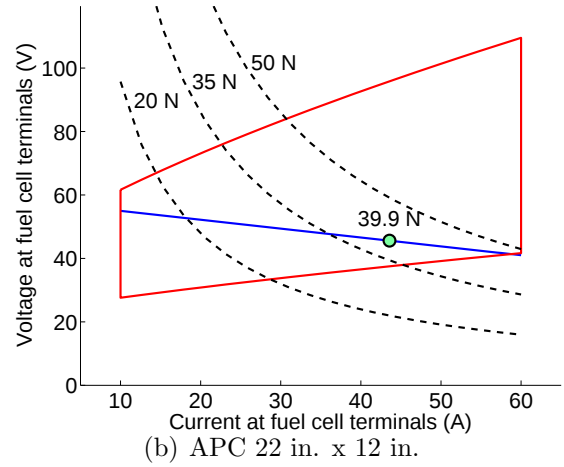
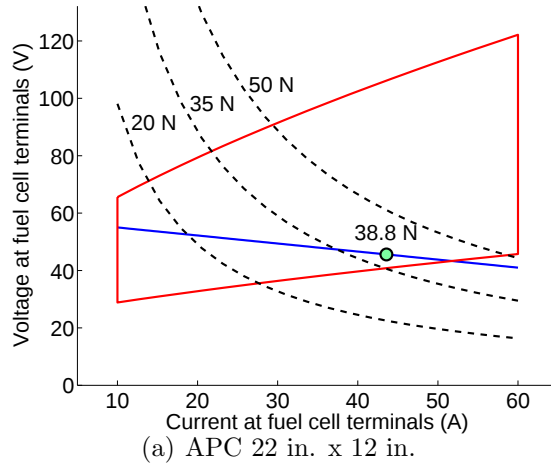


Figure A.19: Simulation results for the propulsion system with components: SOFC Model 12, AXI 5345-18 Motor, and Jeti Spin 99 Controller. The propeller is indicated below each figure.

AXI Motor 5360 BLDC Motor

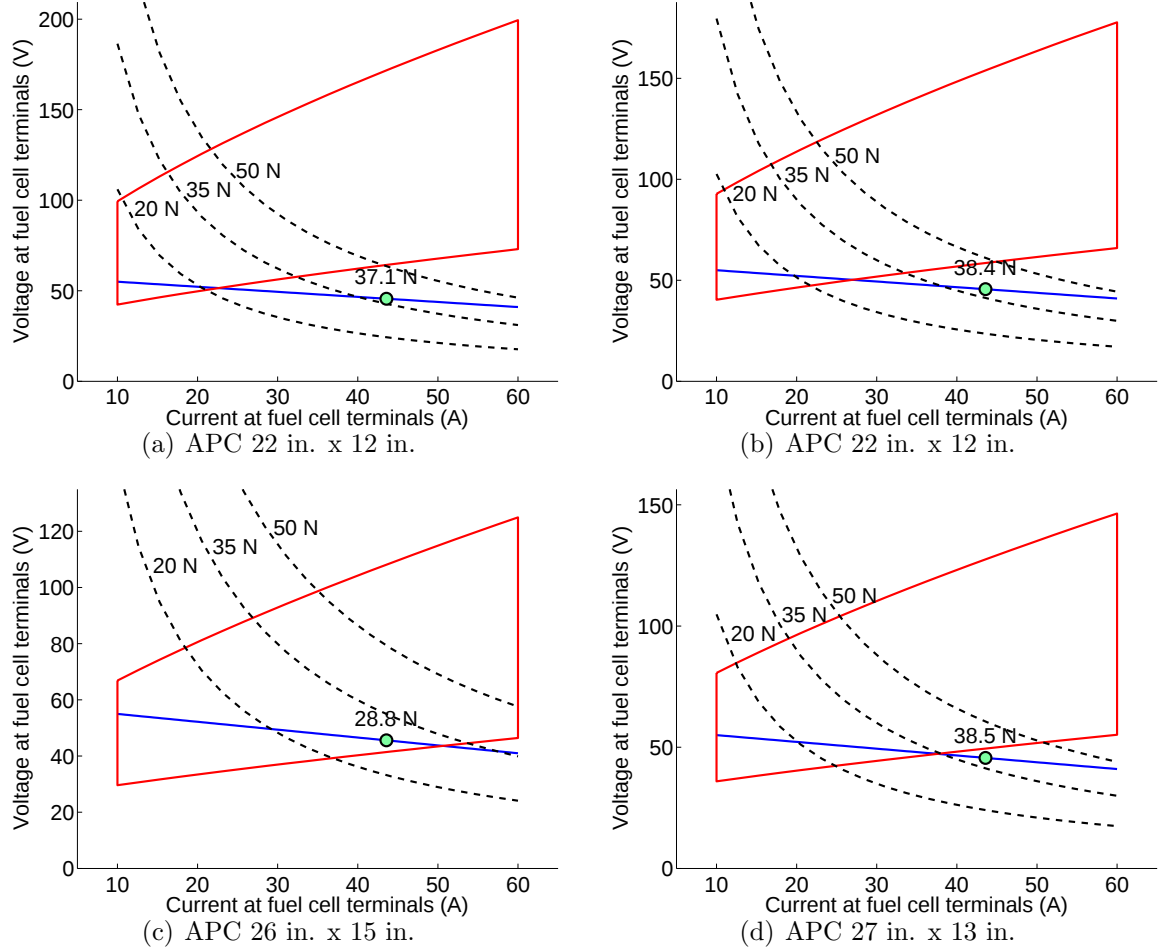


Figure A.20: Simulation results for the propulsion system with components: SOFC Model 12, AXI 5360 Motor, and Jeti Spin 99 Controller. The propeller is indicated below each figure.

Solid Oxide Fuel Cell Model 13

AXI 5330 DBL BLDC Motor

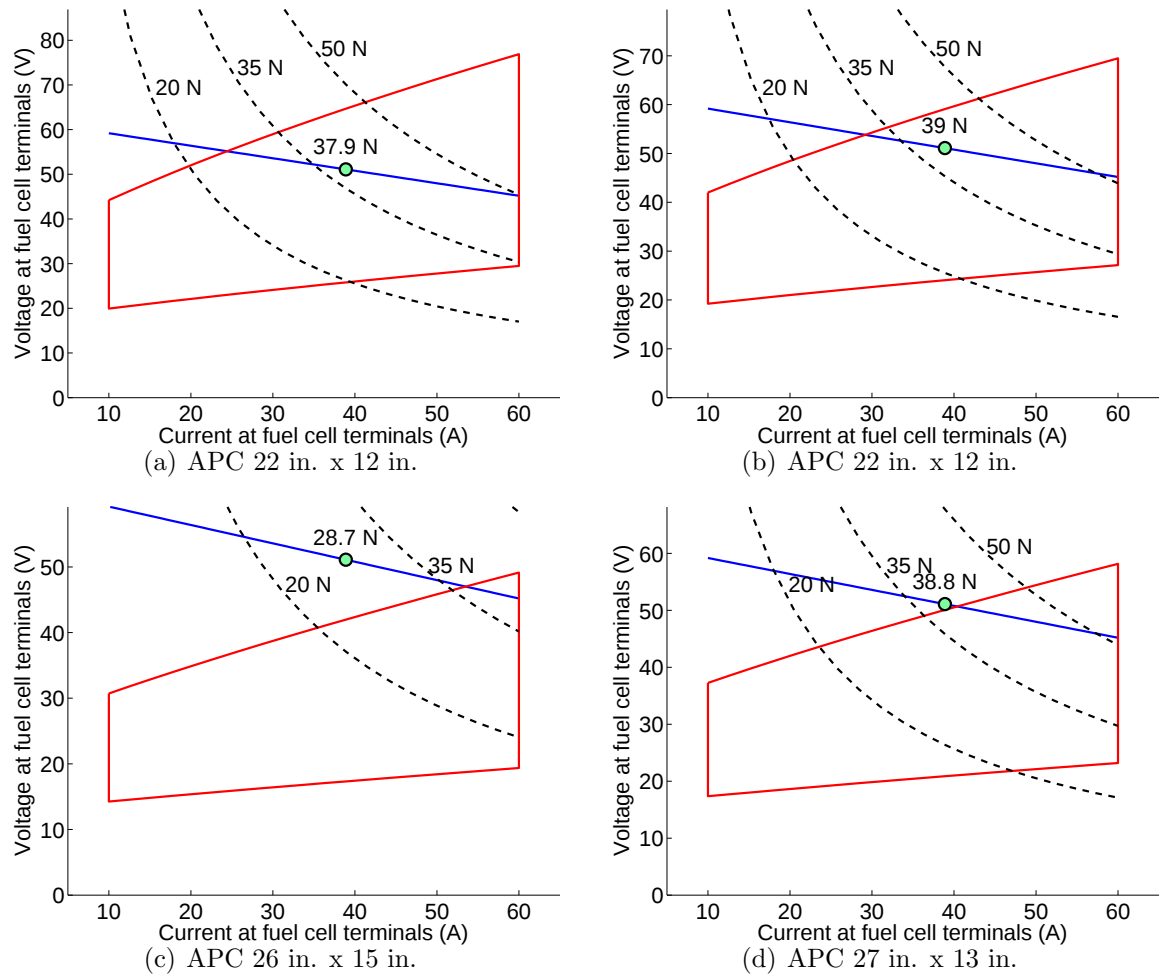


Figure A.21: Simulation results for the propulsion system with components: SOFC Model 13, AXI 5330 DBL Motor, and Jeti Spin 99 Controller. The propeller is indicated below each figure.

AXI Motor 5345-14 BLDC Motor

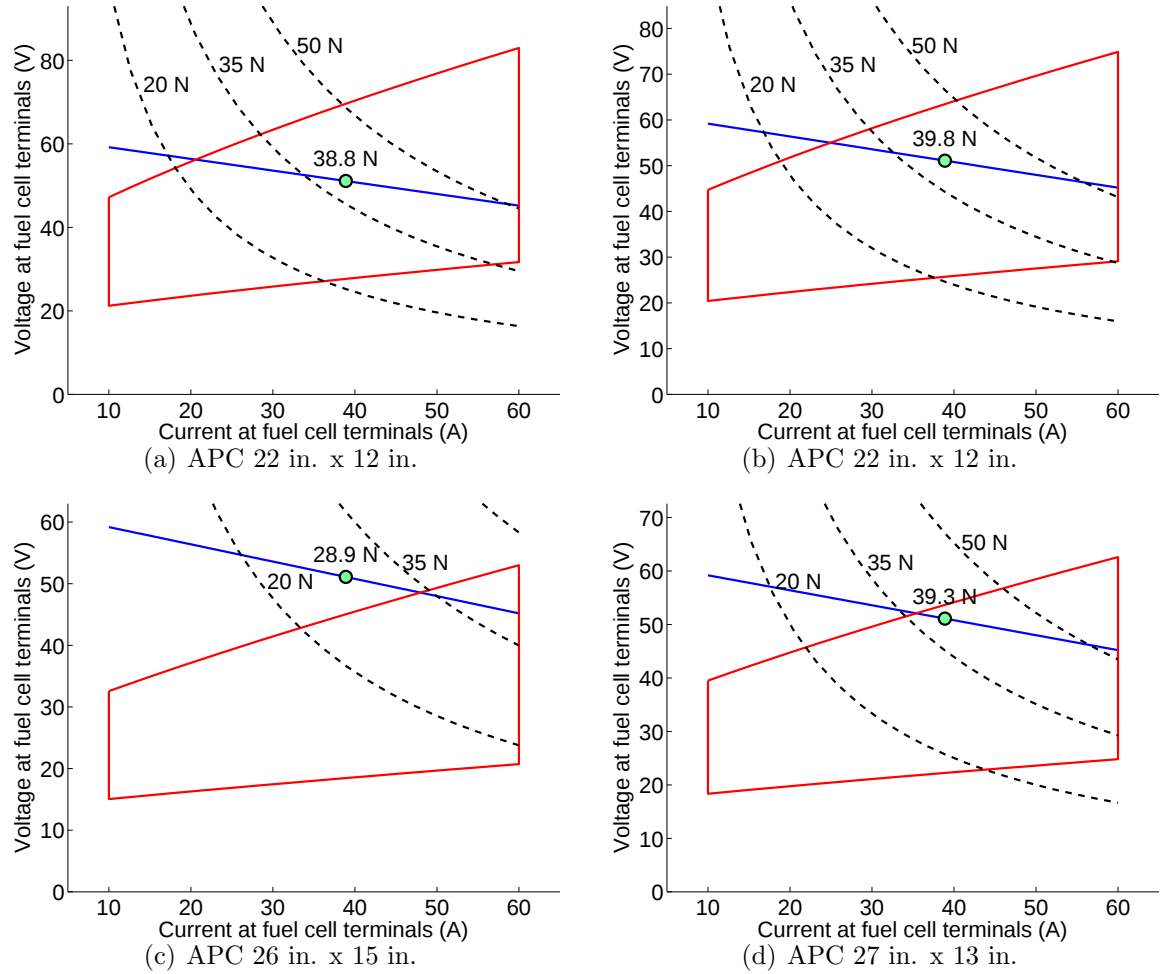
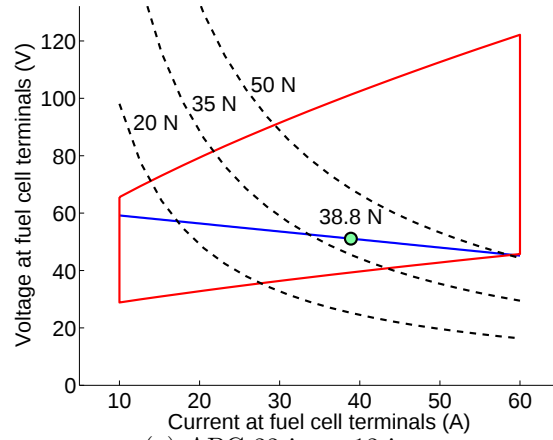
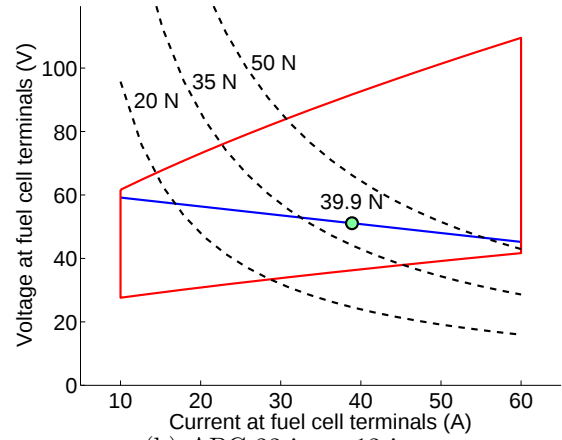


Figure A.22: Simulation results for the propulsion system with components: SOFC Model 13, AXI 5345-14 Motor, and Jeti Spin 99 Controller. The propeller is indicated below each figure.

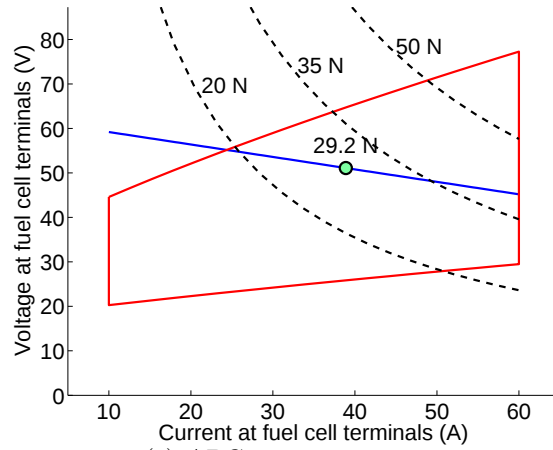
AXI Motor 5345-18 BLDC Motor



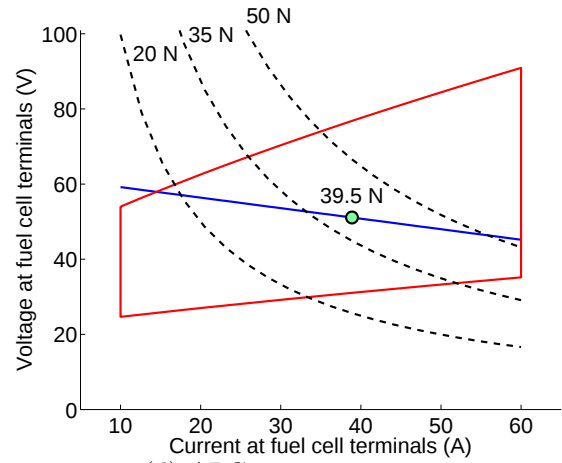
(a) APC 22 in. x 12 in.



(b) APC 22 in. x 12 in.



(c) APC 26 in. x 15 in.



(d) APC 27 in. x 13 in.

Figure A.23: Simulation results for the propulsion system with components: SOFC Model 13, AXI 5345-18 Motor, and Jeti Spin 99 Controller. The propeller is indicated below each figure.

AXI Motor 5360 BLDC Motor

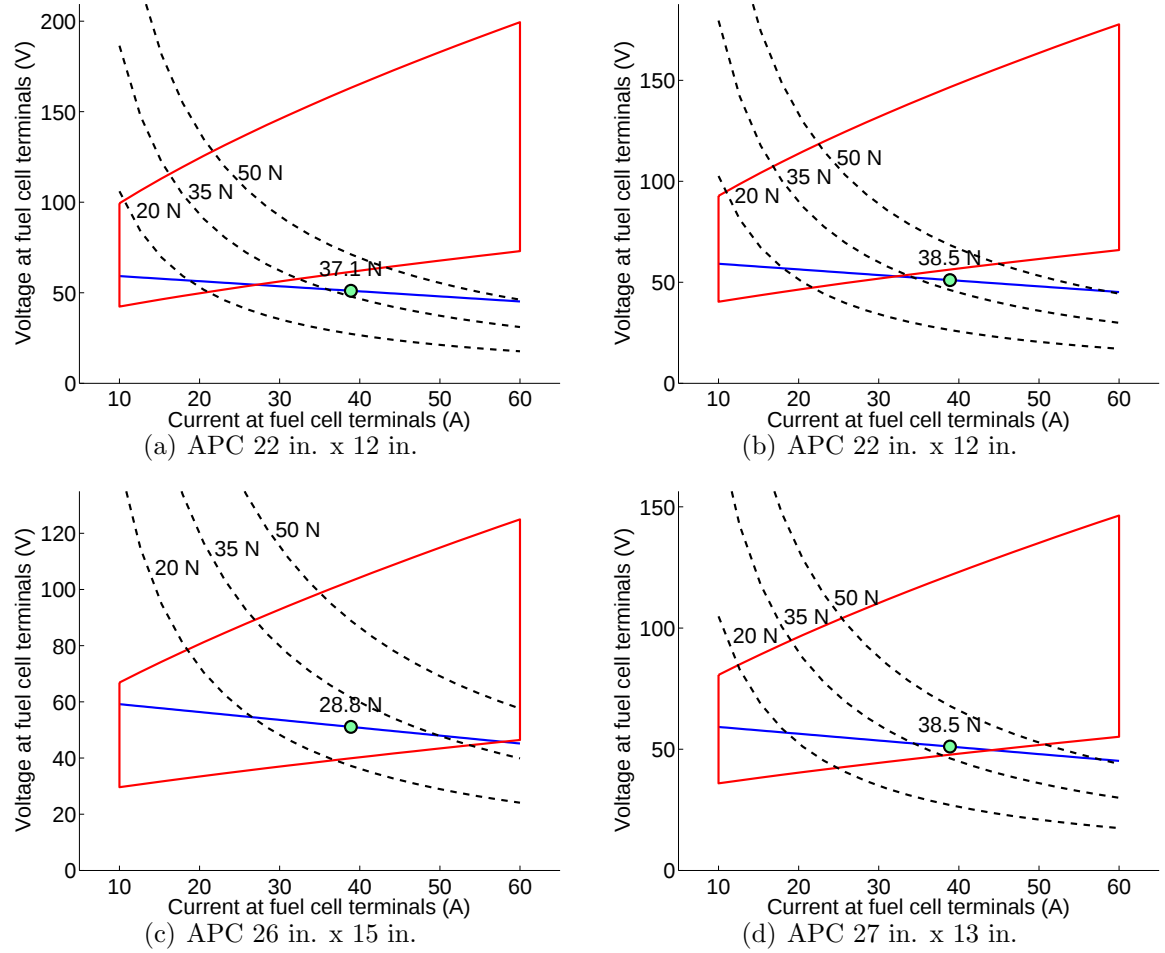


Figure A.24: Simulation results for the propulsion system with components: SOFC Model 13, AXI 5360 Motor, and Jeti Spin 99 Controller. The propeller is indicated below each figure.

APPENDIX B

WIND TUNNEL TEST RESULTS

Appendix B lists the data gathered in the wind tunnel tests along with calculated values of J , C_T and C_P . These calculations assume data measurements with a minimum of 2 significant digits.

Table B.1: Wind Tunnel Data for SOFC Model 08, AXI Double 5330/20 Motor, APC 22 x 12 Prop Wind Tunnel. Air density, ρ was measured to be 1.20 kg/m^3

(a) Without Fuselage									
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.21	66.0	7.6	0.9	12	378	12	0.35 ± 0.06	0.029 ± 0.007	0.025 ± 0.003
0.31	62.3	14.7	1.6	26	462	12	0.30 ± 0.05	0.042 ± 0.005	0.028 ± 0.002
0.43	56.0	26.3	2.3	44	540	13	0.27 ± 0.04	0.051 ± 0.004	0.030 ± 0.001
0.55	49.7	38.0	2.7	54	584	13	0.25 ± 0.04	0.054 ± 0.003	0.030 ± 0.001
0.66	44.0	48.4	3.0	62	611	13	0.24 ± 0.04	0.056 ± 0.003	0.031 ± 0.001
0.80	38.0	59.1	3.2	67	622	13	0.23 ± 0.04	0.058 ± 0.003	0.031 ± 0.001

(b) With Fuselage									
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.20	66.5	6.9	0.9	12	375	12	0.35 ± 0.06	0.029 ± 0.007	0.024 ± 0.003
0.31	62.3	14.6	1.6	28	461	12	0.29 ± 0.05	0.044 ± 0.005	0.028 ± 0.002
0.45	55.9	26.4	2.3	45	540	12	0.25 ± 0.04	0.052 ± 0.004	0.030 ± 0.001
0.55	49.6	37.6	2.8	56	584	13	0.24 ± 0.04	0.055 ± 0.003	0.031 ± 0.001
0.67	43.9	48.4	3.0	63	608	13	0.23 ± 0.04	0.058 ± 0.003	0.031 ± 0.001
0.80	37.8	59.4	3.2	68	622	13	0.23 ± 0.04	0.059 ± 0.003	0.031 ± 0.001

Table B.2: Wind Tunnel Data for SOFC Model 08, AXI Double 5345/14 Motor, APC 27 x 13 Prop Wind Tunnel. Air density, ρ was measured to be 1.18 kg/m^3

(a) Without Fuselage									
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.23	66.1	7.5	1.2	16	308	13	0.38 ± 0.06	0.026 ± 0.005	0.018 ± 0.002
0.31	61.7	15.7	2.1	34	370	13	0.31 ± 0.05	0.038 ± 0.003	0.021 ± 0.001
0.38	58.5	21.6	2.6	44	400	12	0.28 ± 0.05	0.042 ± 0.003	0.022 ± 0.001
0.45	54.0	30.0	3.0	55	429	14	0.30 ± 0.04	0.045 ± 0.002	0.023 ± 0.001
0.53	48.3	40.4	3.5	65	450	14	0.28 ± 0.04	0.049 ± 0.002	0.024 ± 0.001
0.61	43.4	49.5	3.7	70	463	14	0.27 ± 0.04	0.050 ± 0.002	0.024 ± 0.001

(b) With Fuselage									
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.24	66.1	7.5	1.2	19	307	13	0.38 ± 0.06	0.030 ± 0.005	0.018 ± 0.002
0.31	61.6	15.7	2.1	36	371	12	0.30 ± 0.05	0.039 ± 0.003	0.021 ± 0.001
0.38	58.5	21.5	2.6	45	400	13	0.30 ± 0.05	0.042 ± 0.003	0.022 ± 0.001
0.43	54.0	30.0	3.1	56	429	13	0.27 ± 0.04	0.046 ± 0.002	0.023 ± 0.001
0.53	48.4	40.2	3.4	64	451	14	0.29 ± 0.04	0.047 ± 0.002	0.023 ± 0.001
0.63	42.4	51.0	3.7	70	464	14	0.27 ± 0.04	0.050 ± 0.002	0.024 ± 0.001

Table B.3: Wind Tunnel Data for SOFC Model 08, AXI Double 5345/18 Motor, APC 24 x 12 Prop Wind Tunnel. Air density, ρ was measured to be 1.18 kg/m^3

(a) Without Fuselage									
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.31	66.4	6.9	1.1	18	348	13	0.38 ± 0.06	0.037 ± 0.006	0.022 ± 0.002
0.43	62.7	14.0	1.8	35	421	13	0.31 ± 0.05	0.048 ± 0.004	0.025 ± 0.001
0.56	56.6	25.3	2.4	53	486	13	0.27 ± 0.04	0.054 ± 0.003	0.026 ± 0.001
0.67	51.7	34.1	2.8	59	518	13	0.25 ± 0.04	0.053 ± 0.003	0.026 ± 0.001
0.79	46.7	43.5	3.1	60	541	13	0.25 ± 0.04	0.049 ± 0.003	0.026 ± 0.001
0.91	42.5	51.2	3.3	63	552	13	0.24 ± 0.04	0.050 ± 0.002	0.027 ± 0.001

(b) With Fuselage									
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.32	66.4	6.9	1.0	19	348	13	0.38 ± 0.06	0.039 ± 0.006	0.022 ± 0.002
0.43	62.1	15.0	1.8	36	426	12	0.29 ± 0.05	0.048 ± 0.004	0.025 ± 0.001
0.55	56.6	25.1	2.5	53	486	12	0.26 ± 0.04	0.054 ± 0.003	0.026 ± 0.001
0.67	51.7	34.1	2.8	58	520	13	0.25 ± 0.04	0.052 ± 0.003	0.026 ± 0.001
0.80	46.7	43.4	3.2	63	540	12	0.23 ± 0.04	0.052 ± 0.002	0.027 ± 0.001
0.91	42.5	51.0	3.3	66	553	13	0.24 ± 0.04	0.052 ± 0.002	0.027 ± 0.001

Table B.4: Wind Tunnel Data for SOFC Model 08, AXI Double 5360/20 Motor, APC 26 x 15 Prop Wind Tunnel. Air density, ρ was measured to be 1.20 kg/m^3

(a) Without Fuselage									
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.43	65.4	8.8	1.6	19	310	14	0.42 ± 0.06	0.034 ± 0.005	0.028 ± 0.002
0.56	61.5	16.3	2.4	35	365	12	0.32 ± 0.05	0.045 ± 0.004	0.030 ± 0.001
0.68	57.5	23.5	3.0	47	401	13	0.31 ± 0.05	0.050 ± 0.003	0.031 ± 0.001
0.80	53.0	31.7	3.5	58	428	14	0.30 ± 0.04	0.054 ± 0.003	0.031 ± 0.001
0.90	49.3	38.8	3.8	64	445	13	0.28 ± 0.04	0.056 ± 0.003	0.032 ± 0.001
1.00	45.8	45.0	4.0	69	456	14	0.29 ± 0.04	0.057 ± 0.002	0.032 ± 0.001

(b) With Fuselage									
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.43	65.4	8.6	1.6	21	308	11	0.35 ± 0.06	0.038 ± 0.006	0.028 ± 0.002
0.55	61.5	15.8	2.4	35	362	13	0.35 ± 0.05	0.046 ± 0.004	0.030 ± 0.001
0.67	57.6	23.2	3.0	48	399	13	0.30 ± 0.05	0.052 ± 0.003	0.031 ± 0.001
0.78	53.5	30.7	3.4	57	425	13	0.30 ± 0.04	0.054 ± 0.003	0.031 ± 0.001
0.91	49.3	38.5	3.8	64	443	14	0.31 ± 0.04	0.057 ± 0.003	0.032 ± 0.001
1.00	45.7	45.1	4.0	69	454	14	0.29 ± 0.04	0.058 ± 0.002	0.032 ± 0.001

Table B.5: Wind Tunnel Data for SOFC Model 09, AXI Double 5330/20 Motor, APC 27 x 13 Prop Wind Tunnel. Air density, ρ was measured to be 1.20 kg/m³

(a) Without Fuselage									
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.20	63.4	7.7	1.3	13	310	12	0.36 $\pm$ 0.06	0.020 $\pm$ 0.005	0.018 $\pm$ 0.001
0.31	56.3	20.6	2.4	37	389	12	0.29 $\pm$ 0.05	0.036 $\pm$ 0.003	0.022 $\pm$ 0.001
0.44	48.6	34.8	3.2	54	436	13	0.28 $\pm$ 0.04	0.042 $\pm$ 0.002	0.023 $\pm$ 0.001
0.56	40.4	49.8	3.6	62	459	14	0.27 $\pm$ 0.04	0.044 $\pm$ 0.002	0.024 $\pm$ 0.001
0.67	34.5	60.5	3.8	65	466	13	0.26 $\pm$ 0.04	0.045 $\pm$ 0.002	0.024 $\pm$ 0.001

(b) With Fuselage									
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.20	63.6	7.6	1.3	15	310	12	0.35 $\pm$ 0.06	0.024 $\pm$ 0.005	0.019 $\pm$ 0.001
0.31	56.4	20.8	2.4	38	390	13	0.31 $\pm$ 0.05	0.038 $\pm$ 0.003	0.022 $\pm$ 0.001
0.44	48.6	34.8	3.2	55	436	13	0.27 $\pm$ 0.04	0.043 $\pm$ 0.002	0.023 $\pm$ 0.001
0.55	40.3	50.0	3.7	63	459	13	0.26 $\pm$ 0.04	0.045 $\pm$ 0.002	0.024 $\pm$ 0.001
0.67	34.5	60.5	3.8	67	466	14	0.27 $\pm$ 0.04	0.046 $\pm$ 0.002	0.024 $\pm$ 0.001

Table B.6: Wind Tunnel Data for SOFC Model 09, AXI Double 5345/14 Motor, APC 26 x 15 Prop Wind Tunnel. Air density, ρ was measured to be 1.18 kg/m³

(a) Without Fuselage									
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.24	63.0	8.0	1.3	18	292	12	0.40±0.07	0.037±0.006	0.026±0.002
0.32	57.6	18.0	2.3	35	360	13	0.35±0.05	0.047±0.004	0.029±0.001
0.41	53.5	25.4	2.8	45	393	13	0.31±0.05	0.052±0.003	0.030±0.001
0.53	45.8	39.7	3.4	59	428	12	0.27±0.04	0.057±0.003	0.031±0.001
0.63	40.3	49.5	3.6	64	438	13	0.28±0.04	0.059±0.003	0.032±0.001

(b) With Fuselage									
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.24	63.0	8.0	1.3	19	292	13	0.41±0.07	0.040±0.006	0.026±0.002
0.33	57.6	17.9	2.3	36	361	12	0.32±0.05	0.048±0.004	0.029±0.001
0.43	52.5	27.5	2.9	49	400	14	0.33±0.05	0.054±0.003	0.030±0.001
0.53	45.9	39.6	3.4	59	426	13	0.28±0.04	0.058±0.003	0.031±0.001
0.63	40.4	49.7	3.6	64	438	14	0.31±0.04	0.059±0.003	0.031±0.001

Table B.7: Wind Tunnel Data for SOFC Model 09, AXI Double 5345/18 Motor, APC 22 x 12 Prop Wind Tunnel. Air density, ρ was measured to be 1.18 kg/m³

(a) Without Fuselage									
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.31	64.3	5.7	0.8	11	362	13	0.36 $\pm$ 0.06	0.029 $\pm$ 0.008	0.023 $\pm$ 0.003
0.44	61.5	10.8	1.3	22	432	13	0.30 $\pm$ 0.05	0.040 $\pm$ 0.006	0.026 $\pm$ 0.002
0.55	57.0	19.0	1.9	36	507	12	0.25 $\pm$ 0.04	0.049 $\pm$ 0.004	0.028 $\pm$ 0.002
0.68	52.8	26.9	2.3	46	549	13	0.24 $\pm$ 0.04	0.052 $\pm$ 0.003	0.029 $\pm$ 0.001
0.80	48.3	35.2	2.6	53	579	13	0.24 $\pm$ 0.04	0.054 $\pm$ 0.003	0.030 $\pm$ 0.001
0.91	44.4	42.5	2.8	58	599	13	0.23 $\pm$ 0.04	0.056 $\pm$ 0.003	0.030 $\pm$ 0.001
1.00	40.7	49.3	2.9	62	609	14	0.23 $\pm$ 0.04	0.057 $\pm$ 0.003	0.030 $\pm$ 0.001

(b) With Fuselage									
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.32	64.3	5.6	0.8	15	362	14	0.38 $\pm$ 0.06	0.040 $\pm$ 0.008	0.023 $\pm$ 0.003
0.44	61.5	10.8	1.3	25	432	14	0.32 $\pm$ 0.05	0.046 $\pm$ 0.006	0.027 $\pm$ 0.002
0.55	56.9	19.0	1.9	40	506	12	0.25 $\pm$ 0.04	0.053 $\pm$ 0.004	0.028 $\pm$ 0.002
0.67	52.8	27.2	2.3	49	550	13	0.24 $\pm$ 0.04	0.056 $\pm$ 0.003	0.029 $\pm$ 0.001
0.78	48.4	35.4	2.6	57	579	12	0.22 $\pm$ 0.04	0.058 $\pm$ 0.003	0.030 $\pm$ 0.001
0.91	44.2	42.5	2.8	62	599	12	0.21 $\pm$ 0.04	0.060 $\pm$ 0.003	0.030 $\pm$ 0.001
1.00	40.7	49.1	2.9	65	607	13	0.22 $\pm$ 0.04	0.061 $\pm$ 0.003	0.031 $\pm$ 0.001

Table B.8: Wind Tunnel Data for SOFC Model 09, AXI Double 5360/20 Motor, APC 24 x 12 Prop Wind Tunnel. Air density, ρ was measured to be 1.20 kg/m^3

(a) Without Fuselage									
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.43	64.4	5.6	0.9	12	327	13	0.40 ± 0.06	0.026 ± 0.007	0.021 ± 0.002
0.55	62.0	10.1	1.5	23	383	13	0.36 ± 0.05	0.038 ± 0.005	0.024 ± 0.002
0.67	58.9	15.8	2.0	34	434	13	0.30 ± 0.05	0.043 ± 0.004	0.026 ± 0.001
0.80	55.6	22.0	2.4	44	470	13	0.28 ± 0.04	0.048 ± 0.003	0.027 ± 0.001
0.90	52.4	28.0	2.7	56	497	13	0.27 ± 0.04	0.054 ± 0.003	0.027 ± 0.001
1.00	49.4	33.6	3.0	60	516	14	0.27 ± 0.04	0.054 ± 0.003	0.027 ± 0.001

(b) With Fuselage									
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.44	64.4	5.6	0.9	13	326	12	0.37 ± 0.06	0.029 ± 0.007	0.021 ± 0.002
0.55	62.0	10.0	1.4	24	384	12	0.31 ± 0.05	0.038 ± 0.005	0.024 ± 0.002
0.67	58.9	15.8	2.0	35	434	12	0.29 ± 0.05	0.045 ± 0.004	0.026 ± 0.001
0.80	55.6	22.0	2.4	47	471	12	0.27 ± 0.04	0.050 ± 0.003	0.027 ± 0.001
0.91	52.3	28.0	2.7	55	498	12	0.25 ± 0.04	0.053 ± 0.003	0.027 ± 0.001
1.00	49.3	33.5	3.0	61	517	13	0.26 ± 0.04	0.055 ± 0.003	0.027 ± 0.001

Table B.9: Wind Tunnel Data for SOFC Model 10, AXI Double 5330/20 Motor, APC 22 x 12 Prop Wind Tunnel. Air density, ρ was measured to be 1.20 kg/m^3

(a) Without Fuselage									
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.20	62.8	6.5	0.8	9	363	12	0.38 ± 0.06	0.024 ± 0.008	0.023 ± 0.003
0.32	59.1	13.4	1.4	23	443	12	0.31 ± 0.05	0.039 ± 0.005	0.027 ± 0.002
0.45	53.4	24.3	2.1	40	519	13	0.27 ± 0.04	0.050 ± 0.004	0.029 ± 0.001
0.56	47.0	35.7	2.5	49	565	13	0.25 ± 0.04	0.052 ± 0.003	0.030 ± 0.001
0.67	41.8	45.2	2.8	56	590	13	0.24 ± 0.04	0.054 ± 0.003	0.030 ± 0.001
0.79	36.4	55.1	3.0	60	602	12	0.23 ± 0.04	0.055 ± 0.003	0.031 ± 0.001

(b) With Fuselage									
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.20	62.8	6.5	0.8	11	362	12	0.36 ± 0.06	0.028 ± 0.008	0.023 ± 0.003
0.31	59.1	13.4	1.4	24	443	11	0.28 ± 0.05	0.042 ± 0.005	0.027 ± 0.002
0.44	53.2	24.0	2.1	41	518	12	0.26 ± 0.04	0.052 ± 0.004	0.029 ± 0.001
0.56	47.0	35.7	2.5	51	567	12	0.24 ± 0.04	0.053 ± 0.003	0.030 ± 0.001
0.67	41.9	45.3	2.8	57	590	12	0.23 ± 0.04	0.055 ± 0.003	0.031 ± 0.001
0.80	36.5	54.9	2.9	61	602	12	0.23 ± 0.04	0.057 ± 0.003	0.031 ± 0.001

Table B.10: Wind Tunnel Data for SOFC Model 10, AXI Double 5345/14 Motor, APC 27 x 13 Prop Wind Tunnel. Air density, ρ was measured to be 1.18 kg/m^3

(a) Without Fuselage									
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.24	62.7	6.9	1.1	17	297	13	0.41 $\pm$ 0.06	0.029 $\pm$ 0.005	0.018 $\pm$ 0.002
0.33	57.8	16.3	2.0	34	367	13	0.33 $\pm$ 0.05	0.038 $\pm$ 0.003	0.021 $\pm$ 0.001
0.42	53.1	24.8	2.7	46	407	13	0.30 $\pm$ 0.04	0.042 $\pm$ 0.003	0.022 $\pm$ 0.001
0.53	46.2	37.3	3.2	59	437	14	0.29 $\pm$ 0.04	0.047 $\pm$ 0.002	0.023 $\pm$ 0.001
0.62	40.6	47.5	3.5	65	450	13	0.26 $\pm$ 0.04	0.048 $\pm$ 0.002	0.024 $\pm$ 0.001
0.71	36.5	55.0	3.6	67	456	14	0.28 $\pm$ 0.04	0.049 $\pm$ 0.002	0.024 $\pm$ 0.001

(b) With Fuselage									
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.24	62.7	6.9	1.1	17	298	13	0.39 $\pm$ 0.06	0.029 $\pm$ 0.005	0.018 $\pm$ 0.002
0.33	57.8	16.2	2.0	35	368	13	0.32 $\pm$ 0.05	0.039 $\pm$ 0.003	0.021 $\pm$ 0.001
0.42	53.1	24.7	2.7	46	405	13	0.30 $\pm$ 0.05	0.043 $\pm$ 0.003	0.022 $\pm$ 0.001
0.53	46.3	37.3	3.2	59	437	13	0.27 $\pm$ 0.04	0.047 $\pm$ 0.002	0.023 $\pm$ 0.001
0.62	40.9	47.1	3.4	64	450	14	0.28 $\pm$ 0.04	0.048 $\pm$ 0.002	0.024 $\pm$ 0.001
0.70	36.7	54.8	3.6	66	457	13	0.25 $\pm$ 0.04	0.048 $\pm$ 0.002	0.024 $\pm$ 0.001

Table B.11: Wind Tunnel Data for SOFC Model 10, AXI Double 5345/18 Motor, APC 24 x 12 Prop Wind Tunnel. Air density, ρ was measured to be 1.18 kg/m³

(a) Without Fuselage									
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.32	63.1	6.2	0.9	16	337	12	0.37±0.06	0.033±0.006	0.021±0.002
0.44	59.3	13.0	1.6	30	406	12	0.31±0.05	0.044±0.004	0.025±0.002
0.55	54.0	23.0	2.3	47	468	13	0.28±0.04	0.052±0.003	0.026±0.001
0.67	49.5	31.4	2.6	55	501	14	0.28±0.04	0.053±0.003	0.026±0.001
0.91	40.7	47.5	3.1	63	535	12	0.23±0.04	0.053±0.002	0.027±0.001
1.00	37.2	54.0	3.1	63	542	13	0.24±0.04	0.052±0.002	0.026±0.001

(b) With Fuselage									
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.31	63.1	6.2	0.9	17	334	13	0.39±0.06	0.036±0.006	0.021±0.002
0.44	59.4	13.0	1.6	30	406	12	0.31±0.05	0.045±0.004	0.024±0.002
0.56	54.0	23.0	2.3	48	469	13	0.28±0.04	0.053±0.003	0.026±0.001
0.67	49.5	31.8	2.7	56	502	13	0.27±0.04	0.054±0.003	0.026±0.001
0.79	44.6	40.3	3.0	60	524	13	0.25±0.04	0.053±0.003	0.027±0.001
0.91	40.7	47.6	3.1	63	536	13	0.24±0.04	0.053±0.002	0.027±0.001
1.00	37.2	54.0	3.2	65	542	13	0.25±0.04	0.054±0.002	0.027±0.001

Table B.12: Wind Tunnel Data for SOFC Model 10, AXI Double 5360/20 Motor, APC 26 x 15 Prop Wind Tunnel. Air density, ρ was measured to be 1.20 kg/m^3

(a) Without Fuselage									
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.43	62.2	7.9	1.4	18	295	13	0.41 ± 0.06	0.035 ± 0.006	0.027 ± 0.002
0.55	58.4	14.8	2.2	30	351	13	0.36 ± 0.05	0.042 ± 0.004	0.029 ± 0.001
0.63	54.7	21.7	2.7	42	385	14	0.34 ± 0.05	0.048 ± 0.004	0.030 ± 0.001
0.80	50.6	29.2	3.2	51	414	13	0.30 ± 0.05	0.052 ± 0.003	0.031 ± 0.001
0.93	46.1	37.5	3.6	59	432	14	0.30 ± 0.04	0.055 ± 0.003	0.031 ± 0.001
1.00	43.7	41.8	3.7	62	440	14	0.30 ± 0.04	0.056 ± 0.003	0.032 ± 0.001

(b) With Fuselage									
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.42	62.2	7.9	1.4	18	295	12	0.38 ± 0.06	0.036 ± 0.006	0.027 ± 0.002
0.55	58.5	14.5	2.2	30	351	13	0.36 ± 0.05	0.042 ± 0.004	0.029 ± 0.001
0.68	54.7	21.6	2.7	42	385	13	0.31 ± 0.05	0.049 ± 0.004	0.030 ± 0.001
0.80	50.6	29.0	3.2	52	413	13	0.30 ± 0.05	0.053 ± 0.003	0.031 ± 0.001
0.89	47.0	35.8	3.5	59	429	13	0.28 ± 0.04	0.055 ± 0.003	0.031 ± 0.001
1.00	43.7	41.8	3.7	63	440	13	0.29 ± 0.04	0.057 ± 0.003	0.032 ± 0.001

Table B.13: Wind Tunnel Data for SOFC Model 11, AXI Double 5330/20 Motor, APC 24 x 12 Prop Wind Tunnel. Air density, ρ was measured to be 1.20 kg/m³

(a) Without Fuselage									
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.21	63.7	7.5	1.1	14	343	12	0.37 $\pm$ 0.06	0.028 $\pm$ 0.006	0.023 $\pm$ 0.002
0.32	59.3	15.8	1.7	26	421	13	0.31 $\pm$ 0.05	0.035 $\pm$ 0.004	0.024 $\pm$ 0.001
0.56	44.7	42.5	3.1	49	527	13	0.26 $\pm$ 0.04	0.042 $\pm$ 0.003	0.028 $\pm$ 0.001
0.67	38.8	53.3	3.4	63	542	13	0.25 $\pm$ 0.04	0.051 $\pm$ 0.002	0.028 $\pm$ 0.001

(b) With Fuselage									
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.20	64.1	6.8	1.0	15	340	12	0.35 $\pm$ 0.06	0.032 $\pm$ 0.006	0.022 $\pm$ 0.002
0.31	59.3	15.7	1.8	28	420	12	0.29 $\pm$ 0.05	0.038 $\pm$ 0.004	0.026 $\pm$ 0.001
0.44	51.9	29.3	2.6	43	491	12	0.26 $\pm$ 0.04	0.043 $\pm$ 0.003	0.027 $\pm$ 0.001
0.56	44.8	42.5	3.2	58	528	12	0.24 $\pm$ 0.04	0.050 $\pm$ 0.003	0.028 $\pm$ 0.001
0.67	38.8	53.2	3.4	64	543	13	0.24 $\pm$ 0.04	0.052 $\pm$ 0.002	0.028 $\pm$ 0.001

Table B.14: Wind Tunnel Data for SOFC Model 11, AXI Double 5345/14 Motor, APC 22 x 12 Prop Wind Tunnel. Air density, ρ was measured to be 1.17 kg/m^3

(a) Without Fuselage									
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.24	64.7	5.8	0.8	14	357	13	0.40 ± 0.06	0.038 ± 0.008	0.024 ± 0.003
0.34	62.0	11.0	1.3	24	430	12	0.32 ± 0.05	0.044 ± 0.006	0.027 ± 0.002
0.46	56.0	21.9	2.0	42	519	13	0.29 ± 0.04	0.054 ± 0.004	0.029 ± 0.001
0.59	50.1	32.7	2.5	54	568	13	0.26 ± 0.04	0.058 ± 0.003	0.030 ± 0.001
0.70	45.0	42.0	2.6	58	586	14	0.26 ± 0.04	0.059 ± 0.003	0.030 ± 0.001
0.83	39.4	52.5	2.9	63	608	13	0.24 ± 0.04	0.059 ± 0.003	0.030 ± 0.001

(b) With Fuselage									
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.23	64.7	5.8	0.8	14	356	12	0.39 ± 0.06	0.038 ± 0.008	0.024 ± 0.003
0.34	62.0	11.1	1.3	25	429	13	0.35 ± 0.05	0.047 ± 0.006	0.027 ± 0.002
0.46	56.1	22.1	2.0	42	518	14	0.30 ± 0.04	0.054 ± 0.004	0.029 ± 0.001
0.59	49.9	33.3	2.4	53	560	12	0.24 ± 0.04	0.058 ± 0.003	0.030 ± 0.001
0.70	45.3	41.7	2.7	61	589	12	0.22 ± 0.04	0.060 ± 0.003	0.030 ± 0.001
0.81	39.6	52.0	2.9	65	608	13	0.23 ± 0.04	0.060 ± 0.003	0.030 ± 0.001

Table B.15: Wind Tunnel Data for SOFC Model 11, AXI Double 5345/18 Motor, APC 26 x 15 Prop Wind Tunnel. Air density, ρ was measured to be 1.18 kg/m³

(a) Without Fuselage								
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_P
0.31	63.0	9.0	1.5	21	315	13	0.38±0.06	0.038±0.005
0.44	57.1	20.0	2.5	40	375	13	0.32±0.05	0.049±0.004
0.55	51.2	31.0	3.1	54	414	14	0.32±0.05	0.055±0.003
0.72	43.9	44.2	3.6	63	439	13	0.29±0.04	0.058±0.003
0.80	40.5	50.6	3.7	65	445	13	0.28±0.04	0.058±0.003

(b) With Fuselage								
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_P
0.31	63.0	8.9	1.5	23	306	12	0.38±0.06	0.043±0.006
0.44	57.1	19.9	2.5	41	375	12	0.31±0.05	0.051±0.004
0.55	51.2	30.8	3.1	55	414	14	0.32±0.05	0.056±0.003
0.66	45.8	41.0	3.5	62	434	13	0.29±0.04	0.058±0.003
0.79	40.4	50.4	3.7	67	446	13	0.28±0.04	0.059±0.003

Table B.16: Wind Tunnel Data for SOFC Model 11, AXI Double 5360/20 Motor, APC 27 x 13 Prop Wind Tunnel. Air density, ρ was measured to be 1.20 kg/m^3

(a) Without Fuselage									
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.43	64.0	7.1	1.3	16	307	12	0.36 ± 0.06	0.025 ± 0.005	0.019 ± 0.002
0.55	60.4	13.7	2.1	30	361	12	0.31 ± 0.05	0.034 ± 0.003	0.022 ± 0.001
0.67	56.5	20.9	2.7	42	401	12	0.28 ± 0.05	0.039 ± 0.003	0.023 ± 0.001
0.80	52.3	28.6	3.2	52	429	13	0.27 ± 0.04	0.042 ± 0.002	0.024 ± 0.001
0.90	48.8	35.2	3.5	59	447	13	0.27 ± 0.04	0.044 ± 0.002	0.024 ± 0.001
1.00	45.4	41.4	3.7	64	459	13	0.25 ± 0.04	0.045 ± 0.002	0.024 ± 0.001

(b) With Fuselage									
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.43	64.0	7.1	1.3	16	306	13	0.38 ± 0.06	0.026 ± 0.005	0.019 ± 0.002
0.57	60.1	14.3	2.1	32	367	13	0.32 ± 0.05	0.036 ± 0.003	0.021 ± 0.001
0.67	56.5	20.9	2.6	44	401	13	0.29 ± 0.05	0.040 ± 0.003	0.022 ± 0.001
0.79	52.5	28.5	3.1	53	429	13	0.27 ± 0.04	0.043 ± 0.002	0.023 ± 0.001
0.91	48.8	35.3	3.5	60	447	13	0.27 ± 0.04	0.045 ± 0.002	0.024 ± 0.001
1.00	45.4	41.5	3.7	65	460	13	0.26 ± 0.04	0.046 ± 0.002	0.024 ± 0.001

Table B.17: Wind Tunnel Data for SOFC Model 12, AXI Double 5330/20 Motor, APC 26 x 15 Prop Wind Tunnel. Air density, ρ was measured to be 1.20 kg/m³

(a) Without Fuselage

D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.20	55.9	6.7	1.0	11	269	13	0.47±0.07	0.026±0.007	0.023±0.002
0.30	52.9	17.7	2.1	26	348	13	0.35±0.05	0.037±0.004	0.029±0.001
0.39	49.7	29.4	3.0	45	401	13	0.30±0.05	0.049±0.003	0.030±0.001
0.49	45.0	46.1	3.8	62	446	13	0.28±0.04	0.054±0.003	0.031±0.001
0.58	40.9	61.0	4.3	73	471	14	0.29±0.04	0.057±0.002	0.032±0.001

(b) With Fuselage

D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.20	56.0	6.9	1.0	11	267	12	0.43±0.07	0.027±0.007	0.024±0.002
0.31	52.5	19.8	2.3	33	361	13	0.33±0.05	0.044±0.004	0.029±0.001
0.43	48.4	34.7	3.3	52	421	14	0.31±0.05	0.050±0.003	0.031±0.001
0.55	42.1	57.7	4.2	73	467	13	0.27±0.04	0.058±0.002	0.032±0.001

Table B.18: Wind Tunnel Data for SOFC Model 12, AXI Double 5345/14 Motor, APC 24 x 12 Prop Wind Tunnel. Air density, ρ was measured to be 1.19 kg/m³

(a) Without Fuselage									
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.21	56.7	4.2	0.6	9	293	12	0.43±0.07	0.024±0.008	0.017±0.003
0.31	55.4	9.0	1.1	18	354	13	0.37±0.06	0.035±0.006	0.022±0.002
0.37	54.0	13.8	1.6	29	398	13	0.33±0.05	0.043±0.004	0.024±0.002
0.44	51.4	23.3	2.2	43	459	12	0.27±0.04	0.049±0.003	0.026±0.001
0.53	49.0	32.0	2.6	55	496	13	0.26±0.04	0.053±0.003	0.026±0.001
0.59	47.0	39.2	2.9	59	520	13	0.26±0.04	0.052±0.003	0.026±0.001
0.66	44.4	48.4	3.2	63	543	13	0.24±0.04	0.051±0.002	0.027±0.001

(b) With Fuselage									
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.21	56.7	4.2	0.6	10	291	13	0.47±0.07	0.027±0.008	0.017±0.003
0.30	55.5	8.4	1.1	18	348	12	0.36±0.06	0.035±0.006	0.022±0.002
0.38	54.1	13.8	1.6	30	398	13	0.34±0.05	0.046±0.004	0.025±0.002
0.45	52.0	21.1	2.1	40	448	13	0.29±0.05	0.048±0.004	0.025±0.001
0.52	49.3	30.9	2.6	54	492	13	0.27±0.04	0.054±0.003	0.026±0.001
0.58	47.0	39.0	2.9	60	520	13	0.25±0.04	0.053±0.003	0.027±0.001
0.70	44.5	48.0	3.2	64	545	13	0.24±0.04	0.052±0.002	0.027±0.001

Table B.19: Wind Tunnel Data for SOFC Model 12, AXI Double 5345/18 Motor, APC 27 x 13 Prop Wind Tunnel. Air density, ρ was measured to be 1.18 kg/m³

(a) Without Fuselage								
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_P
0.31	56.1	6.1	1.0	13	284	13	0.41±0.06	0.017±0.002
0.44	53.5	15.8	2.0	32	361	12	0.31±0.05	0.021±0.001
0.55	50.3	27.6	2.8	49	415	14	0.30±0.04	0.023±0.001
0.66	46.8	39.9	3.5	64	450	13	0.27±0.04	0.024±0.001
0.80	43.1	53.0	4.0	76	476	13	0.25±0.04	0.024±0.001

(b) With Fuselage								
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_P
0.31	56.1	6.1	1.0	14	285	12	0.39±0.06	0.017±0.002
0.43	53.5	15.7	2.0	33	361	13	0.32±0.05	0.021±0.001
0.56	50.2	27.5	2.8	50	416	13	0.29±0.04	0.023±0.001
0.67	46.8	39.9	3.5	65	451	13	0.27±0.04	0.024±0.001
0.80	43.2	52.9	4.0	77	476	14	0.26±0.04	0.024±0.001

Table B.20: Wind Tunnel Data for SOFC Model 12, AXI Double 5360/20 Motor, APC 22 x 12 Prop Wind Tunnel. Air density, ρ was measured to be 1.20 kg/m³

(a) Without Fuselage							
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	C_P
0.55	56.0	6.6	0.8	12	362	13	0.39±0.06 0.030±0.008 0.024±0.003
0.66	55.0	10.4	1.2	20	417	12	0.33±0.05 0.038±0.006 0.027±0.002
0.78	53.6	15.5	1.6	29	467	12	0.28±0.05 0.045±0.005 0.028±0.002
0.89	52.0	21.2	2.0	39	509	12	0.27±0.04 0.051±0.004 0.030±0.002
1.00	50.4	27.0	2.3	49	542	13	0.26±0.04 0.056±0.003 0.030±0.001

(b) With Fuselage							
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	C_P
0.55	56.0	6.6	0.9	13	361	12	0.36±0.06 0.033±0.008 0.026±0.003
0.67	54.9	10.6	1.2	22	417	13	0.34±0.05 0.042±0.006 0.027±0.002
0.79	53.7	15.0	1.6	30	463	13	0.31±0.05 0.048±0.005 0.028±0.002
0.91	52.1	21.0	2.0	40	509	13	0.28±0.04 0.052±0.004 0.030±0.002
1.00	50.5	26.7	2.3	48	543	14	0.28±0.04 0.055±0.003 0.030±0.001

Table B.21: Wind Tunnel Data for SOFC Model 13, AXI Double 5330/20 Motor, APC 27 x 13 Prop Wind Tunnel. Air density, ρ was measured to be 1.20 kg/m³

(a) Without Fuselage								
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_P
0.22	59.5	9.0	1.3	13	311	12	0.36±0.06	0.021±0.005
0.30	57.0	18.4	2.2	32	376	13	0.31±0.05	0.034±0.003
0.39	53.5	30.8	3.1	51	431	14	0.29±0.04	0.041±0.002
0.49	48.2	50.0	4.1	71	481	13	0.25±0.04	0.046±0.002
0.56	45.1	61.0	4.4	79	500	13	0.24±0.04	0.047±0.002

(b) With Fuselage								
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_P
0.20	60.2	6.6	1.1	10	287	12	0.39±0.06	0.018±0.005
0.31	56.8	18.9	2.2	34	380	12	0.29±0.05	0.035±0.003
0.39	53.7	30.4	3.1	50	430	13	0.28±0.04	0.040±0.002
0.49	48.3	49.8	4.0	71	482	13	0.24±0.04	0.046±0.002
0.56	45.1	61.0	4.4	79	500	14	0.26±0.04	0.047±0.002

Table B.22: Wind Tunnel Data for SOFC Model 13, AXI Double 5345/14 Motor, APC 26 x 15 Prop Wind Tunnel. Air density, ρ was measured to be 1.20 kg/m³

(a) Without Fuselage									
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.24	60.0	7.4	1.2	16	281	13	0.43 $\pm$ 0.07	0.036 $\pm$ 0.007	0.025 $\pm$ 0.002
0.33	57.1	17.6	2.2	36	357	13	0.34 $\pm$ 0.05	0.048 $\pm$ 0.004	0.029 $\pm$ 0.001
0.42	54.3	27.9	3.1	52	407	13	0.31 $\pm$ 0.05	0.054 $\pm$ 0.003	0.031 $\pm$ 0.001
0.54	49.3	46.0	3.9	69	449	13	0.27 $\pm$ 0.04	0.059 $\pm$ 0.003	0.032 $\pm$ 0.001

(b) With Fuselage									
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.22	60.0	7.4	1.2	16	281	12	0.41 $\pm$ 0.07	0.036 $\pm$ 0.007	0.025 $\pm$ 0.002
0.30	58.1	14.1	1.9	30	342	13	0.35 $\pm$ 0.06	0.044 $\pm$ 0.004	0.027 $\pm$ 0.001
0.38	55.5	23.7	2.8	46	391	13	0.32 $\pm$ 0.05	0.053 $\pm$ 0.003	0.030 $\pm$ 0.001
0.45	53.3	31.4	3.2	56	415	13	0.30 $\pm$ 0.05	0.057 $\pm$ 0.003	0.031 $\pm$ 0.001
0.53	49.3	45.8	3.9	71	448	14	0.30 $\pm$ 0.04	0.061 $\pm$ 0.003	0.032 $\pm$ 0.001

Table B.23: Wind Tunnel Data for SOFC Model 13, AXI Double 5345/18 Motor, APC 22 x 12 Prop Wind Tunnel. Air density, ρ was measured to be 1.18 kg/m^3

(a) Without Fuselage									
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.31	60.6	5.3	0.7	13	346	13	0.41 ± 0.07	0.036 ± 0.009	0.023 ± 0.003
0.43	59.3	10.2	1.2	23	420	13	0.34 ± 0.05	0.044 ± 0.006	0.026 ± 0.002
0.56	56.7	19.0	1.9	41	504	13	0.29 ± 0.04	0.056 ± 0.004	0.029 ± 0.002
0.66	54.2	28.8	2.4	54	559	13	0.27 ± 0.04	0.059 ± 0.003	0.030 ± 0.001
0.80	51.1	39.8	2.9	65	605	14	0.25 ± 0.04	0.061 ± 0.003	0.031 ± 0.001
0.91	48.3	50.0	3.3	74	636	14	0.24 ± 0.04	0.063 ± 0.002	0.032 ± 0.001

(b) With Fuselage									
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.31	60.6	5.3	0.7	13	347	13	0.41 ± 0.06	0.038 ± 0.008	0.023 ± 0.003
0.43	59.2	10.2	1.2	24	418	12	0.33 ± 0.05	0.048 ± 0.006	0.027 ± 0.002
0.56	56.7	19.4	1.9	42	504	13	0.28 ± 0.04	0.056 ± 0.004	0.029 ± 0.002
0.66	54.2	28.7	2.4	55	559	12	0.25 ± 0.04	0.061 ± 0.003	0.030 ± 0.001
0.80	51.1	39.7	2.9	66	606	13	0.24 ± 0.04	0.062 ± 0.003	0.031 ± 0.001
0.89	48.2	50.0	3.3	75	637	13	0.23 ± 0.04	0.064 ± 0.003	0.032 ± 0.001

Table B.24: Wind Tunnel Data for SOFC Model 13, AXI Double 5360/20 Motor, APC 24 x 12 Prop Wind Tunnel. Air density, ρ was measured to be 1.20 kg/m^3

(a) Without Fuselage									
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.44	60.7	5.0	0.8	10	313	13	0.43 $\pm$ 0.07	0.025 $\pm$ 0.007	0.021 $\pm$ 0.002
0.55	59.5	9.2	1.3	21	372	14	0.38 $\pm$ 0.06	0.036 $\pm$ 0.005	0.024 $\pm$ 0.002
0.67	57.8	15.3	1.9	33	426	13	0.32 $\pm$ 0.05	0.043 $\pm$ 0.004	0.026 $\pm$ 0.001
0.79	55.9	22.2	2.4	44	473	14	0.30 $\pm$ 0.04	0.047 $\pm$ 0.003	0.027 $\pm$ 0.001
0.90	54.0	29.5	2.9	58	509	13	0.26 $\pm$ 0.04	0.053 $\pm$ 0.003	0.027 $\pm$ 0.001
1.00	51.9	36.8	3.3	66	539	13	0.25 $\pm$ 0.04	0.054 $\pm$ 0.002	0.028 $\pm$ 0.001

(b) With Fuselage									
D	V_c (V)	I_c (A)	τ (N-m)	T (N)	ω (rad/s)	S (m/s)	J	C_T	C_P
0.43	60.7	5.0	0.8	12	312	13	0.42 $\pm$ 0.07	0.031 $\pm$ 0.007	0.021 $\pm$ 0.002
0.55	59.5	9.4	1.4	22	372	12	0.34 $\pm$ 0.06	0.038 $\pm$ 0.005	0.024 $\pm$ 0.002
0.67	57.8	15.2	1.9	33	426	12	0.29 $\pm$ 0.05	0.043 $\pm$ 0.004	0.026 $\pm$ 0.001
0.80	55.9	22.4	2.5	48	473	13	0.28 $\pm$ 0.04	0.051 $\pm$ 0.003	0.027 $\pm$ 0.001
0.91	53.9	29.6	2.9	60	510	13	0.26 $\pm$ 0.04	0.055 $\pm$ 0.003	0.028 $\pm$ 0.001
1.00	52.0	36.8	3.3	68	538	14	0.26 $\pm$ 0.04	0.056 $\pm$ 0.002	0.028 $\pm$ 0.001