Cal Poly Hydrogen Fuel Cell Senior Project
Air Plane Galley Demonstrator

Laurel Fee
Adam Ferrarelli
Nick Hasheider
Jeff Massman
Alex Mosbacher
David Mravca
Brian Noland
Levi Sternberg
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Introduction

As the consumer market becomes more energy conscious, businesses are looking to become more efficient in their operations. Boeing has invested into the feasibility of using a fuel cell to power future planes galleys. Cal Poly’s role is to aide in the research by creating a hydrogen fuel cell powered galley demonstrator to be delivered June 1st, 2011 and shown at trade-shows as well as Boeing’s concept laboratory. Boeing has supplied the senior project team with a beverage maker and convection oven currently used in the airline industry, and given the team the option to alter the design of these appliances as necessary.

Background

The fuel cell galley demonstrator is an integration project aimed towards improving fuel efficiency. Currently, an aircraft galley draws power from the left and right engines’ integrated drive generators. Meals are cooked on the ground before take-off and are merely kept warm during flight in the ovens until they are served. This requires the galley to be routed with power at all times, either from the integrated drive generators or from an external power source while on the tarmac. An aircraft galley usually consists of ten beverage makers, five ovens, and five refrigeration units.

Boeing is researching effective methods of powering a galley without having to divert power from the engines, reduce overall fuel consumption, and have the galley’s power supply be independent from the aircraft. A fuel cell creates the power necessary without having to divert it from another source; it takes in hydrogen and oxygen to produce electricity, heat, and water. If both the heat and electricity can be harnessed as power for the galley, then it becomes a more efficient energy producing system than the integrated drive generators.

Originally, Boeing outsourced the fuel cell galley project to the aviation division of the design firm Teague. The main concept developed there was to use a reservoir to store the output water from the fuel cell and then reheat it in a boiler when a beverage was to be made. Though this project had good potential in its design, it was littered with issues that had not been fixed. After reviewing Teague’s phase review, Boeing decided to hand off the project to Cal Poly senior standing students.

Boeing supplied the Cal Poly senior project team with three key components: a hydrogen fuel cell, a galley beverage maker, and a galley convection oven. The provided fuel cell is a Serenus 390 Air C High Temperature Proton Exchange Membrane (HTPEM) fuel cell. An HTPEM fuel cell was selected because of the high temperature exhaust and high electrical load put out from the fuel cell. The beverage maker supplied is a BE Aerospace Endura Beverage Maker, and the oven a DF3000 Convection Oven. Both of these appliances are commonly found on airplanes and were supplied with the aim to mimic a real airplane galley. The other components needed for
a functioning system were procured by students on the Cal Poly team and the design firm Teague.

Problem Statement

Design and build an airplane galley demonstration unit powered exclusively by both the electrical and thermal energy output of a hydrogen fuel cell. The unit will consist of two appliances (a coffee pot and an oven) and inform the user or auto-respond to any conditions that pose a threat to system integrity or human safety.

Requirements

The system must be designed to operate within the following constraints:

I. An airplane galley demonstration system (“the system”) will be delivered which uses a Serenergy Serenus 390 Air C hydrogen fuel cell as the energy source to deliver electrical and/or thermal power (“power”) to appliances.

II. Energy storage devices will be used for any power required beyond what the fuel cell can provide.

III. The system will power a B/E Aerospace 4510 series beverage maker.

IV. The system will power a B/E Aerospace DF3000 convection oven.

V. The system must inform the user or auto-respond to any conditions that pose a threat to system integrity or human safety.

VI. The airplane galley demonstration system must be delivered by 6/1/2011.

Design

In designing the hydrogen fuel cell galley demonstrator, the team broke up the design into the following subsystems: fuel cell, electrical, thermal, appliances, and controls. A detailed design of the different subsystems is outlined below.

Fuel Cell / Electrical

The Serenus 390 Air C HTPEM fuel cell consumes a mixture of air and pure hydrogen gas to produce 3.2kW of DC electrical power while exhausting a hot gas containing byproducts of the reaction. The fuel cell is set up to run in a dead-end configuration,
which means that hydrogen does not continuously flow through the fuel cell. Instead, the internal pressure of the hydrogen is kept at 50 mbar and must be purged occasionally to allow new fuel to enter. The fuel cell begins operation by charging an energy storage device, which acts as the main electrical load for the fuel cell. Operation of the fuel cell generates a hot exhaust, which is used to preheat the air and water in the oven and coffee pot, respectively. After the hydrogen fuel tank is depleted, the storage device can supply the necessary electrical power to run the system.

Our system uses a 4th Generation Toyota Prius lithium ion battery pack as the energy storage device. This battery pack requires a nominal voltage of 201.6V to charge efficiently. The fuel cell outputs only 140V at optimum performance, therefore a DC-DC converter is needed to step up the output voltage of the fuel cell.

The DC-DC converter selected for the system is a model CH40040F-SSU from Zahn Electronics, Inc. This model has an input range of 80V-298V and an output range of 82V-300V, which comfortably fits within the system requirements. Four inductor-capacitors are used at the input to the Zahn DC-DC converter to filter out the excess noise and protect the converter from potential voltage spikes. The output voltage of the Zahn converter is currently set to approximately 200V and an external potentiometer limits the current to 23 Amps. The output of the DC-DC converter is wired to the power bus bar, which provides power to all the appliances in the system.

It is imperative to keep the fuel cell’s voltage below the battery voltage. In the event that the fuel cell’s voltage exceeds the battery voltage, a bleed resistor directs any current spikes from the fuel cell to the heating elements inside the oven. After current spikes recede, relays close and allow power to again be converted to the positive power bus bar. From the power bus bar, relays to the battery, oven, beverage maker, or the 24V converter may be closed to continue operation of the system.

**Thermal**

The purpose of the thermal loop is to route the hot exhaust from the HTPEM fuel cell through a series of two heat exchangers to recover waste heat from the fuel cell. This waste heat recovery effort will preheat both the oven and the beverage maker. An intercooler heat exchanger is used for the oven’s air loop and a radiator heat exchanger is used for the beverage maker’s water line. The exhaust is channeled by two pieces of expansion ducting, first a 90-degree expanding elbow followed by a round to rectangular transition. The ducting design was aimed to minimize both heat and flow losses to allow a uniform flow with a cross sectional area equivalent to both heat exchangers. The flow of the exhaust is downward to allow any condensation to drip out of the system.

The oven loop has a turbo-compressor that circulates the air in the oven through the intercooler. This loop is closed and separate from the exhaust to maintain sanitation standards. There are valves in both the oven’s inlet and outlet piping that close off the
oven loop. This helps internalize heat inside the oven when the oven temperature exceeds the temperature of the heat exchanger loop (about 250° F).

The water loop carries water from a large storage tank through the radiator and into the beverage maker’s internal storage tank. A small pump operated at two distinct speeds will drive this line. The first speed is slow in order to obtain maximum temperature rise through the heat exchanger while the beverage maker’s internal tank is filling up. The second speed is during the brewing stage when the flow needs to be faster to maintain the beverage maker’s tank level during brewing.

The thermal loop design can be seen in the Appendix. Figure 4 shows an exploded view of the ducting and heat exchangers. Figure 5 and Figure 6 show an exploded view of the radiator heat exchanger and turbo-compressor system.

**Appliances**

The two galley supplied appliances are a convection oven and beverage maker. Both appliances were originally three-phase with a frequency of approximately 400 Hz. The convection oven requires an input voltage of 200V AC and consumes approximately 3800 Watts of power in one cooking cycle. The beverage maker requires an input voltage of 115V AC and consumes approximately 2745 Watts of power in one brewing cycle. Our model beverage maker is unique in that it was modified to plug into any standard wall socket.

The demonstration unit was designed so the AC electrical load of the appliances could be supplemented with the DC voltage and the thermal energy outputted from the fuel cell. Both appliances had to be converted from their original AC electrical components to comparable DC components. Most of the beverage maker’s original hardware was salvageable including: the solenoid valves, the heating coils, all of the plumbing, and the water tank temperature and level sensors. All of the computer logic and hardware provided was reconfigured due to the lack of necessary schematics. The oven’s original 28 V DC three-phase brushless motor was replaced with a less complex 24 VDC brush motor. An Omega temperature controller was installed to replace the oven’s original controls.

The fuel cell’s thermal output is routed through a radiator heat exchanger to preheat water before it enters the beverage maker’s storage tank. This process is explained in more detail in the thermal portion of the report. The beverage makers total power consumption is greatly reduced by preheating the water before it enters the storage tank. This is because a large amount of electrical energy is required to raise the water in the tank to the appropriate brewing temperature of 90°C. A radiator is used to allow the heat exchange between the fuel cell exhaust and water, as described in the Thermal Loop portion of the report.

The thermal energy is also used to help preheat the inside of the oven. Two additional
holes were machined out of the oven’s walls so it could be connected to an air-to-air heat exchanger. A 24V DC brush motor is used to circulate the air in the oven. Circulating the air in the oven reduces the need of the oven’s heating coils to increase the oven’s internal temperature, thus reducing the oven’s total power consumption.

Controls

The AC powered appliance controls were replaced to better suit the fuel cell’s output DC voltage. Using DC power simplified the design process by avoiding the need to invert the fuel cell’s DC voltage to AC. The oven and beverage maker’s controller logic was simplified to perform the appliances’ basic functions. These basic functions were broken down into analog and digital inputs and outputs.

Control of the oven begins with the user pressing sustained button on its face, connected as a digital input to the Arduino thermal system controller. When the button is on, the Arduino supplies 24VDC power to an Omega temperature controller. The desired temperature of the oven is initially set by the user on the user interface of the temperature controller. If the fuel cell is running and the oven temperature is below the fuel cell’s exhaust temperature, the Arduino turns on a 24VDC blower to circulate air in the oven through the external heating loop for preheating. Once the oven temperature is stabilized, or it is above the fuel cell’s exhaust temperature, the blower loop is turned off, as it would only remove heat from oven at this point, rather than assist the process, as detailed in the thermal section. The temperature feedback of the oven is via a resistance temperature detector (RTD) connected to the Omega 24 Volt DC temperature controller.

The Omega temperature controller selected has a single pole double throw (SPDT) relay and analog outputs. The analog output indicates the oven’s inner temperature to the Arduino controller so that it may decide whether to run the exhaust assist loop as described previously. The temperature controller opens/closes the SPDT relay depending on whether the oven temperature is at its user-prescribed set-point or not. The state of the relay is not switched, however, if the temperature is within a certain dead-band about the set point. When the user button is off, power to the temperature controller is removed, as is power to the blower and oven fan.

The beverage maker controls are somewhat more complex since a premade controller was not used and its functionality involves more inputs and outputs. To operate, the beverage maker controls need to know the water tank is full and up to a brewing temperature of 90ºC. The original tank level sensor and temperature sensor are used as feedback for control of the pump and heating elements, respectively. The Arduino beverage maker controller uses a 24VDC control signal to switch a single pole single throw relay connecting/disconnecting power to the heating coils. Once the beverage maker’s tank is full and up to operating temperature (nominally 91 °C), a brewing cycle can be started by pressing the brew button. This causes the controller to put out a 24 Volt signal to a solenoid valve, allowing water to flow from the tank, into the coffee
grounds, and dripping into the pot. Because information for using the level sensor originally in the beverage maker, which indicated the pot’s coffee level, was not available, it has not been integrated and the brew process stops filling the pot by use of a software timer.

[The beverage maker Arduino microcontroller node and the thermal system Arduino node have been discussed. Still to be explained in an addendum to this report is the third, fuel-cell-system Arduino node. This node, communicates with the fuel cell and the other two nodes with the Controller Area Network 2.0A protocol. It supervises the loads and bus voltages (DC/DC converter input and output) to perform such functions as making sure the DC/DC converter is operated in the proper boost configuration, making sure the loads do not attempt to draw power when the fuel cell is not ready for a load or in some other error state, etc. Furthermore it relays “load-requests” from the beverage maker and thermal system controller to the fuel cell, so it may be started up from a stand-by state simply by pressing the appliance’s “on” buttons.]

**Fabrication**

The galley demonstrator system unit was created using a three tier structure, pictured in Figure 1 in the Appendix. The top tier of the structure holds the keystone of our project, the fuel cell, which is located on the top tier for two reasons. The exhaust of the fuel cell contains moisture, and by routing the exhaust downward we avoid having the corrosive moisture accumulate and pool. Also, the fuel cell is located on the top tier in case any hydrogen gases were to escape, then the likelihood of them igniting from any electrical source in our system would be minimized.

The second tier of our structure contains the galley appliances, the heat exchangers, the water tank, and controls. Appliances are located on the second tier to mimic the height of a galley countertop. The water tank is located on the same plane as the coffee pot to prevent overflow, as the pump cannot regulate the flow if the tank is up to high, due to gravity, and the water tank could not be on the same level as the high voltage battery located below. Controls are kept near the appliances for convenience.

The bottom tier of the structure contains our high voltage electrical tray. The structure required some of the heavy components be placed on the bottom for stability reasons, and due to the dangers associated with high voltage, the tray fit best down below out of reach.

**Testing**

[To be completed when system is fully operational]

**Results**

[To be completed when system is fully operational]
Conclusion

[To be completed when system is fully operational]

User’s Manual

[To be completed when system is fully operational]
Appendix

Figure 1: Galley Demonstrator View 1
Appendix

Figure 2: Galley Demonstrator View 2
Appendix

Figure 3: Galley Demonstrator View 3
Appendix

Figure 4: Heat Exchanger Box

Figure 5: Oven Loop Exploded View 1
Appendix

Figure 6: Oven Loop Exploded 2
Figure 7: Oven Blower and Thermal Loop
Appendix

Figure 8: Electrical Tray Schematic