Solid-Oxide Fuel Cell Heat Exchanger

PRELIMINARY DESIGN REPORT

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We commit to deliver our final report to our industry contact and we grant permission to the course professors to deliver our final report should we fail to do so.

Executive Summary

The purpose of this project is to design a heat exchanger for a solid oxide fuel cell system. The general idea behind applying a solid oxide fuel cell system to the automotive industry is to provide a meaningful solution to address the shortcomings of internal combustion engines (ICE), as well as emerging electric vehicle technology (EV). ICE vehicles have a very low overall efficiency and are a large contributing factor to the world's pollution. EV's have a critical drawback in the way they store energy; lithium ion batteries have very low mass and volume energy densities compared to liquid fuel, and require significant amounts of natural resources to produce. A solid oxide fuel cell system would take advantage of the efficiency of electric drivetrains while avoiding the battery issue by generating electricity as needed.

To maintain the high operating temperature required for SOFC's, a need arises to exchange heat from the hot exhaust gases to the cold fuel and air on their way in to the system. Heat exchanger design for the anode branch of the system will be the focus of this project. The device will also have to withstand high operating temperatures, resist corrosion, and be feasible for mass scale production. This report discusses the development of a heat exchanger configuration that can facilitate sufficient heat transfer in a compact form factor.

The team determined that a microchannel heat exchanger fits these constraints best. This heat exchanger maximizes surface area, is efficient and is able to operate at extreme temperatures. The appropriate material to be used is nickel, due to its high thermal conductivity and melting point. The general design of the heat exchanger is proposed in this report.

To conclude, the general design of the heat exchanger is proposed in this report. This includes the type, material to be used, layout, manufacturing and flow type. A technical memo will be delivered March 8th. This report will focus on pressure and efficiency calculations.

Table of Contents

Proposal Statement

Problem

There are many improvements to be made in the automotive industry in terms of energy efficiency and pollution. The vast majority of vehicles in the world today are powered by internal combustion engines. These types of engines have thermal efficiencies of only around 30% [6]. Electric vehicles are currently still a niche market. They also have several limitations such as a limited range, long recharge time and expensive batteries. Considering the quantity of vehicles on the earth, it is obvious the substantial impact engines have on the environment and economy.

Solid oxide fuel cells (SOFC) convert fuel into electricity through chemical reactions. They have substantial advantages over current engine technology and provide a solution to environmental concerns. In addition to producing cleaner emissions, SOFCs have up to twice the efficiency than combustion engines. Implementing SOFCs into vehicles would reduce fuel consumption and emissions significantly. In addition, fuel cells do not have the limitations of electric vehicles. With rising environmental and public health concerns, it is necessary to change the power source of vehicles.

To implement solid oxide fuel cells in vehicles, a heat exchanger is essential to increase the efficiency of the system. Our team is designing a heat exchanger configuration for a SOFC powered vehicle. Size and temperatures are the main challenges associated with integrating a heat exchanger within a SOFC vehicle. Using a heat exchanger to increase efficiency of a system is not a new concept, but most of these devices are designed for power plants, not vehicles. The heat exchanger needs to be designed to maximize surface area and handle extreme temperatures with a good reliability to pass all vehicle regulations.

Literature Review

Fuel cells in vehicles can be thought of as an on-board battery charger, using an easily refillable fuel source in a chemical reaction that converts into electrical energy. At a basic level, fuel cells consist of three components, the cathode, the anode and an electrolyte. To generate electricity, a fuel undergoes oxidation reactions at the anode using a catalyst. This generates protons and electrons, with the former flowing to the cathode through the electrolyte, and the latter flowing through an external circuit, producing DC power. The protons and electrons meet again at the cathode, which again using a catalyst react and produce the by-product of pure water. A single fuel cell does not produce a substantial amount of voltage (<1V), but the connection of many fuel cells in what's known as a stack allows for a usable voltage to be produced.

Fuel cells are then further categorized by the type of electrolyte used. Currently, Toyota, Hyundai and other manufacturers are using Proton Exchange Membrane fuel cells (PEMFC) in their fuel cell vehicles due to the quick start up time and lower operating temperature, but these require expensive platinum catalysts and the membrane used as an electrolyte is prone to problems with contamination and must be kept at a specific level of wetness during operation, at the threat of decreased efficiency. SOFCs on the other hand use a solid oxide or ceramic electrolyte, as well as ceramic cathodes and anodes. They are less prone to catalyst contamination than PEMFCs and can use a wider variety of fuel sources. In addition, SOFC have very high efficiencies (up to 60%) and long service lives. These traits make SOFCs an appealing technology to be used in transportation.

Solid oxide fuel cells have substantial advantages over internal combustion engines. Efficiencies and limitations of modern vehicles need to be addressed. Due to the large number of vehicles on the road today, increasing efficiency will have a large, positive impact on the environment and economy. SOFCs have very few emissions, only releasing H_2O, N_2, CO_2 and O_2. With rising climate change concerns, it is necessary to implement this into transportation. The greatest challenge to accomplishing this is the difficulty in reducing the form factor of the system from large scale power generation to fitting in a compact car.

The foreseeable future of personal transportation is a cloudy one but while electric vehicles are growing in popularity, they are still currently a niche market, with several limitations compared to traditional internal combustion. The next 10-20 years will likely see a huge rise in alternative power options, with many believing that the plug-in electric car is only a stepping stone towards a fuel cell powered future. The critical drawback of electric vehicles is the large battery they require, as lithium ion batteries currently have low energy density by mass and volume and are also very resource intensive to produce. This project is needed to bring that future a step closer. SOFC has a large potential as a power source, with the potential for low emission, high efficiency, and high output electricity to power not only the consumer's vehicle, but could theoretically address the household's power needs, drastically reducing the strain on the world's power generation plants.

The goal to shrink SOFC technology to a size practical for use personal transportation has several benefits. Firstly, SOFC has the ability for flexible fueling, meaning it can use several different fuels with the limitation being that they contain hydrogen. This includes potential fuels like methane, natural gas, propane and others, which are already widely available fuels, reducing the cost of ownership, as well as reducing the need for new infrastructure to be built. SOFC are also the most efficient, and most environmentally friendly hydrogen fuel cell technology [3] when paired with a co-generation process, and less expensive to produce because there is no need for a platinum catalyst like current PEMFCs.

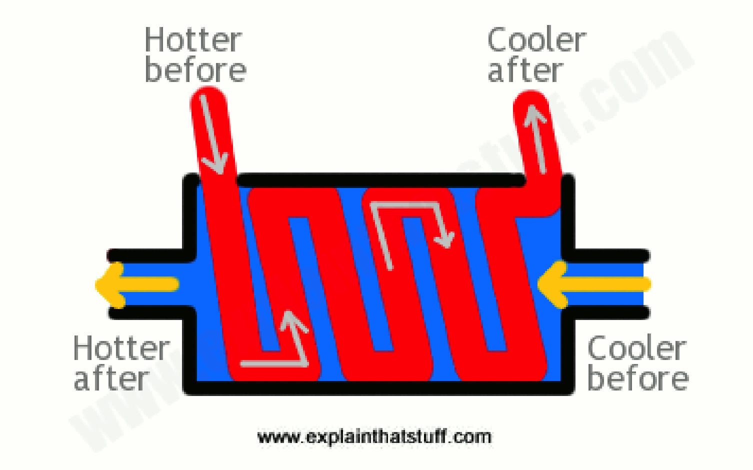


Figure 1: Basic heat exchanger

However, for the solid oxide fuel cell to operate at the maximum efficiency, high inlet air temperatures are required to heat the ceramics, which causes a slow start-up time of the SOFC. The high temperature of the afterburner exhaust and leftover fuel (1000C and 600C respectively) can be used for the purposes of overcoming this issue through a co-generative process, using a heat exchanger. Heat exchangers work on the theory of heat transfer, which allows the heat of one fluid to be transferred to another. By recycling the heat, it lowers the amount of input energy needed to run the system [2]. Figure 1 illustrates a basic heat exchanger. The heat exchanger should operate safely at the high temperatures, imparting the otherwise wasted heat onto the inlet air and fuel. Heat exchangers for this purpose within SOFCs is not a new idea. Nonetheless, fuel cells in the modern world are mostly used in power plants, where size is not a constraint. If it is to power a vehicle, the entire configuration should not exceed the volume of an internal combustion engine. It is a major challenge to design a configuration with the appropriate size and durability required to be mounted within a passenger vehicle, while operating at a high efficiency.

Scope & Objective

To maintain the high operating temperature required for SOFC's, a need arises to exchange heat from the hot exhaust gases to the cold fuel and air on their way in to the system. As seen in figure 2 below, some form of heat exchanger will be required on both the anode and cathode side of the proposed system; this project will focus on designing for the anode conditions. An important consideration is that the focus of this course is towards the earlier stages of the design process and no manufacturing or testing can occur. However, due to the nature of this project, the need to provide strong evidence to justify design choices is especially important. Therefore, the group believes that fully modelling a prototype and providing simulation data to support it is an ambitious approach.

The general goals to be accomplished during this project are as follows:

- An investigation of different heat exchange configurations with a determination of which is most effective and what size will be required for proper function.
- A suitable material for the device is to be found that can also withstand the extreme temperatures and internal fluid pressures, which are to be specified by the client.
- An evaluation of the overall long-term durability that includes consideration of the need for adequate corrosion resistance.
- Determination of costing and overall feasibility for large scale production
- Consideration of the environmental impacts associated with the theoretical manufacturing process

Evaluation Criteria

Constraints

- The volume of the heat exchanger should not exceed 0.03 cubic meter.

  The entire solid oxide fuel cell must fit into the engine bay of a vehicle. Due to considerations for the size of other system components, the heat exchanger should not exceed this volume.

- The heat exchanger and pipes must be able to withstand temperatures up to 800℃.

  The fuel cell operates at extremely high temperatures (for maximum efficiency around 800℃).

- The heat exchanger and pipes must be corrosion resistant

  The heat exchanger must resist corrosion to increase longevity and keep up the performance of the vehicle.

- The device must be capable of accommodating flow rates up to 10 L/s.
  The overall cross-sectional flow area must be reasonably large such that excessive velocities are not required to reach this flow rate.

Criteria

- Final product must be built and assembled efficiently.

Since the final product will have to be mass produced, the manufacturing of the Heat exchanger should be taken into consideration. The part needs to build with a process that will allow mass production efficiently. Different manufacturing processes will have to be taken under consideration.

- The efficiency of the heat exchanger should be maximized.

If it is found that several heat exchangers withstand the high temperature and meet the volume constraint, the efficiency should be considered.

- The overall pressure loss that occurs through the device should be minimized.

- Reducing size beyond the specified 0.03 cubic meters.

Conceptual Design

The team has done intensive research on modern heat exchanger designs. Below are the top 3 suited designs and some information about them.

Microchannel Plate Heat Exchanger

The first heat exchanger design being considered is the microchannel heat exchanger. As the name implies, the fluid flows through small diameter tubes called microchannels. The dimensions of these channels are typically no larger than 1mm. [2] The benefit of constraining the stream through these small openings is that it reduces the thermal resistivity [1]. These microchannels can come in many different shapes (i.e. triangular, rectangular tubes) and can be made from various materials [2]. Figure 2 displays what rectangular microchannel can look like.

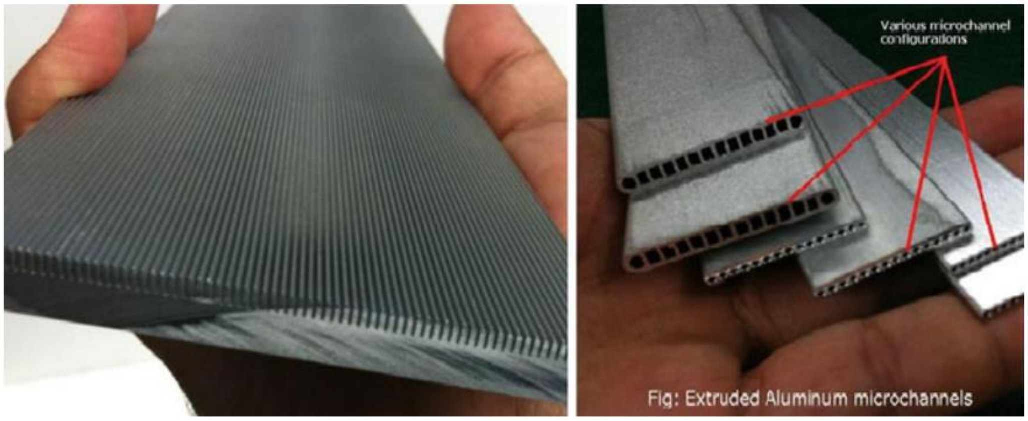


Figure 2:Example of a microchannel heat exchanger

For the purposes of this heat exchanger, a metal alloy that has a very high melting point (above 1000K) that is also resistant to corrosion will be chosen. Ceramics are another alternative; however, the structural integrity of ceramic is much less than that of a metal alloy. The material has yet to be decided, but it will most likely be a nickel based alloy.

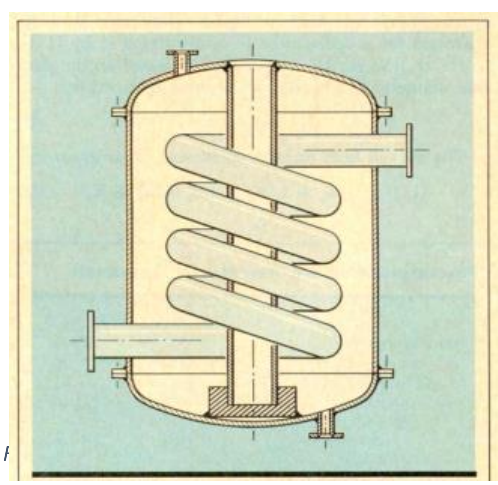
This type of heat exchanger has many advantages; the heat transfer coefficient is increased due to the many channels (meaning heat can transfer more easily). They can be manufactured smaller which is very beneficial in the case of designing this heat exchanger for a solid-oxide fuel cell car. Finally, since there is less material being used in manufacturing, the weight of the unit will be lower as well as the cost which is great for mass production [1]. There is however a drawback. With the small dimensions of the channels, there is a pressure loss due to the inability to maintain the uniform flow [1]. Due to the design of the microchannels, this problem is unavoidable.

Double Pipe Heat Exchanger

Another option is a double pipe heat exchanger in which a smaller pipe is contained within a larger pipe. The separate fluids then flow through the pipes and the heat exchanging surface is the inner pipe [3]. Double pipe heat exchangers can support both counterflow and parallel flow with counterflow being the more efficient of the two options. The smaller internal pipe also has the option to be multiple pipes or tubes so that the surface area for heat transfer is increased. In both options it is necessary to shape the heat exchanger so that it is not one long pipe and instead a more compact unit with many passes. Passes are the number of times the fluid runs the length of the device by making sequential 180 degree turns.

This type of heat exchanger is a simpler option and the manufacturing of this type of heat exchanger would not limit material choice drastically. The size of the heat exchanger can be determined by the configuration of the bends however the length and diameter needed are dependent on the desired performance. The efficiency of this heat exchanger will vary with the diameter of piping used so in cases where a large flow rate is required a double pipe heat exchanger will not be the best choice. This loss of efficiency can be counteracted by breaking the heat exchanger into multiple smaller systems or using multiple internal pipes rather than one. However, these options will have drawbacks in pressure drop as well as manufacturing. As a double pipe heat exchanger can be assembled by connecting multiple pipes and pipe bends together the manufacturing cost of double pipe heat exchanger is low and therefore desirable.

Helical-Coil/Spiral Heat Exchanger



To begin a description of the spiral heat exchanger (SHE), the helical-coil design with which it's based must be explained first. The helical-coil heat exchanger (HCHE) consists of a pipe formed into a helical coil and placed between two concentric cylinders as shown in figure 3. This design has similar principles to the double-pipe design, except can fit into much smaller space requirements and have higher heat-transfer rates

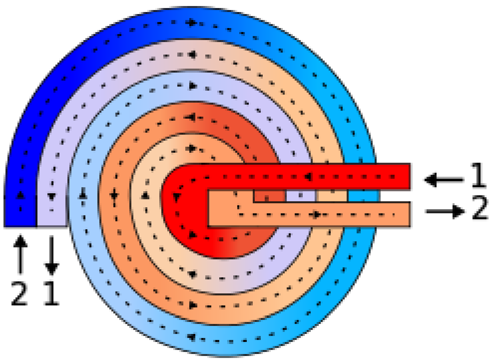


Figure 4: Spiral heat exchanger diagram [5]

at lower flowrates but can have difficulties being cleaned and more complications with manufacturing [4]. The SHE is a modification to the principles of the HCHE, with the outer shell being replaced with another spiral pipe, running parallel to the first (seen in figure 4). This allows the two fluids to flow parallel to one another, allowing for the same benefits of low pressure drop, but an even smaller footprint for the same heat transfer. The SHE is simpler to manufacture, being only two plates coiled around each other, forming the two channels, with the added ability to self-clean, as any deposits on the inner surfaces cause an increase in drag and are more easily dislodged by the heat exchangers operation [5].

Design Evaluation

To decide which design alternative will best suit the design criteria a decision matrix was made. By weighing the criteria and scoring all the options, the best configuration can be determined by the highest total score. A maximum possible score of 100 is used.

Parameter	Microchannel PHE	Double Pipe	Spiral	Weight
Overall Efficiency	5	2	3	5
Required Size	5	1	2	5
Pressure Drop	2	4	4	2
Ease of Manufacturing	2	3	2	4
Overall Cost	2	3	3	4
Total	***70***	***47***	***53***	

Table 1: Decision Matrix

Scoring

Efficiency

- Microchannel heat exchangers are known to have exceptional efficiency due to high amount of heat transfer surface per volume (area density), so it was scored the highest.
- Double Pipe heat exchangers are simple but the least efficient due to a smaller surface for heat transfer.
- Helical-Coil/Spiral heat exchangers are similar in theory to double pipe heat exchangers but have better heat transfer rates due to their configuration, so it was scored second.

Pressure Drop

- Microchannel heat exchangers are known to have large pressure drops due to the size of the channels. With small hydraulic diameters, the combined effect of fluid viscosity and the no-slip condition result in lower velocities and reducing pressure. However, because gases will be flowing through the device, this concern is much less prominent than it would otherwise be for liquids, which are much higher viscosity.
- Double Pipe heat exchangers do not suffer from large pressure drops as the pipes are normally larger, so it was ranked above Microchannel.
- Spiral heat exchangers are like double pipe heat exchangers but can offer better performance at a wider range of flowrates, so it was ranked first.

Manufacturing

- Microchannel heat exchangers are difficult to manufacture due to their complicated geometries and as a result was ranked second.
- Double Pipe heat exchangers are relatively simple to manufacture due to their simple design, so it was ranked first in this category.

- Spiral heat exchangers involve complicated processes to achieve the geometries required, while remaining sealed and insulated during manufacturing, so it was ranked last.

Size

- Microchannel heat exchangers are known for their compact size, so it was ranked first
- Double Pipe heat exchangers can be bulky and are not as effective when in compact sizes, so it was ranked last.
- Spiral heat exchangers are an effective method to make double pipe more compact and more efficient, so it was ranked second.

As seen in the matrix the Microchannel heat exchanger had the largest score and therefore would be the most appropriate option. The option that scored the lowest and would therefore meet the criteria the least was the double pipe heat exchanger.

When slightly changing the weights of the criteria, the results still favour the Microchannel heat exchanger. A series of matrices where the weights were slightly changed can be found in the appendix. In two of the three new matrices, the Microchannel heat exchanger still scored the highest and, in all variations, the double pipe heat exchanger scored the lowest. Any other variations to the weights would be significantly different than the original weights and would result in significantly different scores.

Decision Making

Ultimately, the most important factors in the decision-making process are the overall efficiency of the unit, and by extension, the size that would be required to function effectively. Due to the tight design constraints and high performance required, the advantages of microchannel efficiency are of utmost importance. Although both the double tube and spiral heat exchangers do offer some advantages in other areas such as manufacturing and cost, it can be safely said that a microchannel design is the only option with a reasonable chance of feasibility. Double tube and spiral heat exchangers are more suitable for the large-scale power generation environments they are typically found in, where size limitations are not a prominent concern. They would therefore be difficult to adapt to this application.

With a general configuration clearly determined, there are many more decisions to be made and details to define as the design progresses. Some of the preliminary ideas in these areas are detailed below:

Material: A material is needed that can withstand maximum temperatures of 1300 K, has a high thermal conductivity value, and can be used to create a unit with high precision tolerances. Ceramics, although otherwise used in some heat exchange applications, appear unsuitable because they are generally more thermally insulating than metal. Readily available metals with acceptably high melting temperatures include stainless steel, nickel, and titanium. Of these options, nickel appears to be the most attractive choice because its k-value far exceeds either of the others [7]. Although nickel is relatively expensive, its high thermal conductivity justifies its use, especially because the anticipated size of the unit will be small.

General Design: The device should use counter-flow rather than parallel flow, as this results in a more constant temperature difference along the running length, reducing thermal stresses on the material. Overall diameters, running length, number of passes, and the required velocity remain to be determined.

Manufacturing: Because microchannel devices require a complex arrangement of small diameter high precision tubes, the best strategy is to section the device into plates which are made individually. The plates can be photo-chemically etched, and then combined into one unit using diffusion bonding [8].

General Design

The design of the entire fuel cell system has been provided by the client in Figure 5 below. This displays the general interactions of the entire configuration.

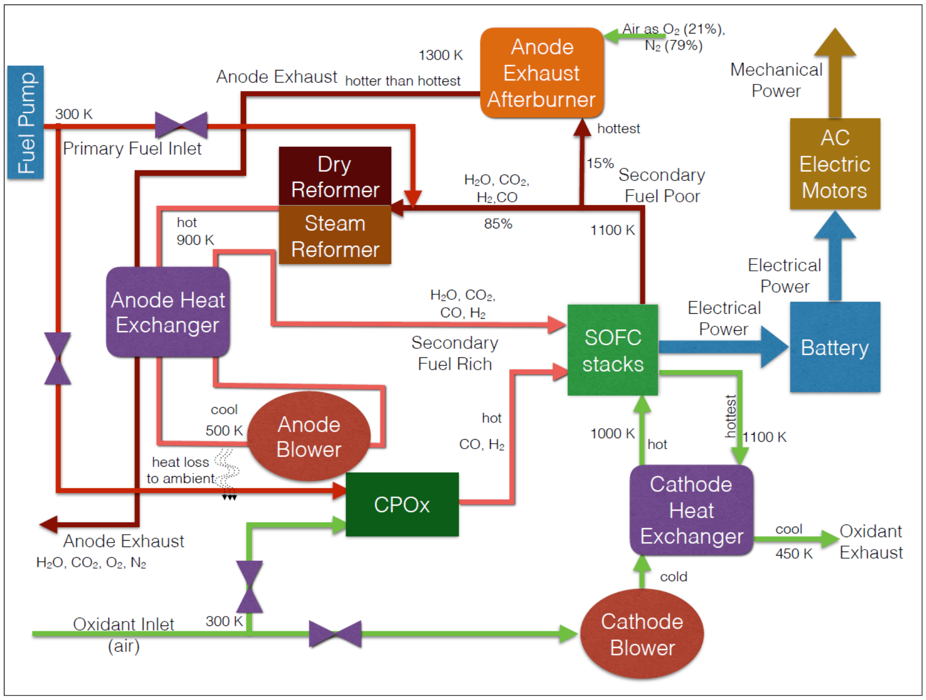


Figure 5: Solid Oxide Fuel Cell System Configuration

This projects purpose is to develop the Anode Heat Exchanger portion of the system. After further considering the given requirements, a revised system diagram focusing on this section is now proposed.

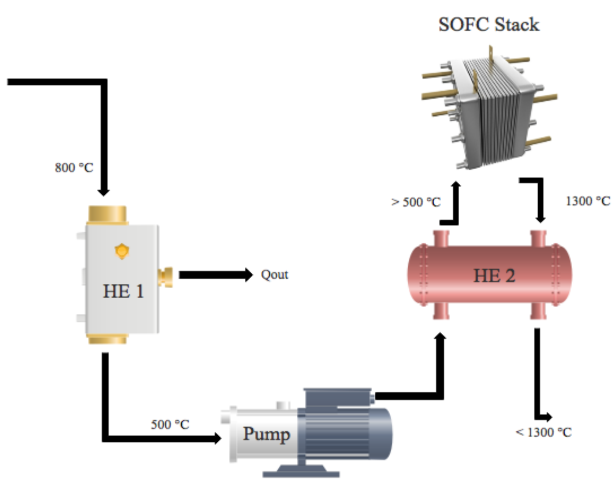


Figure 8: Proposed heat exchanger system

Firstly, the thing that makes the heat exchanger necessary is the requirement for the pump (Anode Blower) to circulate the fuel. This pump cannot withstand the high temperatures the fluid is in upon exiting the steam reformer; a need therefore arises to lower the temperature to an acceptable one, and then afterward raise it back up to the previous point to maintain temperature in the fuel cell stack. The 1300 K exhaust gases provide a very convenient source of energy to accomplish this reheating. Although it was initially thought that the entire process could occur by building one streamlined unit, it is likely that two separate heat exchangers will be necessary. In order for the fuel to cool down to pump temperature it must have its own heat exchanger where it dissipates heat to the surrounding air, as routing this flow through the second unit shown would likely produce the opposite of the desired effect because of proximity to the exhaust gases.

Updated Work Plan and Resources

The Gant Chart shown in figure 6 below illustrates the schedule for this project. The projected duration of every key deliverable is clearly shown and updated as of February 14th, 2018. Note: this information is also displayed in a table in the Appendix.

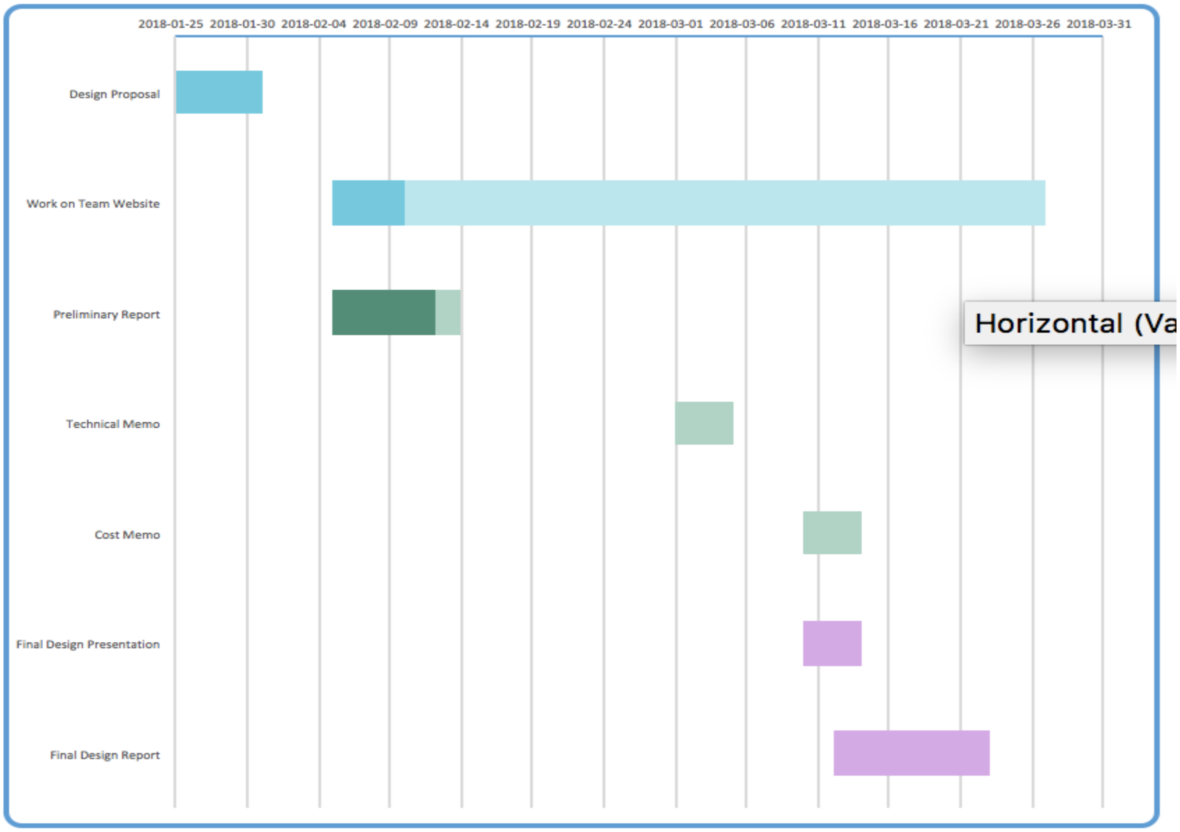


Figure 5: Gantt chart for project completion

An updated budget schedule is displayed in table 2 below. The hours are categorized by each deliverable and team member. As previously discussed, the service charge comes to $80 per hour. The expended time spend on the first 3 deliverables (design proposal, project website update #1 & preliminary report) totals to 106 hours. This gives a current balance of $8480 excluding tax. The estimated time has been provided for the other deliverable, with a total estimated time of 475 hours. Using this method, an estimated project cost is $37,600 excluding tax. Please be advised this could fluctuate slightly due to unexpected circumstances.

The computational fluid dynamics (CFD) program has been chosen to be Fluent instead of Star CCM Plus. Along with this software, SolidWorks will be used to create a 3-D model of the heat exchanger to provide an accurate representation of what the final product will look like.

Deliverable	Chase	Jameson	Mike	Orion	Ian	**Total**
	Estimated Time (Hours)					
Design proposal	9	10	9	8	8	**42**
Project Website Update (w5)	2	2	3	5	4	**18**
Preliminary Design Report	11	9	9	8	9	**46**
Project Website Update (w7)	4	3	4	3	2	**16**
Design Review Tech Memo	9	8	11	10	10	**48**
Project Website Update (w9)	4	3	2	4	4	**17**
Cost Memo	8	8	7	4	8	**35**
Final Presentation	11	10	13	12	13	**59**
Project Website Update (w11)	3	3	2	6	5	**19**
Final Report	15	15	14	15	15	**74**
Total Research	22	27	24	23	20	**81**
Total	**98**	**98**	**98**	**98**	**98**	**475**

Table 2: Displays the estimated time budgeted by person per deliverable.

References

1. “Thermal Systems.” *Micro Scale Heat Exchangers – Thermal Systems*, http://www.me1065.wikidot.com/micro-scale-heat-exchangers

2. “Emerging Applications of Heat Exchangers.” http://www.link.springer.com/content/pdf/10.1007%2F978-1-4614-0779-9_3.pdf

3. “Double Pipe Heat Exchanger Design” – Bright Hub Engineering, http://www.brighthubengineering.com/hvac/64548-double-pipe-heat-exchanger-design/

4. “Designing a helical-coil heat exchanger” – Ramachandra K. Patil, http://users.ugent.be/~mvbelleg/literatuur%20SCHX%20-%20Stijn%20Daelman/ORCNext/Supercritical/Literature%20Study/Literature/Heat%20exchanger%20design/Helical%20coil/Designing_Helical_Coil_Heat%20Exgr_1982.pdf

5. “Spiral Heat Exchangers” – Wikipedia, https://en.wikipedia.org/wiki/Heat_exchanger#Spiral_heat_exchangers

6. “Comparison between a petrol and diesel engine” – ME Mechanical, https://me-mechanicalengineering.com/comparison-between-petrol-and-diesel-engines/

7. “Thermal conductivity of Metals” – Engineering Toolbox, https://www.engineeringtoolbox.com/thermal-conductivity-metals-d_858.html

8. “Demonstration of a Highly Efficient Solid Oxide Fuel Cell Power System” -Mike Powell, Kerry Meinhardt, Vincent Sprekle, Larry Chick, Gary McVay, https://www.engineeringtoolbox.com/thermal-conductivity-metals-d_858.html

Appendix

A: Response to Proposal Feedback

The feedback to the initial proposal was constructive and made some good points. Below is the groups response and the actions taken to improve on the report.

Title Page – The title page’s fonts were not uniform. This problem has been resolved.

Problem Statement – The problem statement was heavily revised to include more information on heat exchangers to provide a better understanding to the reader.

Literature Review – The initial literature review really focused on the heat exchanger itself. However, the heat exchanger is only one component of a large system. As recommended in the feedback, the whole SOFC fuel system was explained in more detail to give the reader a better understanding how what the heat exchanger is being designed for. Also providing information on the other types of fuel cells.

Constraints and Criteria – The feedback about the constraints and criteria made a lot of sense. The payback period was taken out because the team is not designing/manufacturing the whole vehicle. There are a lot more components than just the heat exchanger so that was not necessary. Also, making the corrosion resistance a constraint made more sense. The comment about the assembly however was a bit confusing. The team meant that this part needs to be easy enough to build so that it can be mass produced and not too expensive. By keeping this in mind, the team can choose materials that are both efficient enough as well as reasonable to produce.

Tool Consideration: The fluid software to be used was not given in the proposal, so it was added into this report.

Fee: The fee did not follow the rubric, so the low mark was reasonable. The budget was mentioned in this report in better detail.

Timeline: The timeline was also missing so that too was added to this report.

B. Additional Information

The information being used to design the heat exchanger has been provided by the client. They are as follows;

Flow Rate: 10 L/s (can vary depending on desired power)

Exit Temperature of SOFC: 1000K

Exit Temperature of Reformer: 800K

Entrance to Centrifugal Pump: 500K

Further into the design process when the fluid software is used, there will be more concrete numbers to base the final design from.

Table 3 below displays the information provided by the Gantt chart in the report in a table.

Task Name	Start Date	End Date	Duration (Days)	Days Complete	Days Remaining	Percent Complete
Design Proposal	2018-01-23	2018-01-31	8	8.00	0.00	100%
Work on Team Website	2018-02-05	2018-03-27	50	5.00	45.00	10%
Preliminary Report	2018-02-05	2018-02-14	9	7.20	1.80	80%
Technical Memo	2018-03-01	2018-03-05	4	0.00	4.00	0%
Cost Memo	2018-03-10	2018-03-14	4	0.00	4.00	0%
Final Design Presentation	2018-03-10	2018-03-14	4	0.00	4.00	0%
Final Design Report	2018-03-12	2018-03-23	11	0.00	11.00	0%

Table 3: project status

Sensitivity Analysis

	Weight	Microchannel	Double Pipe	Spiral
Efficiency	3	3	1	2
Pressure drop	4	1	2	3
Manufacturing	2	2	3	1

Size	1	3	1	2
Total		20	18	22

Table 4: Ranking pressure drop above efficiency.

	Weight	Microchannel	Double Pipe	Spiral
Efficiency	4	3	1	2
Pressure drop	2	1	2	3
Manufacturing	3	2	3	1
Size	1	3	1	2
Total		23	18	19

Table 5: Ranking manufacturing above pressure drop.

	Weight	Microchannel	Double Pipe	Spiral
Efficiency	4	3	1	2
Pressure drop	3	1	2	3
Manufacturing	1	2	3	1
Size	2	3	1	2
Total		23	15	18

Table 6: Ranking size above manufacturing.