

A Hierarchical Procedure for Synthesis of a Base Case Solid Oxide Fuel Cell System in Aspen HYSYS

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Abstract

Presented is a computer-aided process design and analysis procedure for use in creating Aspen HYSYS-based base-case design simulations for a Solid Oxide Fuel Cell. This procedure is based on the work of Douglas. This approach provides a step by step method to system design that permits preliminary assessments of the economic viability, which allows for expeditious creation of realistic and economic design simulations. Each step presents heuristics designed to aid in the specific design element addressed in that step. An example design of a Solid Oxide Fuel Cell from the Department of Energy's Fuel Cell Handbook is used to illustrate the design process. This example answers the questions presented by Douglas, and culminates in an energy balance and a capital cost table for the process. The example illustrated has an expected return on investment of 15% and serves as a guide for teaching the use of a hierarchical procedure for the synthesis of a modern chemical process.

Keywords: HYSYS; Simulation; Solid oxide fuel cell

Introduction

The rise of domestic production of natural gas is reshaping the U.S. energy economy, spurring the increased use of natural gas for electricity generation [1]. The fuel cell represents an effective process to produce electricity from natural gas. A fuel cell operates electrochemically, and is not limited by the Carnot Cycle. It therefore emits lower emissions of NO_x and CO_2 compared to systems using the combustion process [2]. A Solid Oxide Fuel Cell (SOFC) operates at a high temperature, easily reforming natural gas within the cell, promoting rapid electro catalysis with nonprecious metals, and producing high quality by product heat for cogeneration [2]. Using cogeneration a SOFC can reach efficiencies exceeding 70%, where a typical efficiency for a conventional power plant is 35% [2].

The potential of SOFC's has prompted a number of studies into the design of SOFC's. These include work at the Pacific Northwest National Laboratory on the design of low-cost modular SOFC using lower temperatures, a comparison of a 1 MW SOFC to a conventional thermal power generation plant and finding the optimal design as well as the capital and life cycle costs [3-5]. The purpose of this paper is to provide a step-by-step procedure, for use with Aspen HYSYS, for the base case design of a SOFC system in which the economics of the project are examined at every level of the design process. This procedure allows the overall economic impact to be calculated so that non-economic process/systems can be identified and rejected early in the process before expensive design or testing is carried out. Douglas' Hierarchical Decision Procedure for Process Synthesis is used for this purpose [6]. Douglas' procedure breaks down the design procedure into steps in order to determine whether a process flowsheet is viable as the process synthesis proceeds. The example process used in this paper to illustrate the process is a natural gas fueled SOFC outlined by the Fuel Cell Handbook [7]. Figure 1 shows the schematic used to represent this fuel cell process.

The hierarchy of decisions for creating a viable process synthesis expands Douglas' method to 7 levels.

Level 1: Process Classification and Input Information

Level 2: Input-Output Analysis of the Simulation

Level 3: Reactors and Compressors Analysis

Level 4: Separation Analysis

Level 5: Heat Exchanger Networking Analysis

Level 6: Energy Balance and Analysis

Level 7: Capital Cost Summary and Return on Investment Analysis

At every level, the economic potential is estimated. If the economic potential of the process proves to be undesirable, the designer may alter the decisions made to accommodate a more economical process.

Level 1

Process classification and input information

The first level of the HYSYS-based design methodology is the gathering of information about the process. The input information for the process being developed includes the following:

The components: Every chemical compound that is used or synthesized within the process must be accounted for in the HYSYS setup stage. Hypothetical components may be defined for cases which include components that are not defined within HYSYS.

The equation of state: HYSYS includes a number of methods for thermodynamic calculations, including several Equations of State.

The reactions: The reactions which occur during the simulated process may be defined in HYSYS to ensure that material and energy balance issues are handled appropriately. These reactions can be assigned to specific reactors within the simulation. It is also possible to use a HYSYS module called a Gibbs Reactor, in which HYSYS brings all of the reactants into equilibrium based on the Gibbs free energy.

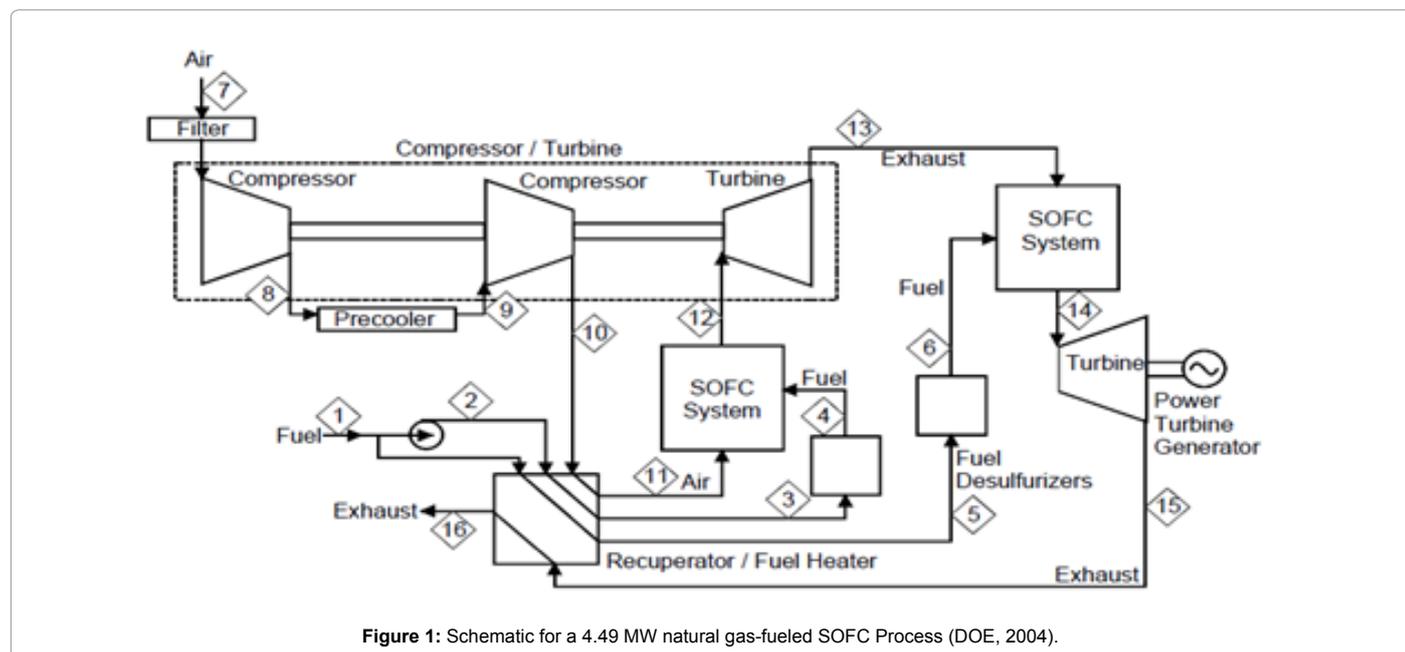
Stream properties: Each component stream in the process must

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Received July 01, 2015; Accepted July 25, 2015; Published August 01, 2015

Citation: Moore M, Herrell B, Counce R, Watson J (2015) A Hierarchical Procedure for Synthesis of a Base Case Solid Oxide Fuel Cell System in Aspen HYSYS. J Adv Chem Eng 5: 129. doi:10.4172/2090-4568.1000129

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have values for temperature, pressure, composition, and flow rate. HYSYS uses a degree of freedom analysis to calculate these stream properties, the user only needs to define some and HYSYS will calculate the rest. In addition, HYSYS alerts the user as to what is needed if the stream is underspecified. Downstream properties will commonly be calculated automatically in HYSYS, leading to consistency errors when the user definitions do not match the HYSYS calculations.

Level 1 example

Conditions within the simulation were chosen to match those in the DOE Fuel Cell Handbook. Some important conditions that should be met to properly simulate the fuel cell system are in Table 1. The fuel utilization value is the percentage of the fuel that goes through the fuel cell, the remaining fuel is combusted. The electrical efficiency of the fuel cell is measured with only the fuel that is used by the fuel cell. An overall efficiency measuring the amount of electricity produced from the total feed would then be the product of the electrical efficiency and the fuel utilization.

To complete the first level of the methodology, the reactions which occur within the SOFC must be taken into account, and from these reactions, the chemical compounds may be found. The following reactions are utilized within the SOFC:

- $\text{CH}_4 + \text{H}_2\text{O} \leftrightarrow \text{CO} + 3\text{H}_2$
- $\text{CO} + \text{H}_2\text{O} \leftrightarrow \text{CO}_2 + \text{H}_2$
- $\text{CH}_4 + \frac{1}{2}\text{O}_2 \leftrightarrow 2\text{H}_2\text{O} + \text{CO}$
- $2\text{CO} + \text{O}_2 \leftrightarrow 2\text{CO}_2$
- $2\text{H}_2 + \text{O}_2 \leftrightarrow 2\text{H}_2\text{O}$
- $\text{C}_2\text{H}_6 + 2\text{H}_2\text{O} \leftrightarrow 2\text{CO} + 5\text{H}_2$
- $\text{C}_2\text{H}_6 + \frac{5}{2}\text{O}_2 \leftrightarrow 3\text{H}_2\text{O} + 2\text{CO}$

These reactions all occur within the vapor phase. From these reactions it is clear that the chemical components carbon monoxide, water, carbon dioxide, methane, ethane and hydrogen gas must be

added to the component list in the basis environment. It would be impractical to use pure oxygen as the feed to the fuel cell, so argon and nitrogen gas should be added as well to simulate the air feed. With the component and reaction lists defined, an equation of state may be chosen. Because of its accuracy with hydrocarbon systems, the chosen equation of state was Peng-Robinson.

The raw material and product prices used in Level 2 for the input-output cost analysis are presented in Table 2. The main product of the system is the electricity produced by the fuel cells and the expanders, with the heat associated with the exhaust stream having value as well. The value of waste heat in the steel industry in 2004 was \$0.04 per 4.18 MJ, assuming that this value would hold for the SOFC system it is used to value the waste heat in the final exhaust.

The price of natural gas used as the fuel for the system is based on the United States Energy Information Administration listed price in March of 2012, while the price of electricity per kWh sold is based on rates set by the Knoxville Utilities Board in April 2012 [8,9]. Air is supplied at atmospheric pressure and 21°C, and natural gas is supplied at 8.85 atm and 15°C.

Level 2

Input-output analysis of the simulation

The second level of the process focuses on the overall economic potential. The primary feed and effluent streams, as well as their values, must be identified. This is done with an overall mass balance of the input streams and the outlet streams of the simulation. The economic potential of the design can then be approximated by taking the difference of the value of the product produced by the system and the material costs required to create those products. Since the design process has not begun yet the values for the natural gas feed stream and the electricity produced should be the theoretical design values. It is also impossible to judge the amount of waste heat provided by the final exit stream, so calculating the value of this will be done in level 5 when heat exchangers are added [10].

Component	Value
Air to Fuel Ratio	20.8 (mole to mole)
Electrical Efficiency of Fuel Cells (LHV)	66.6%
Fuel Utilization	78%
Electrical Efficiency of Turbines	75%
Fraction of Feed of Natural Gas Going to HPFC	0.021 (mole to mole)
Fraction of Feed of Natural Gas Going to LPFC	0.021 (mole to mole)
Temperature of HPFC	860°C
Temperature of LPFC	875°C
Pressure of HPFC	8.39 atm
Pressure of LPFC	2.83 atm

Table 1: Important conditions of the fuel cell system from fuel cell handbook.

Utility	Cost
Electricity	\$0.09756 per kWh
Natural Gas	\$0.0466 per kg
Waste Heat	\$0.04 per 4.18 MJ

Table 2: Input-Output Material and Utility Costs.

Level 2 example

The flow rates of the feed streams provided by the FCHB are in Table 3. Assuming the base cost for natural gas (listed in Level 1) in the simulation, the annual cost for the natural gas consumed would be approximately \$211,619. All methane is considered to have reacted within the process. Air is not assigned a value here. The amount of electrical production in the FCHB is 4.49 MW. Table 4 indicates the annual values for the power produced by the 4.49 MW SOFC simulation, assuming continuous use throughout the year. Finally, Table 5 illustrates the summary of costs and economic potential for the Level 2 analysis.

Level 3

Reactors and compressors

Douglas provides several questions which may be adapted for consideration within this level [6].

1. How many reactors are necessary to use the design, and which material streams are associated with these reactors? Are there specifications within the design which require additional unit operation modules in HYSYS to adapt to the program's limitations?

The number of reactors in a fuel cell system will be equal to the number of fuel cells in the network. HYSYS does not have a unit operation module for the fuel cell, so a Gibbs reactor can be used as a substitution. The Gibbs reactor will combine the reactions of the anode, the cathode, the reformation reaction and, if necessary, the combustion reaction into one module. In an internally reforming SOFC the heat of the fuel cell reaction, and the heat provided by the combustion chamber, is used for the endothermic reforming reaction. A Gibbs reactor in HYSYS has no energy stream for electricity, so that all of the energy created by the fuel cell and combustion reactions that is not used by the reforming reaction goes to heat. By defining the temperature of the material stream leaving the Gibbs reactor the temperature of the Gibbs reactor is defined. HYSYS calculates the amount of heat that must be removed from the reactor to reach this temperature and assigns it to the energy stream of the Gibbs reactor. This energy stream then represents the electricity generated by the SOFC.

2. Are there recycle streams present in the design? Would the design benefit from additional recycle streams?

Possible benefits to a recycle stream are to recycle any unused fuel

into the anode to provide a higher utilization rate of the fuel source, to recycle any carbon dioxide into the cathode to act as an oxidant, or to recycle any water formed as a result of the fuel cell reaction for use in the reforming reaction.

3. Does using an excess feed stream have an effect on the production of the desired product(s)? Is there an economic potential gain or loss from using an excess?

An excess feed stream of air makes the fuel the limiting reactant in the reactions, ensuring that the fuel is fully utilized in the system. Excess air is also a method for controlling the temperature of the fuel cells and the material streams by removing heat from the reactor. The temperature can be controlled in this manner without the utilization of cooling water.

4. How many compressors and expanders are required by the design, and how many may be excluded? What is the effect of these units on the economic potential of the design?

Compressors will be necessary to bring the air feed stream to the pressure of the fuel cell. Caution must be taken when compressing the air stream so that the stream does not become too hot and damage the compressor. It may be necessary to compress the stream in 2 or more steps while cooling the stream between the compressors. The general rule is that if the desired ending pressure is more than 4 times the initial pressure another step should be added [11]. Providing expanders associated with the effluent stream from the SOFC systems recovers some of the energy associated with the SOFC process.

Once the fuel cells, expanders and compressors are added to the HYSYS simulation, the next step in Level 3 is to estimate the cost of the compressors, expanders, and SOFCs to determine their impact on the economic potential. Compressors and expanders are valued similarly by their respective power in Watts. The value of the power of a compressor/expander in HYSYS is provided by the energy stream of the unit operation module. HYSYS assigns the energy streams on compressors and expanders as positive, regardless of whether electricity is being produced or consumed. 75% adiabatic efficiency is assumed for all compressors and expanders. These values for the efficiency, and the costs of the equipment, are from "Chemical Engineering Process Design and Economics: A Practical Guide" by Ulrich [11].

The fuel cells have their capital costs approximated at \$175 per kW produced [12]. To estimate the economic potential for level 3 and beyond it is necessary to annualize the capital costs. The annual expenses including equipment depreciation are used in the annualization calculation. Annual expenses are those that are directly proportional to the capital costs and are listed in Table 6. Straight line depreciation over a lifespan of 10 years is used to calculate depreciation. Cost of capital is not included in the annualization of the capital costs.

The economic potential for level 3 is then:

$$EP_3 = EP_2 - \text{Capital costs for Level 3} \times 0.24$$

Level 3 example

The first SOFC system operates at a high pressure (~9 atm) and the feed air will require compression prior to entering the fuel cell. The effluent from the first SOFC then becomes the air feed for the second lower pressure SOFC. An expander is added to the effluent stream of the first SOFC to lower the pressure of the material stream before it is fed into the lower pressure SOFC. A final expander is used on the LP Exhaust recovering energy from the second SOFC effluent as electricity.

Material component	Hourly projections	Annual projection
Consumed Air	18,540 kg	1.62×10^8 kg
Consumed Natural Gas	518.4 kg	4.54×10^6 kg

Table 3: Projected annual consumption and production of material components in a 4.49 MWh SOFC.

Component	Approximate value in 2012 US dollars
Annual Electrical Production from SOFC	3.94×10^7 kWh
Annual Electrical Value from SOFC	\$3,837,268

Table 4: Electrical cost analysis for a 4.49 MW SOFC located in the Southeastern United States.

Annual component consumption/production	Approximate annual cost/value
Natural Gas Costs	\$211,619
Economic Potential for Level 2	\$3,625,650

Table 5: Summary of Level 2 Costs and Profits for a 4.49 MW SOFC system.

Capital-related cost item	Fractions of fixed capital
Maintenance and repairs	0.06
Operating supplies	0.01
Overhead, etc.	0.03
Taxes and insurance	0.03
General Depreciation	0.10
Total	0.24

Table 6: Annual expenses proportional to fixed capital.

Compressor	Adiabatic efficiency	Shaft work (kW)	Capital cost	Annualized cost
Compressor1	75.00%	634.3 kW	\$1,757,325	\$421,758
Compressor2	75.00%	663.2 kW	\$1,820,750	\$436,980
Expander1	75.00%	1408 kW	\$3,446,813	\$827,235
Expander2	75.00%	1292 kW	\$2,409,063	\$578,175
HPFC			\$303,800	\$72,912
LPFC			\$239,050	\$57,372

Table 7: Specifications and approximated costs for compressors, expanders, and fuel cells.

Table 7 shows the capital costs for the compressors, expanders, and the fuel cells. A lifespan of 10 years was used for the annualization costs for depreciation and the return of investment factor. The economic potential for level 3 is then: \$1,231,218.

Level 4

Structuring a separations system

Douglas devotes Level 4 of his design method to the creation of a separations system within the flowsheet to recover products and byproducts at marketable concentrations. While the design of a separations system applied to SOFCs is unnecessary due to the nature of the example, it is a notable step in the design process and therefore is mentioned here. Many HYSYS design simulations do include separations systems, and as such, principles which Douglas takes into consideration should be referred to in his 1985 work [6].

Level 5

The heat exchanger network

The use of heat exchangers in a simulation serves to reduce overall energy costs by recycling heat produced by the system to heat the

feed streams. Heat exchangers which utilize the exhaust streams in the process are a cost-effective way of optimizing operations. To add heat exchanger networks, a number of questions must be asked and answered:

1. What type of heat exchanger should be used?

The academic version of HYSYS gives a few options when selecting a heat exchanger design, with shell and tube heat exchangers being standard. TEMA type E (one shell pass) or type F (two shell passes with a longitudinal baffle) can be selected, co-current or countercurrent flow can be selected, and the number of tube passes can be defined.

Solid Oxide Fuel Cells operate at high temperatures, so it can be anticipated that the effluent streams will also be at high temperatures while the air and natural gas feed streams are at room temperature. Because of the large temperature difference between the streams, countercurrent exchangers are recommended for these heat exchangers [13]. Since the pressure of the feed streams is higher than the exhaust streams, the feed streams should be on the tube side while the exhaust stream can be on the shell side. The high temperatures of the effluent streams can also cause expansion of the tubes during start up, so that a U-Tube type arrangement (2 tube passes) of the tubes is also recommended [11]. If the heat flow is such that two Shell and Tube heat exchangers are necessary, a second shell pass can be added to save the expense of a second heat exchanger [13]. One shell pass exchangers are the most common, however [13].

The heat exchanger used to remove heat from the air feed between compressors needs other considerations than the exchangers between the effluent and the feed streams. Countercurrent flow allows the hot stream to approach the temperature of the entering cold stream, and generates less entropy than co-current flow [13]. The use of cooling water means the possibility of mineral deposit build up in the exchanger, so the ease of cleaning the exchanger is an issue. Running the water through the tubes, and designing the exchanger for one tube pass, allows for easy cleaning of these mineral deposits. Expansion of the tubes should not be an issue because of the relatively low temperature of the air feed stream.

1. Does a product stream within the simulation have a high enough temperature to provide heat for other streams?

Setting the tube side exit temperature and pressure will allow HYSYS to calculate the exit temperature of the shell side. If the temperature difference is inadequate HYSYS will give an error message and the tube side exit temperature can be adjusted.

2. Is it possible to link several heat exchangers within the simulation with the same exhaust stream feed, thus maximizing the exhaust's potential within the plant?

Once the exhaust stream being used for the shell-side feed of the heat exchanger has passed through, it may be possible to use the exhaust from the heat exchanger shell to feed another heat exchanger. This can continue on until all heating needs have been satisfied or the heat of the effluent stream is exhausted. If all of the feed streams have been heated to the desired temperature the final exhaust stream may still have value. Exhaust streams from natural gas can be cooled to a temperature of 120°C with the sensible heat taken from the stream sold at the rate of \$0.04 per 4.18 MJ [13,14]. A unit operation module called a cooler can be used to cool the final exit stream to 120°C with the energy stream giving the value of heat removed from the stream. This value is assuming 100% efficiency of heat exchange, which is optimistic, but for simplicity reasons is used in the example calculations.

The level 5 EP is then:

$$EP5 = EP3 + \text{Value of sensible heat sold} - \text{Annualized cost of heat exchangers}$$

Level 5 example

The exhaust from the final expander in the simulation has a high temperature and is utilized in a heat exchanger network to provide heat for the feed streams. This may be simulated through placement of a shell-and-tube heat exchanger on each feed stream so that the feed streams may be heated in series by the hot effluent stream. A cooler can then be placed on the final exhaust stream to cool the stream to 120°C so that the value of the stream as a heat source can be estimated.

The next step of Level 5 is the calculation of the effect on the economic potential of the heat exchangers added. The relevant figures for determination of heat exchanger costs are found in the book by Ulrich [11]. The method for calculating the capital costs for heat exchangers in Ulrich is by the heat transfer area. The academic version of HYSYS uses a heat transfer area of 60.32 m² regardless of the use or function of the heat exchanger. This means that it is necessary to calculate the size of the heat exchangers by hand. HYSYS provides the stream temperatures, pressures and enthalpies of the material streams so that a short cut calculation is relatively easy. The capital costs of the heat exchangers and their annualized costs are in Table 8. The value of the heat in the final exhaust stream was found to be \$315,058 per year with a rate of sensible heat removal of 1,044 kW. The Economic Potential for Level 5 is then: \$1,516,069.

Level 6

Energy analysis

One of the most important considerations of any process design is that of the energy balance of the process. In Level 6, one must not only perform an energy balance on the process as a whole, but also on the individual energy-producing elements of the process (such as fuel cell stacks). An advantage of using computer design software, such as HYSYS, is that the enthalpy of the streams and energy required by the unit operation modules is readily available. There are several questions which must be asked by the process designer:

1. Is the process as a whole balanced? If not, how must it be changed?

Aspen HYSYS provides indicators if part or all of a simulation is unbalanced. Unit operation modules and material streams will appear yellow if they are under-defined or if there is a conflict between a user input value and a calculation performed by HYSYS. Many times HYSYS will provide a notification about where the error is being detected. The energy streams of the unit operation modules indicate the amount of energy (heat or electricity) needed to operate the module at the user defined quantities. Care must be taken in examination of these values as it is often difficult to distinguish if the energy is being produced by the module or is being supplied to the module.

The energy associated with the material streams is represented by the "heat flow" of the stream in the dialog window of the stream. This heat flow is based on the enthalpy calculation of the material stream and is relatively meaningless on its own. The heat flow becomes meaningful when used in an energy balance equation since it represents the change in the heat flow of the process. HYSYS provides a spreadsheet applet that can be used for the energy balance. Values associated with a material stream, energy stream, or unit operation module can be input into the spreadsheet by dragging the value into the spreadsheet while holding down the right mouse button. When inputting the values in

this manner any change in the HYSYS simulation will be represented automatically in the spreadsheet. This dynamic property of the applet makes it a convenient tool for energy and material balances.

The balance equation for the entire process is then: heat flow of input streams + energy in = heat flow of output streams + energy out. The energy in and energy out terms represent the energy streams of the unit operations, in this case the expanders, compressors, pumps and Gibbs reactors. To calculate the total electrical energy produced by the system subtract the energy in from the energy out. To calculate the energy produced by just the fuel cells take the sum of the energy streams of the Gibbs reactors.

1. Are the energy-producing elements of the process balanced? If not, how must they be changed?

If the energy producing elements are outlined in yellow then they are unbalanced, if the dialog box of the unit operation module has a green bar at the bottom then it is balanced. Another indication is the color of the material streams; a yellow stream represents an unbalanced system while a blue stream represents a balanced system.

2. Is the energy production by the process the desired amount? If not, how can the process be scaled to fit the needs of the designer?

The system takes into account energy production and heat production. Calculations are required to determine how much energy is being produced by the simulation. This information may be used to scale the simulation to the desired result. Achieving the exact desired number may be difficult within HYSYS.

Level 6 example

The task for Level 6 is to perform required energy balances for the process. This includes not only the system as a whole, but each individual SOFC system within the simulation.

Level 7

The capital cost table is shown in Table 9. The actual costs are the installed costs of the equipment. The costs of contingencies and auxiliary facilities have been neglected.

Results and Conclusion

The goal has been to use the procedure and heuristics outlined by Douglas to design a system for a Solid Oxide Fuel Cell [6]. The Douglas procedure proceeds as a series of levels, 1 to 7, in which design decisions must be made and questions presented by Douglas must be answered. The process is illustrated at every level using an example SOFC system outlined in the Department Of Energy's Fuel Cell Handbook. With this example process the questions and design decisions in each level have been answered and addressed (Table 10).

In level 1 the components, chemical reactions, and stream properties of the system are identified, as well as the equation of state to be used by HYSYS for the calculations. In level 2 the total economic potential of the system is evaluated by calculating value of the natural gas needed as a raw material for one year of operation and subtracting that from the value of the electricity to be generated. Level 3 proceeds by determining the number of reactors (fuel cells) necessary, whether recycle streams are needed, if using an excess of the feed stream benefits the process, and the number of compressors and expanders required for the design. Level 4 of the Douglas method is dedicated to the structure of a separations system, which is not required in a fuel cell process. The heat exchanger network is the focus of level 5. The

Exchanger	Capital cost	Annualized cost
E-101	\$44,475	\$10,674
E-102	\$8,006	\$1,921
E-103	\$6,671	\$1,601
E-104	\$66,713	\$16,011

Table 8: Heat exchanger capital and annualized costs.

Equipment ID	Number	Capacity	Cost	Bare Module Factor	Actual Cost
Compressor1	K-101	643.3 kW	\$667,350	2.5	\$1,668,375
Electric Motor - Compressor1	S-101	643.3 kW	\$59,300	1.5	\$88,950
Compressor2	K-102	663.2 kW	\$685,700	2.5	\$1,714,250
Electric Motor - Compressor2	S-102	663.2 kW	\$71,000	1.5	\$106,500
Expander1	K-103	1406 kW	\$1,334,250	2.5	\$3,335,625
Electric Motor - Expander1	S-103	1406 kW	\$74,125	1.5	\$111,188
Expander2	K-104	1289 kW	\$924,487	2.5	\$2,311,218
Electric Motor - Expander2	S-104	1289 kW	\$65,230	1.5	\$97,845
HPFC	G-101	1736 kW	\$303,800	1	\$303,800
LPFC	G-102	1366 kW	\$239,050	1	\$239,050
Air Feed Cooler Heat Exchanger	E-101	91.37 m ²	\$14,825	3	\$44,475
HP Fuel Cell Fuel Feed Heat Exchanger	E-102	0.69 m ²	\$2,669	3	\$8,006
LP Fuel Cell Fuel Feed Heat Exchange	E-103	0.55 m ²	\$2,224	3	\$6,671
Air Feed Heater Heat Exchanger	E-104	159.3 m ²	\$22,238	3	\$66,713
Total Cost					\$10,101,666

Table 9: Capital cost summary.

	FCHB	Simulation
Air to Fuel Ratio	20.8 (mole to mole)	21.05 (mole to mole)
Electrical Efficiency of Fuel Cells (LHV)	66.6%	NA
Fuel Utilization	78%	NA
Combined Electrical Efficiency and Fuel Utilization	51.9%	51.2%
Electrical Efficiency of Turbines	75%	75%
Fraction of Feed of Natural Gas Going to HPFC	0.021 (mole to mole)	0.025 (mole to mole)
Fraction of Feed of Natural Gas Going to LPFC	0.021 (mole to mole)	0.020 (mole to mole)
Temperature of HPFC	860°C	860°C
Temperature of LPFC	875°C	874°C
Pressure of HPFC	8.39 atm	8.37 atm
Pressure of LPFC	2.83 atm	2.96 atm

Table 10: Important conditions of the fuel cell system from fuel cell handbook and of the simulation.

type of heat exchangers needed and the possibility of linking several heat exchangers together are addressed as well as whether the product stream has the heat flow necessary to heat the feed stream. An energy balance is performed in level 6, and the procedure culminates in level 7 with a capital cost table.

Level 2 requires an economic analysis of the costs of the raw materials vs the potential income of the finished product. Levels 3 through 5 each continue this analysis by deducting the annualized capital costs of the equipment added to the design at that level from the profit calculated in the previous level. An approximate rate of return of the example design is about 15%. This differs from a standard rate of return in that the annual profit approximated by the economic potential calculated in level 5 only includes capital related expenses with the working capital being neglected.

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