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Optimization of 5-kW Mobile and Portable PEMFC System via Energy Integration

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The main objective of this study is to design an energy recovery system for the Proton Electrolyte Membrane Fuel Cell (PEMFC) that will optimize energy use through heat integration. A PEMFC system with a power output of 5 kW was used in the case study. Methanol, which served as primary fuel source of the autothermal reformer (ATR) system, was fed together with steam and oxygen. Based on the conceptual design, the ATR product contains about 73% H_2, 2% CO, and 25% CO_2. The hydrogen-rich reformate produced by reforming primary fuels in the fuel processor system, which contains a significant amount of CO, was reduced further via Water Gas Shift (WGS) reactor, Tubular Ceramic Membrane (TCM), and Pressure Swing Adsorber (PSA) in series. From the plots, the pinch point was determined at 540°C, the minimum process heating requirement from hot utilities $Q_{H_{min}}$ at 140 W, and the minimum process cooling requirement from cold utilities $Q_{C_{min}}$ at 96 W. Furthermore, energy recovery for both heating and cooling purposes after heat integration registered at 92% and 95%, respectively. Also, the number of heat exchangers reduced from 7 to 4 after heat integration.

Keywords: Autothermal reformer (ATR), energy optimization, heat exchanger network (HEN) system, heat integration, proton electrolyte membrane fuel cell (PEMFC), *and* pinch technology.

INTRODUCTION

Fuel cell power plants using reformates from methanol or from other hydrocarbons, such as gasoline, are actively being developed. One of the drawbacks of reformate-based fuel cell power plants, however, is the large amount of energy needed for fuel processing. It has been estimated that a heating value of 20–30% for the hydrogen produced in the reformer would be needed to provide a fuel stream with sufficient heat to meet the heating requirements of the reformer. It is evident that energy input to the reformer must be reduced for increased fuel cell power efficiency (Cao and Guo 2002). Due to this consideration, an autothermal reformer (ATR) was introduced in this study.

The *autothermal process* combines steam reforming (SR) and partial oxidation (POX). Hydrogen is produced from the SR process, a highly *endothermic* reaction, which consumes a large amount of energy; while the POX of methanol is an *exothermal* process. Thus, conceptually, coupling POX and SR (POX–SR) in a single reaction unit could yield an energetically self-sufficient system for the production of H_2 (Mizsey et al. 2001, Heizel et al. 2002, Zalc and Loffler 2002). Another processing unit in the proton electrolyte membrane fuel cell (PEMFC) plant is the water gas shift (WGS) reactor. The WGS acts both as a secondary H_2-producing unit and as a primary CO-removal system. The WGS reaction converts CO in the presence of steam producing into CO_2 and H_2. This reaction is exothermic and thermodynamically preferred at lower temperatures.

Two separation units were introduced in this study, the (a) *tubular ceramic membrane* (TCM) and (b) *pressure swing adsorber* (PSA). Both TCM and PSA were operated in parallel to gain a product purity of 99.9% for H_2 and of less than 10 ppm for CO. These two units, however, were not involved in the energy recovery system because both are temperature-independent and are operated at isothermal and adiabatic conditions.

One problem generally associated with a PEMFC power plant is the difficulty in dissipating the waste heat generated in the fuel cell stack. The voltage efficiency of a PEMFC stack under normal operating conditions is about 50–70% (Cao and Guo 2002). This means that 30–50% energy content must be removed from the fuel cell stack, which normally operates at 70–80°C, and higher temperatures can cause thermal management problems and membrane dry-out (Chu and Jiang 1999). Likewise, in order to achieve optimum total plant efficiency, it is important that the amount of exhaust gas be maintained as low as possible. Then, the usable heat content in the gas during the last cooling steps of the process is minimized (Riensche et al. 1998). Thus, an energy recovery system becomes necessary in a fuel cell power plant. With the energy recovery system, the efficiency of the system can be increased and the waste from the fuel cell stack reduced. Lastly, to achieve adequate efficiency for small-scale hydrogen-generation, the design should take into account the thermal and physical integration of components.

With the main objective of reducing process energy consumption, the research considered the possibilities for energy integration and made use of the pinch analysis. Energy recovery through the exchange of heat flow between streams requires (a) identifying all the streams that need to be cooled or heated first then (b) maximizing the recovery enthalpy flow rate between these streams.

This paper presents then the heat exchanger network (HEN) system design, a key aspect in a chemical plant, which is capable of yielding 20–30% energy usage (Linhoff 1993). The use of the HEN system, however, in a fuel cell plant is not well known.

METHODOLOGY

Heat integration plays an important role in designing a process plant. *Pinch technology* is a methodology comprised of a set of structured techniques for the systematic application of the first and second laws of thermodynamics. The application of these techniques enables process design engineers to gain fundamental insight into the thermal interaction between chemical processes and the utility system that surrounds them. Such knowledge enables engineers to optimize overall utility consumption and set process and utility system configurations prior to the final detailed simulation and optimization (Ahmad et al. 2000, Wang 2003, Ruyck 2003).

Pinch technology was developed both for analyzing energy and for identifying energy-saving opportunities. The pinch methodology typically involves two major steps. The first step is the *targeting phase*, wherein the minimum energy requirement of the system is identified by computing possible energy recovery from the hot stream that heats up the cold stream. The second step is the *synthesis phase* of the

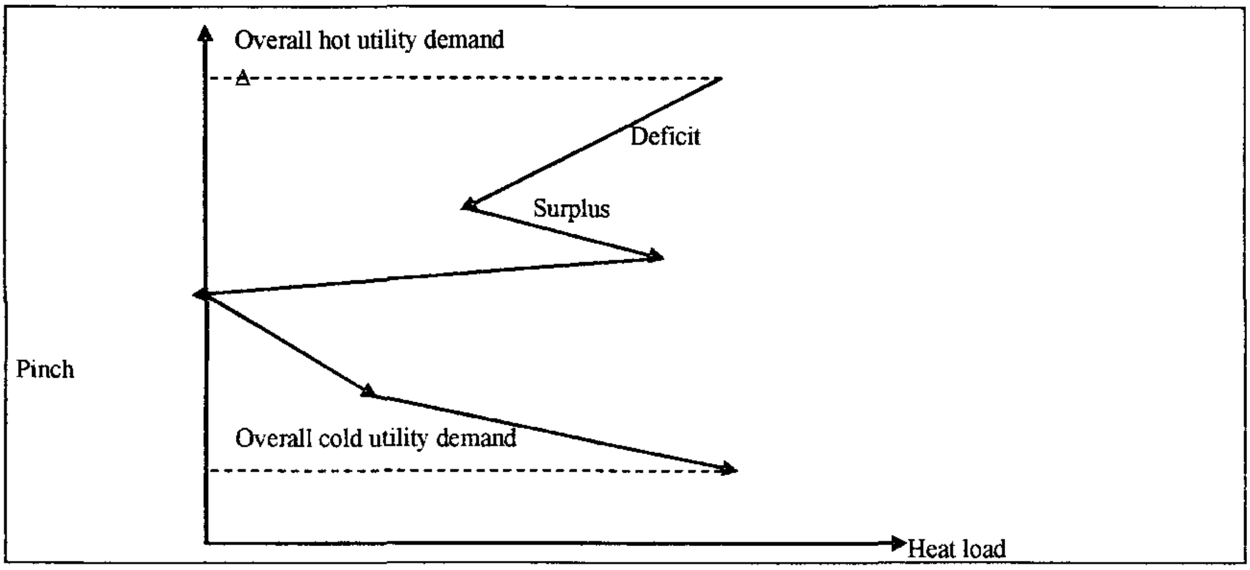


Figure 1. Heat and Demand Supply Diagram

HEN that will implement the target energy recovery.

Process integration studies start from the definition of hot streams and cold streams. The hot and cold streams define, respectively, the system's heat source and heat requirements. These are characterized by a heat–temperature diagram called the *composite curve* or CC (refer to Figure 1) and are usually represented by the heat load, inlet, and target temperatures. Composite curves, however, may be considered for a single hot and cold stream that will exchange heat in a virtual counter-current heat.

Aside from the CC, the *problem table algorithm* (PTA) can also be used to calculate—and even more precisely—the minimum and maximum utilities required as well as the pinch temperature. This algorithm was developed to determine the utility needs of a process, in general, and the location of the process pinch, in particular. The initial procedure for PTA is to convert the actual temperature T_{act} for every stream to the interval temperature T_{int} using Eqs. (1) and (2),

$$\text{Hot Stream,}\quad T_{\text{int}} = T_{act} - 1/2\,\Delta T_{\text{min}} \qquad (1)$$

$$\text{Cold Stream,}\quad T_{\text{int}} = T_{act} + 1/2\,\Delta T_{\text{min}} \qquad (2)$$

The next step is to yield the heat balance for every T as shown in Eq. (3) with:

$$H_i = \left(\sum Cp_C - \sum Cp_H\right)_i T_i \qquad (3)$$

where ΣCp_C = total heat capacity for cold streams, ΣCp_H = total heat capacity for hot streams, and ΔT_i = the difference for T_{int}.

If the value of ΔH is positive, then T_{int} has less energy; if the value is negative, then there is excess energy. This excess energy can be cascaded from one T_{act} to another in order to transfer heat from the hot streams to the cold streams. From the PTA, the *Grand Composite Curve* (GCC) may be plotted. The *GCC*, the graphic representation of the heat cascade for multiple hot and cold streams, determines the overall hot $Q_{H_{\min}}$ and cold $Q_{C_{\min}}$ utilities demand.

PROCESS DESCRIPTION

The purpose of the energy recovery system is to recover a substantial amount of the waste heat generated by fuel cell components and utilize it for the other heating requirements of the system. From the basic concept plant, the orientation of the flow sheet will be verified to obtain an optimized system design by taking into consideration both energy- and water-recovery systems.

Figure 2 shows the schematic diagram of the PEMFC power plant proposed in this study. The PEMFC data are listed in Table 1 for reference.

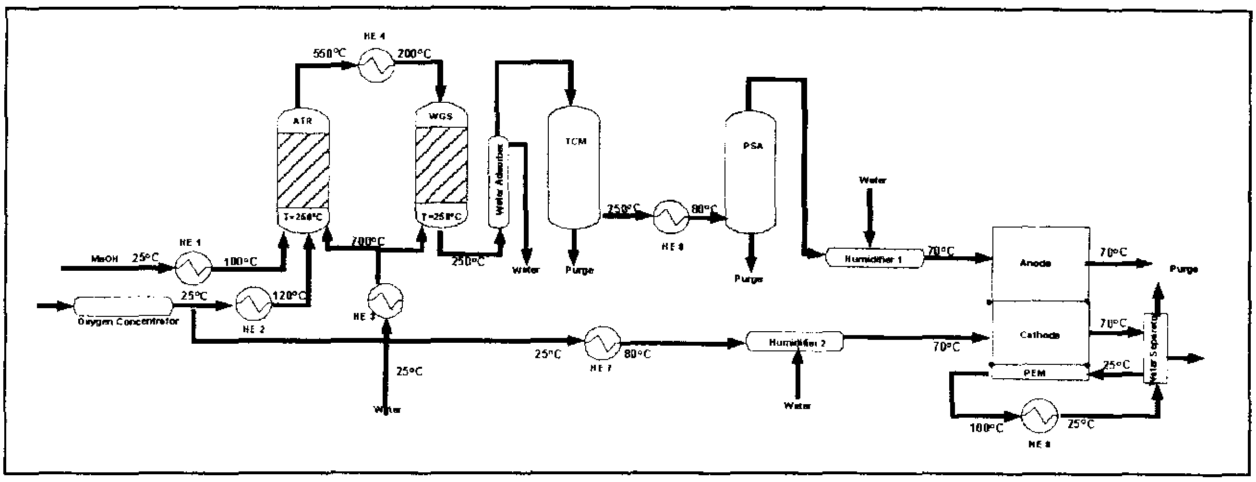


Figure 2. Schematic Diagram of the PEMFC Power Plant

Table 1. PEMFC Reference Data

Parameter	Alternative 1
Reformer Temperature	250°C
Feed Flow Rate of MeOH	0.0015 m^3/s
MeOH: Steam (% mole)	1.3:1
MeOH: O_2 (% mole)	0.25:1
WGS Temperature	250°C
Steam: CO	30:1
TC Membrane Temperature	250°C
PSA Temperature	80°C
Stack Temperature	70°C
H_2/O_2 Ratio in the Stack	1.5

The fuel flow circuit begins at the methanol fuel tank. From the tank, methanol is pumped into the fuel vaporizer where it is heated and vaporized. It is then fed into the ATR where it reacts with the preheated O_2-enriched air and superheated steam to yield the raw reformate. The hot reformate is used to superheat the ATR steam feed. Additional water may then be mixed before it is fed into the WGS. In the WGS reactor, excess steam is needed to prevent reverse WGS from occurring. The fuel gas leaving the WGS reactor passes through the water adsorber unit where excess steam is removed before the gas enters the TCM unit. The flow that leaves the membrane unit is cooled before it enters the adsorber. Finally, the purified hydrogen fuel flow, which will be humidified to 100%, enters the anode side of the stack.

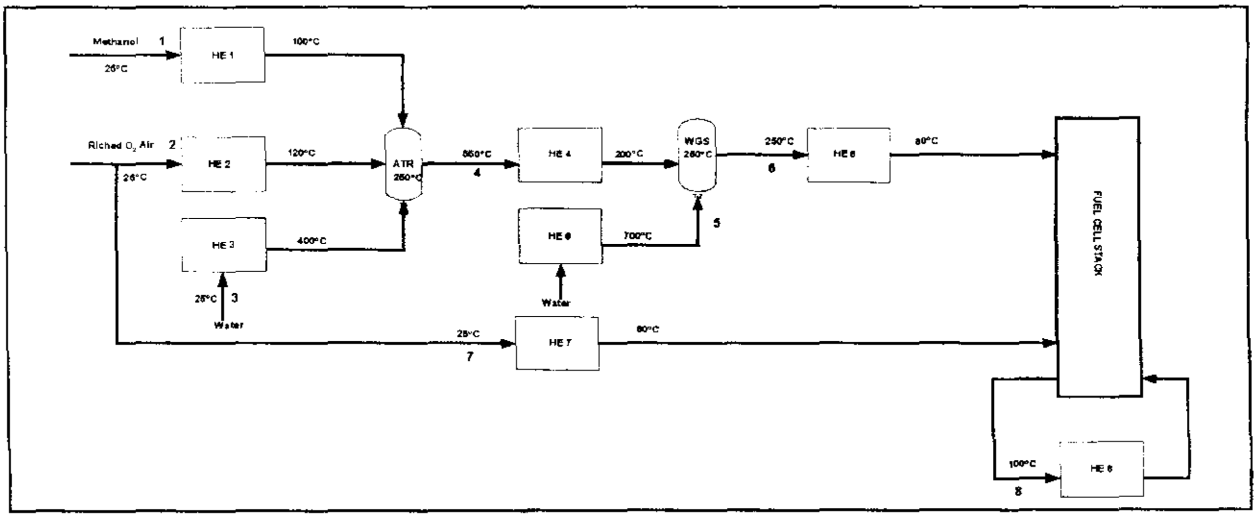
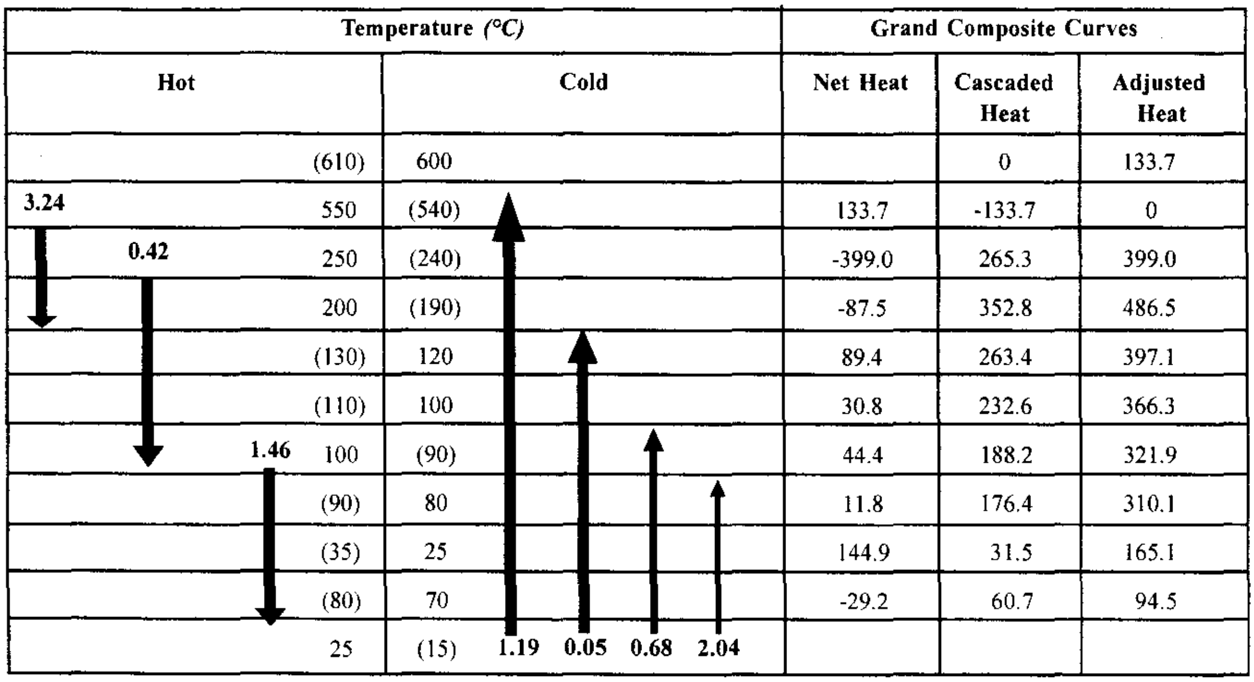


Figure 3. Temperature Profile of the Proposed PEMFC System (Unoptimized)

Table 2. Data for Pinch Analysis

Stream	Condition	Flow rate, *F* (g-mol/s)	T inlet, *Ti* (°C)	T target, *Tt* (°C)	Heat, *Q* (W)
1	Cold	0.10	25	100	51.3
2	Cold	0.03	25	120	5.1
3	Hot	0.36	550	200	-1,135.0
4	Cold	0.22	25	600	1,003.0
5	Hot	0.12	250	80	-62.6
6	Hot	0.20	100	25	-109.5
7	Cold	0.17	25	70	91.9

Table 3. Extended Problem Table Algorithm (PTA)



Temperature *(°C)*				Grand Composite Curves		
Hot		Cold		Net Heat	Cascaded Heat	Adjusted Heat
	(610)	600			0	133.7
3.24	550	(540)		133.7	-133.7	0
0.42	250	(240)		-399.0	265.3	399.0
	200	(190)		-87.5	352.8	486.5
	(130)	120		89.4	263.4	397.1
	(110)	100		30.8	232.6	366.3
1.46	100	(90)		44.4	188.2	321.9
	(90)	80		11.8	176.4	310.1
	(35)	25		144.9	31.5	165.1
	(80)	70		-29.2	60.7	94.5
	25	(15)	1.19 0.05 0.68 2.04			

Ambient air will pass through an oxygen concentrator to separate O_2 from N_2. This stream will split into two main streams.

On the one hand, the smaller oxygen (or air) flow is preheated and fed into an ATR reactor. On the other hand, the larger oxygen (or air) flow is humidified to 80% and then cooled by injecting liquid water prior to being supplied into the cathode inlet of the fuel cell stack.

RESULTS AND DISCUSSION

Data extraction

Figure 3 presents a temperature profile of the PEMFC system, while Table 2 gives the details of the streams being considered for heat integration.

The varying amounts of heat for the hot and cold streams were tabulated using both PTA

Table 4. Summary of Results

Minimum Process Heating Requirement from Hot Utilities, $Q_{H_{min}}$	134 W
Minimum Process Cooling Requirement from Cold Utilities, $Q_{C_{min}}$	96 W
ΔT_{min}	20°C
Pinch (Interval) Temperature	540°C
Hot Stream Pinch Temperature	550°C
Cold Stream Pinch Temperature	530°C

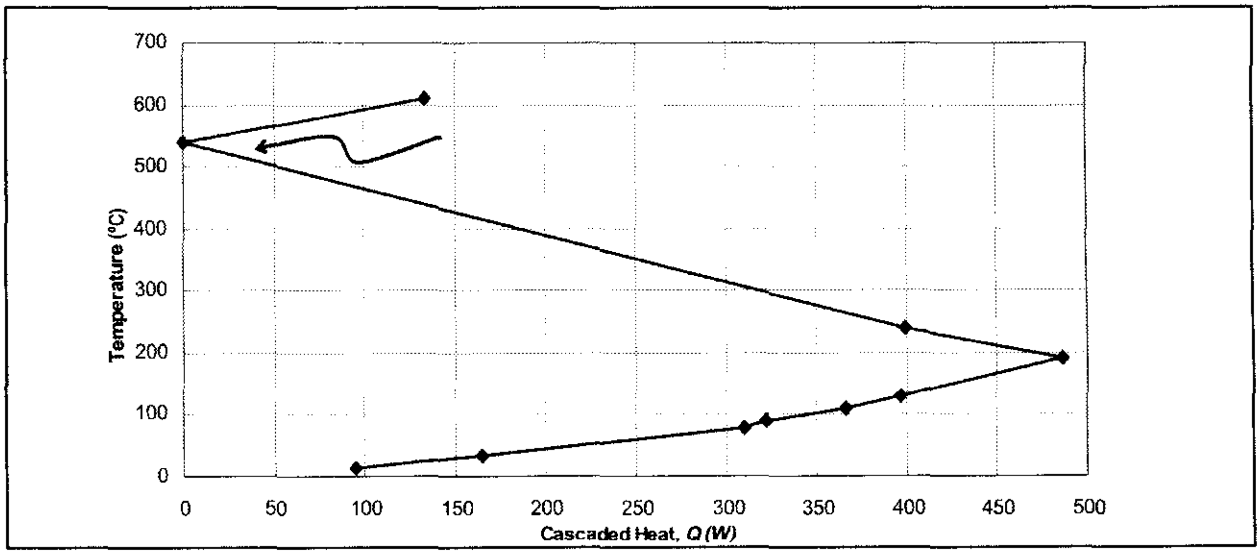


Figure 4. Grand Composite Curve

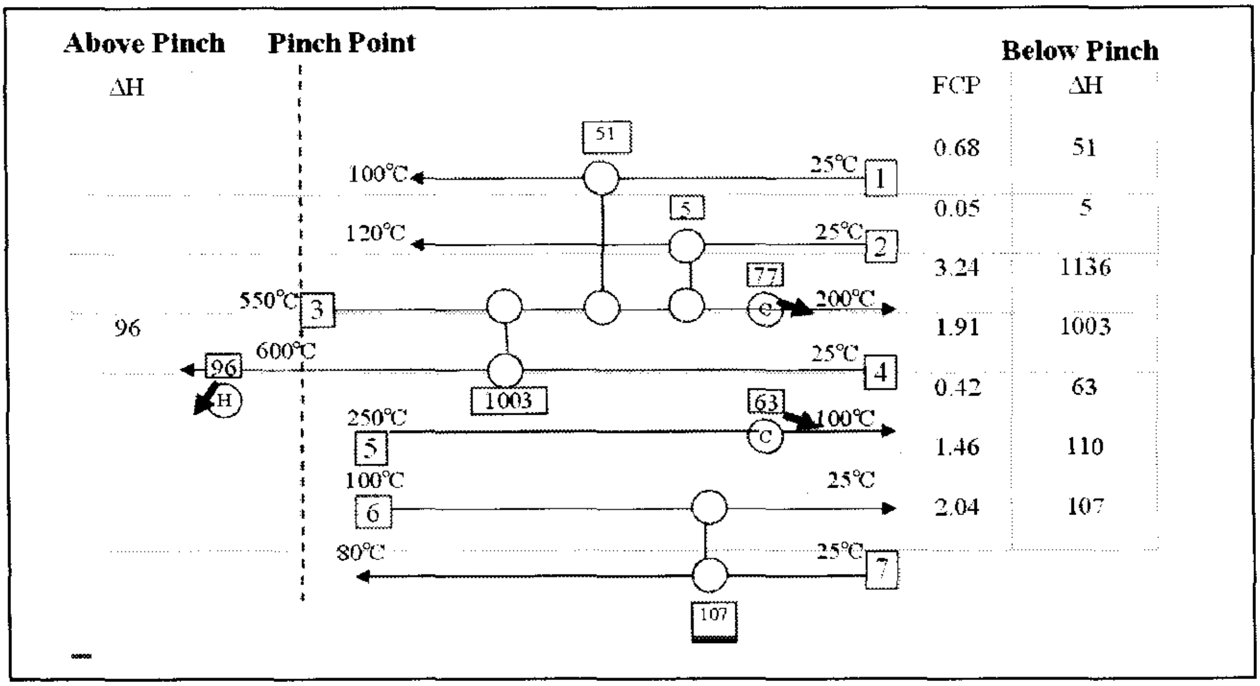


Figure 5. Grid Diagram of the PEMFC System

and cascaded heat as illustrated in Table 3. The temperature difference between the cold stream and the hot stream ΔT_{min} was pegged at 20°C. Table 3 likewise shows the actual and interval temperatures for the process streams.

From the PTA, the calculation may be carried out one step further to subsequently generate data that would represent the overall net heat flow for the problem. The resulting plot would be the GCC seen in Figure 4. The GCC was plotted using the interval temperature versus the enthalpy from cascaded energy based on the last three columns in Table 3.

The first column shows the net heat expelled from an interval and obtained by subtracting the heat required by the cold streams from the heat produced by the hot streams. After that, these numbers were cascaded in order to derive the cascaded heat.

Cascaded heat is the amount of heat that the systems have available from the hot streams over that required by the cold streams, while moving from higher to lower temperatures. The negative values in this column show that the hot streams have not produced enough heat to satisfy the needs of the cold stream above this entry. The first number in the last column represents the minimum amount of heat supplied into the hot utilities ($Q_{H_{min}}$), while the last number represents the minimum amount of heat removed from the system using cold utilities ($Q_{C_{min}}$).

From the plots, it can be observed that every interval that acts as a heat sink has a line segment that moves down to the left; whereas every interval that acts as a heat source has a line segment that moves down to the right. The pinch point crosses at 540°C, which is about the temperature of the ATR product. Likewise, it has been observed that

Table 5. Energy Recovery

Utility type	**Energy (W)**	
	Before Integration	**After Integration**
Heater (HE1)	51.3	0
Heater (HE2)	5.1	0
Heater (HE3)	1,003.0	96
Heater (HE7)	91.9	0
Cooler (HE4)	1,135.0	63
Cooler (HE6)	109.2	0
Total	2,395.5	159

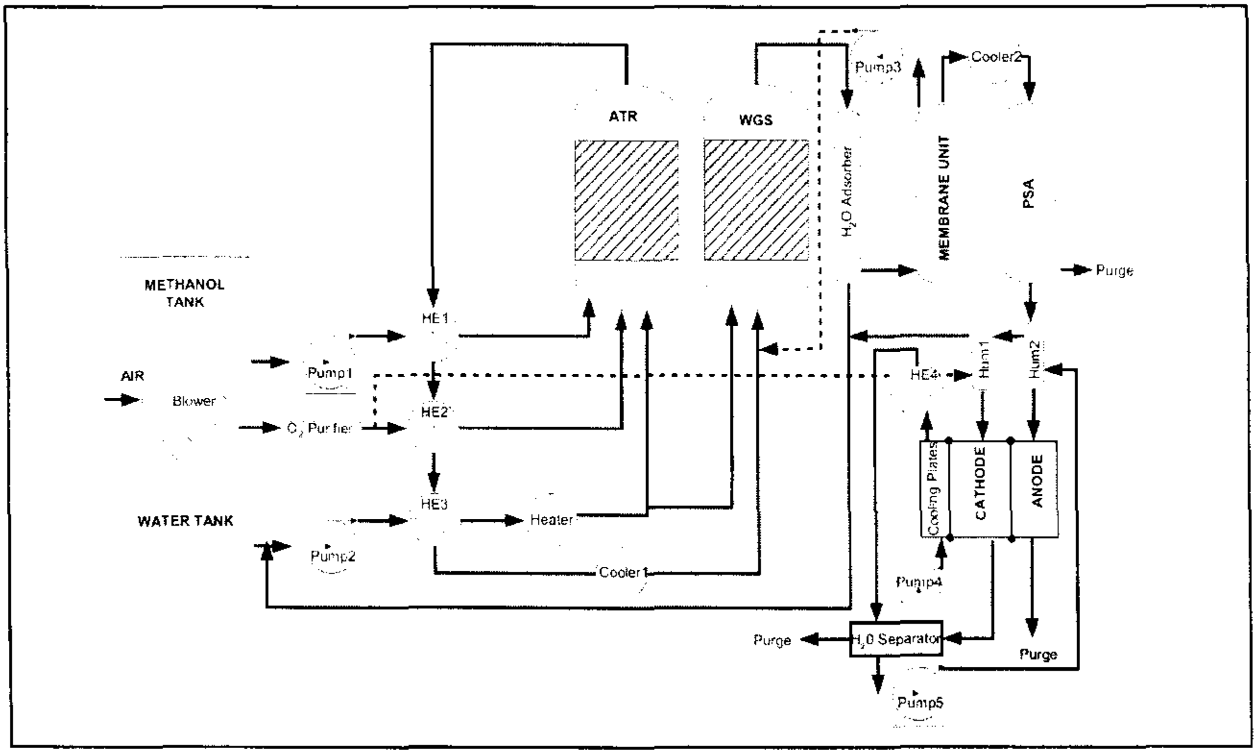


Figure 6. The Optimized PEMFC System

most of the heat went into superheating the steam. These values agree with those in Figure 4 and Table 4.

Heat exchanger network (HEN) design

Figure 5 represents the grid diagram for the HEN system. Basically, the system is divided into two sections, namely (a) *above the pinch* and (b) *below the pinch*. From the figure, it can be observed that for above the pinch, stream 4 needs one unit of heat exchanger and one unit of heater.

For below the pinch, it has been determined that stream 3 (the product from the ATR at 500°C) requires three units of heat exhanger and one unit of cooler attached to streams 1, 2, and 4; while streams 6 and 7 exhange heat with one cooler to cool down the stream from the membrane unit before entering the PSA.

Figure 6 presents the optimized PEMFC system after heat integration. It has been observed that the hot stream from the ATR can be recycled to evaporate the methanol and oxygen streams to the ATR and superheat the water stream to the ATR and WGS reactor. While in the fuel cell stack, waste heat can be used to heat up the oxygen flow before it enters the humidifier unit.

Finally, Table 5 shows the scenario of energy saving before and after heat integration. From this table one can see that the percentages of energy recovery for both heating and cooling purposes after heat integration have been calculated at 92% and 95%, respectively.

CONCLUSIONS

From the overall heat exchanger network design, it was observed that a total of about 140 W of cold utilities would be needed below the pinch point and 96 W of hot utilities above the pinch point.

The results also revealed that the percentage of energy recovery for heating and cooling purposes after heat integration were at 92% and 95%, respectively; while the number of heat exchangers went down from 7 to 4.

Thus, adopting the proposed design can consequently (a) reduce capital costs and utilities, (b) maintain operating costs for the fuel cell system, and (c) minimize both the system's size and weight.

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