Proceedings of POWER2008
ASME Power 2008
July 22-24, 2008, Orlando, Florida, USA

POWER 2008-60111

USING STAGED COMPRESION TO INCREASE THE SYSTEM EFFICIENCY OF A COAL BASED GAS TURBINE FUEL CELL HYBRID POWER GENERATION SYSTEM WITH CARBON CAPTURE

John G. VanOsdol, Randall Gemmen, and Edward Parsons
National Energy Technology Laboratory
3610 Collins Ferry Road
Morgantown, WV 26507-0880

ABSTRACT

This paper examines two coal-based hybrid configurations that employ separated anode and cathode streams for the capture and compression of CO_2. One system uses a single compressor to compress and partially preheat the cathode air flow. The second system replaces the single compressor with a two stage compression process with an intercooler to extract heat between the stages, and to reduce the work that is required to compress the air flow in the cathode stream. Calculations are presented for both systems with and without heat recuperation. For the single compressor system with heat recuperation the hybrid system assumes the form of a recuperated Brayton cycle; when the recuperator is not present the hybrid system assumes the form of a standard Brayton cycle. The calculation results show that an increase of 2.2% in system efficiency was obtained by staging the compression for these cycles.

1.0 INTRODUCTION

In recent years there has been significant growing interest in different carbon capture technologies that might be applied to fossil fuel power generation plants. These technologies reduce the amount of CO_2 that would normally be emitted into the atmosphere from the daily operation of these plants. Adding carbon capture to any system changes the thermal process in ways that reduce the thermal efficiency. The additional equipment required to separate and compress the CO_2 also greatly adds to the complexity of the system.

Likewise, there has also been significant growing interest in coal based gas turbine fuel cell hybrid power plants, This has been led primarily by DOE's Solid State Energy Conversion Alliance Program [1,2] .The reason for this increased interest is that a hybrid power plant can have greater system efficiency than a conventional gas turbine power plant because of the higher conversion efficiency of a fuel cell, and the fact that the heat that is evolved from a fuel cell can be utilized in a gas turbine generator. It is expected that the increased system efficiency of the hybrid system might compensate for the increased expense of performing carbon capture.

Studies showing the effects of the system operating pressure ratio on the gas turbine fuel cell hybrid system were performed by Liese [3] and VanOsdol [4]. These studies were performed for general gas turbine fuel cell hybrid systems and did not include several processes that would be present in a coal fired system. Coal fired hybrid systems will be powered by a synthesis gas (SYNGAS) which is generated from a gasifier. In order to use the syngas in a SOFC it must first be cooled so that it can be cleaned. It must then be reheated to the SOFC operating temperature. Management of these additional heat streams inside the system adds to the complexity of the configuration. These studies are a first attempt manage these heat flows and to integrate them into the hybrid system.

In this work, a 100 MW class coal fired gas turbine solid oxide fuel cell (SOFC) hybrid power generation system with carbon capture is presented. We specifically investigate a configuration that is uniquely inherent to fuel cell technology—one employing separated anode/cathode streams. The carbon capture is performed by maintaining a separated anode gas stream, and burning the unused fuel in this stream using pure O_2. The resulting heat that is generated from this process is then used to reheat the syngas after cleaning and then to drive a secondary turbine where more work is extracted. The products of combustion from this secondary

This material is declared a work of the U.S. Government and is not subject to copyright protection in the United States.
Approved for public release; distribution is unlimited.
Downloaded From: https://proceedings.asmedigitalcollection.asme.org on 06/30/2019 Terms of Use: http://www.asme.org/about-asme/terms-of-use

combustion process are mostly water and carbon dioxide. The water by-product is then condensed out of the stream leaving a relatively high concentration of CO_2. This stream is then compressed and removed from the system.

In the present work we investigate the performance of system configurations using both the standard and the recuperated Brayton cycles to utilize the heat from the cathode air stream that has been generated by the SOFC. We then replace the single stage compression leg of each system configuration with a two stage compression leg. Each configuration uses the same carbon capture scheme discussed above. We show that staging the compression leg of both the recuperated and non-recuperated hybrid systems is marginally beneficial at increasing the overall system efficiency.

2.0 DESCRIPTION OF BASIC SYSTEM AND MODEL

2.1 Recuperated Brayton cycle hybrid system with CO2 capture.

The basic gas turbine fuel cell hybrid system with carbon capture loop, and with a single compressor for the cathode air flow is shown in Figs. 1 and 2. The hybrid system without the carbon capture loop follows the low pressure recuperated system presented by Tucker and VanOsdol [5, 6]. The carbon capture loop was later added to study the effects of CO_2 removal on system performance [7]. In the upper left hand corner of Fig. 1 a single compressor CMP-1 and cathode turbine TRB-1 are shown. The turbine is solely driven by heat that is generated by the SOFC and picked up in the cathode air stream. In this arrangement the cathode turbine is a low temperature turbine operating with an inlet temperature which is equal to the SOFC outlet temperature, ca. 1123 K. It therefore requires no cooling air.

The heat recuperator is shown as the heater blocks RGN-C and RGN-H connected by a heat stream. When the recuperator is active it serves two purposes. It preheats the SOFC inlet air, and it increases the thermal efficiency of the gas turbine part of the cycle for low operating pressures. The system model is constructed so that the heat recovered in the recuperator may be turned off. This reduces the gas turbine system shown in Fig. 1 to a simple Brayton cycle. With the heat recuperator turned on, the system is a recuperated Brayton cycle. This feature allows for a direct comparison between the two systems.

In general the inlet cathode air flow for the system shown in Fig. 1 can be heated both by compression and by heat recuperation. For a power plant of this size with lower operating pressures, i.e. PR<10, previous calculations have shown that this is not adequate to control both the SOFC inlet temperature and the temperature change through the SOFC. There is therefore a cathode air flow recirculation loop around the SOFC. This recirculation air is driven by the pump RCR-1 which operates at a pressure ratio which is equivalent to the pressure drop across the SOFC. With the system pressure ratio set as an input parameter, the system inlet air flow is changed in a convergence loop so that the SOFC inlet temperature is maintained at 973 K. The cathode air recirculation is also simultaneously changed in a convergence loop so that the temperature change through the SOFC is 150 K.

2.2 SOFC Model.

The hybrid system and the SOFC were modeled using the Aspen system simulation software. Details of the basic system model are described by Tucker and VanOsdol [4, 5, 6]. The SOFC is shown in the lower left hand corner of Fig. 1. It is comprised of three flow blocks that operate in conjunction with a FORTRAN module that calculates the electrochemical performance of the fuel cell. In the calculations presented here the fuel mass flow rate and the fuel utilization factor are fixed input parameters. The amount of O_2 passing out of the cathode stream into the fuel stream can then be directly calculated. This O_2 then reacts with the fuel (H_2 and CO from the syngas inlet stream) in the anode reaction block to release chemical energy. The extent of this energy converted to heat depends on the temperature of the reaction so an initial temperature for the SOFC reactor block is arbitrarily assigned. The heat is then passed into the cathode heater block where it heats the oxygen depleted cathode air stream to the assigned reaction temperature. The balance of energy is shown as LD-SOFC in Fig. 1. By the conservation of energy this energy must be equal to the electrical power that is produced by the SOFC which is separately calculated by the FORTRAN block. The reaction temperature is then varied in a convergence loop until the residual energy, i.e. LD-SOFC, from the cathode heater block and the fuel cell electrical power calculated from the FORTRAN block are equal.

2.3 Carbon capture scheme.

Syngas passes into the hybrid system via the fuel cell anode inlet shown as stream 13 in Figs. 1 and 2. This stream is completely isolated from the cathode flow. A more common configuration for hybrid systems is where anode exit and cathode exit streams are combined in order to complete the oxidation of the residual fuel cell anode gas. This helps to maintain a balanced pressure across the fuel cell which reduces the chance of cell damage through mechanically induced fracture. However, because of the combined streams, there remains the risk of anode gas reaching the cathode, or cathode gas reaching the anode. Such events could be possible during flow upsets or shutdown conditions where anode and cathode flows cannot be maintained. The point being raised here is that the configurations using combined streams present risks that are not present with isolated streams. Carbon capture is performed by taking the un-reacted fuel from the SOFC anode outlet stream 14 and burning it in a

Downloaded From: https://proceedings.asmedigitalcollection.asme.org on 06/30/2019 Terms of Use: http://www.asme.org/about-asme/terms-of-use

separate combustion chamber shown in Figs. 1 and 2 as POST. This combustion process is fed with a pure oxygen stream. The source for this O_2 stream is the air separation unit (ASU) which is an integral part of the gasification process. In our calculations the amount of oxygen in this stream is regulated so that 99% of the unused hydrogen is oxidized. This leaves a post combustion mixture consisting mostly of high temperature carbon dioxide and water. This high temperature gas is then expanded in a secondary anode gas turbine TRB-2 to a pressure of .9 atm. producing work. The stream leaving the anode turbine is still at a high quality temperature, ca. 1079 K. A condenser is added which liberates heat and removes the water. This high quality heat is then used to drive a steam bottoming cycle shown in Fig. 1 as STM-2 with an assumed overall conversion efficiency of 30%. There is another recirculation loop around the anode turbine. This flow is driven by the recirculation compressor RCR-2 which is included in order to maintain the inlet temperature of the anode turbine at 1400 K. The final step in the carbon capture scheme is to compress the CO_2 outlet stream 22 to 2000 psi. For the present work this is done using a single compressor shown as CMP-2. We could have used multiple compressors with intercoolers to do this resulting in a lower cost in compression power for the CO_2 [8]. This would result in a higher system efficiency, and an additional low grade heat source from the intercoolers between the compressors which could then be integrated back into the system. For reference, in the present work, the cost of CO_2 compression was approximately 700. kJ/kg-CO2. With multiple compression designs the cost can be as low as 450. kJ/kg-CO_2. We did not stage the CO_2 compression in the present calculations because we are specifically concerned with the compression cost of the cathode air flow.

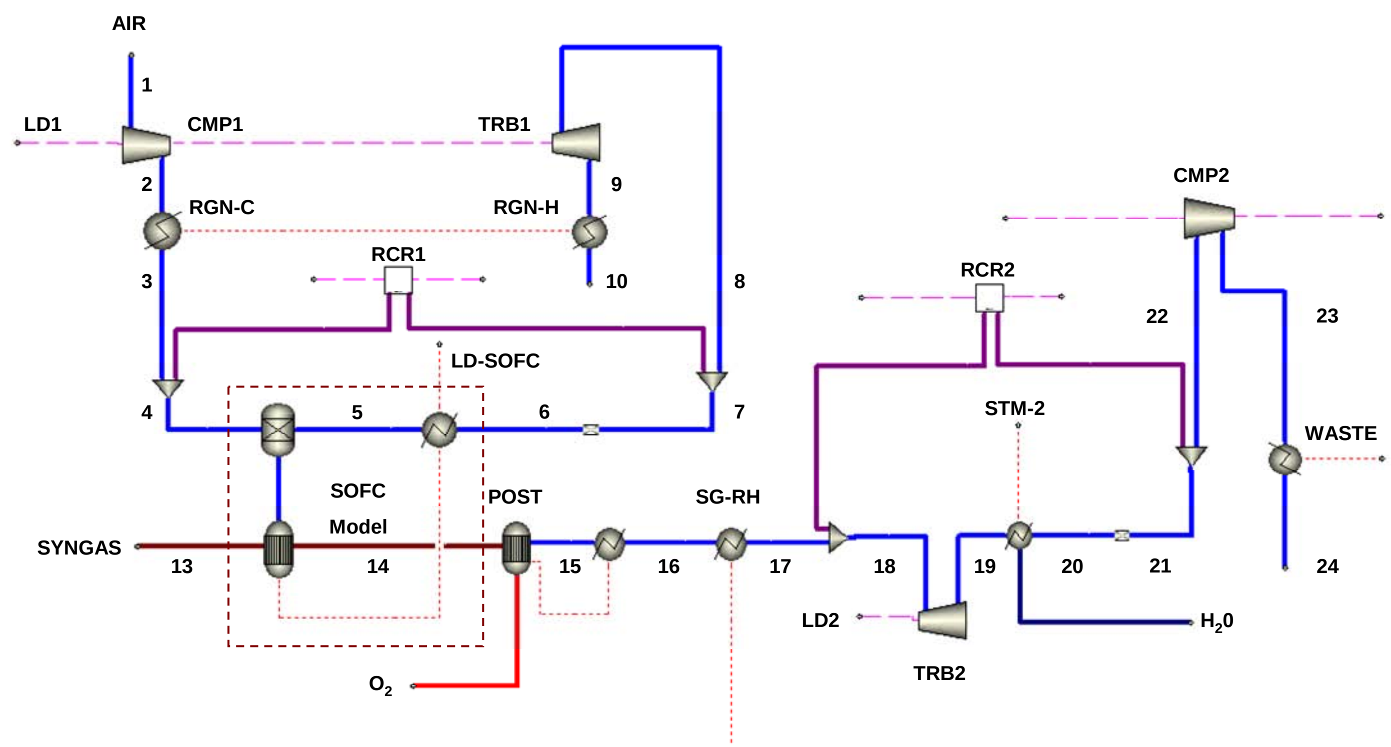

FIGURE 1. GAS TURBINE FUEL CELL HYBRID SYSTEM WITH CARBON CAPTURE.

Downloaded From: https://proceedings.asmedigitalcollection.asme.org on 06/30/2019 Terms of Use: http://www.asme.org/about-asme/terms-of-use

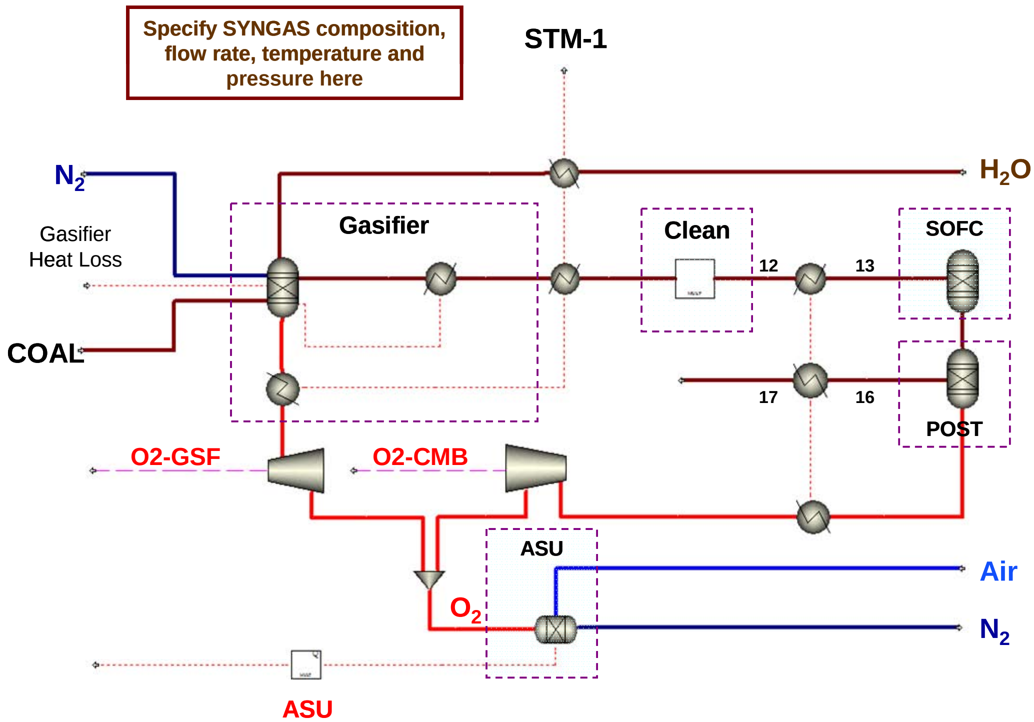

FIGURE 2. SYNGAS PROCESSING STREAM.

2.4 Syngas processing.

The syngas fuel is produced by the oxygen blown gasifier shown in Fig. 2. The syngas composition for the gasifier outlet stream is given on Table 1. Oxygen blown gasification systems typically have low concentrations of higher hydrocarbons. This allows us to do the present calculations without a separate reforming reaction (internal or external to the fuel cell stack). In our calculations the mass flow rate of the syngas is fixed in stream 13 at 14.5 kg/sec. With a fixed composition and flow rate of the syngas stream the flow rates for the individual gasifier inlet streams can then be directly calculated. The syngas flow is made of approximately 3.9 kg/sec of coal, 4.7 kg/sec of water, 5.3 kg/sec of oxygen and 0.6 kg/sec of nitrogen. The heating value for the coal input stream is taken to be 7795 kcal/kg [9]. This gives a total power input to the system of 127.3MW which is the value that is used in the system efficiency calculations.

TABLE 1. SYNGAS COMPOSITION.

Species	Mole Fraction
CO	0.291
H_2	0.285
CO_2	0.118
H_2O	0.276
N_2	0.02991
CH_4	0.00009

In the gasifier under consideration the syngas is generated at a high temperature of 1777 K. Gasification systems operate at many different pressure ranges. Some operate at high pressure; some operate at low pressure near atmospheric. To accommodate for this variability an intermediate gasification pressure of 7 atm. was chosen for our "generic" gasifier. This is a reasonable approximation for the present study since gasifier operating pressure has only a minor effect on the overall system efficiency. (It may have a significant effect on cost, but that is not part of this study.) The main issue for the gasifier in regards to system efficiency is how the heat is managed through syngas cooling and reheating, and these impacts are directly analyzed in this work.

In order for the syngas to be used in a fuel cell application, it must first be cooled so that sulfur, particulate matter, and other trace material can be removed. In this work, it has been assumed that the syngas has been cooled to 400K. In the system diagram shown in Fig. 2 this cooling process is shown as the heat transfer block prior to stream 12. For these conditions, and the 7 atm. gasifier operating pressure, the water in the syngas is not condensed out by the cleanup process. The heat that is liberated by the syngas cooling process is then used to generate enough steam to feed the gasifier, and to drive a steam cycle STM-1 with a turbine and an electrical generator. The useful energy that can be recovered from this process occurs at only about 30% efficiency.

Downloaded From: https://proceedings.asmedigitalcollection.asme.org on 06/30/2019 Terms of Use: http://www.asme.org/about-asme/terms-of-use

The syngas must then be reheated to the operating temperature of the fuel cell. The cold side for the syngas reheating operation is shown in Fig. 2 as the heater block between streams 12 and 13. A convenient means of reheating the syngas for this system is to use heat from the same isolated anode stream that was generated by the post combustion process used for the carbon capture scheme. The hot side for the syngas reheat process is shown in the system diagram as the heater block between streams 16 and 17. The high grade heat obtained from the anode post combustion process is obtained by purposely running the SOFC with a low fuel utilization factor of 70%. This was required so that there would be enough heat processed in the isolated anode stream to reheat the syngas, drive the anode turbine and also drive the bottoming steam cycle STM-2.

2.5 Cost of producing oxygen.

As shown in Fig. 2 there are two separate oxygen requirements in this system. The first is used in the gasification process to produce the syngas, and the second is used in the anode post combustion reactor to burn the unused fuel from the SOFC anode outlet stream. The cost of producing oxygen is shown on Fig. 3. Data was extracted from operational conditions specified for commercially available units [10, 11], and in the literature [12, 13]. For the present work, the cost factor used for oxygen supply is taken from Fig. 3 as .424 MW/(kg/sec).

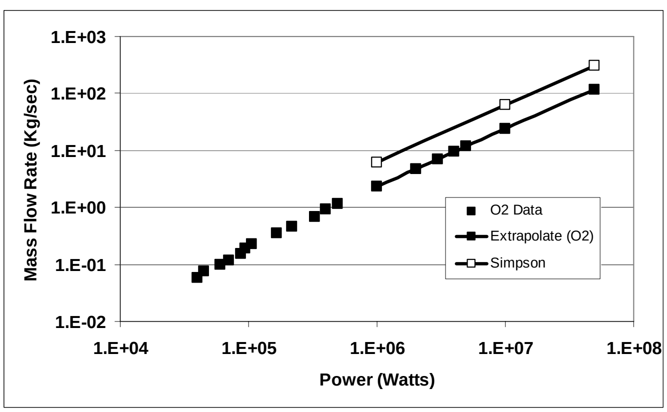

FIGURE 3. POWER COST TO PRODUCE O_2.

2.6 Calculation of internal thermal loads and pressure drops.

All heat exchangers are modeled using a pair of standard Aspen heater blocks which are connected by a heat transfer stream. The two blocks in each pair individually calculate changes in the flow for the hot side and the cold side of the heat exchanger. The performance of the heat transfer process was then calculated using the standard definition of heat exchanger effectiveness. For the heat recuperator the amount of heat that passes from the hot side to the cold side was changed in a convergence loop during calculation until a heat exchanger effectiveness of .86 was achieved. For the syngas reheat operation the temperature rise of the syngas from 400 K to the SOFC input temperature of 973 K was specified, and the heat exchanger effectiveness was simply calculated. In each case the value was between .25 and .36 indicating that there was more than sufficient heat present in the post combustion high temperature syngas stream to accommodate the re-heat operation.

The isentropic efficiency of all compressors, pumps and turbines is taken to be 90 %, and the various pressure drops throughout the system are calculated according to the losses shown on Table 2.

TABLE 2. PRESSURE LOSSES FOR HYBRID SYSTEM.

System Element	Pressure Drop (% inlet pressure)
Recuperator (cold side)	2.0
Recuperator (hot side)	2.0
SOFC	3.0
Combustion Loss	6.0
Bottom Loss	5.0
Inter Cooler (hot side)	2.0

3.0 PERFORMANCE OF BASIC SYSTEM

3.1 Performance of the basic system with single stage compression for cathode air flow.

As a nominal reference point, the energy balance for the hybrid system configured as a Brayton cycle system with no heat recuperation and a single compressor for the cathode air flow was studied with a pressure ratio of 8 and an SOFC fuel utilization of 70%. The stream temperatures and mass flow rates for both the cathode air flow and the anode flow are shown in Fig.4. The stream numbers in Fig. 4 refer to the system diagrams previously shown in Figs. 1 and 2.

As can be seen, without the heat recuperator the cathode air recirculation rate is very high at approximately three times the cathode air flow rate. This may not be obtainable in a practical system but was necessary in order to maintain the SOFC inlet temperature at 973 K and the SOFC temperature change at 150 K. The SOFC inlet and outlet temperatures for the cathode air flow are shown in Fig. 4 as streams 5 and 6. The inlet and outlet temperature for the anode flow are shown as streams 13 and 14.

Immediately downstream of the SOFC anode outlet stream is the post combustion reactor. Since the fuel utilization factor in this case was only 70% there is a significant amount of

Downloaded From: https://proceedings.asmedigitalcollection.asme.org on 06/30/2019 Terms of Use: http://www.asme.org/about-asme/terms-of-use

unburned fuel left in the anode stream. This is what gives this particular system a source of high grade heat which raises the temperature of the anode effluent stream to 2000 K. This high grade temperature source is significantly reduced with increased fuel utilization. There is also a reduction in the oxygen required by the post combustion reactor.

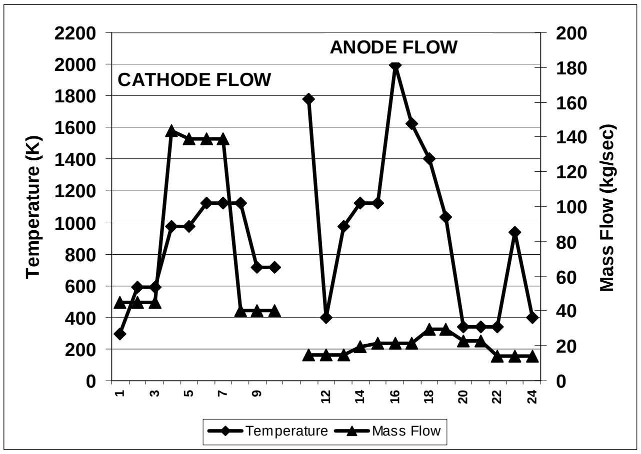

FIGURE 4. TEMPERATURE AND MASS FLOW WITH FUEL UTILIZATION OF 70%.

The power budget for this system is shown in Fig. 5. The power producers are the two steam cycles, STM-1 and STM-2, the net load LD-1 from the cathode compressor CMP-1 and the cathode turbine TRB-1, and the load from the anode turbine TRB2. The power consumers are the work inputs to the air separation unit ASU, the oxygen compressors which feed the gasifier and the post combustion process, O2G and O2C, the recirculation pump RCR-1, the recirculation compressor RCR-2, and the CO_2 compressor CO2. The black connecting bars marked "shaft power out" and "steam power out" indicate the mechanical and thermal power output for the system. The red connecting bar marked "shaft power cost" indicates the mechanical power required by the various compression and pumping unit operations which are a cost to the system. For the system efficiency calculations the power extracted from the heat sources STM-1 and STM-2 is multiplied by 30% representing the efficiency of steam cycles with steam turbines and electrical generators which would be incorporated with the system but are not shown in the system diagrams [14]. The system efficiency can then be given by:

$$Eff = \frac{SOFC + (shaft\ \ out) - (shaft\ \ cost) + 0.3(steam\ \ out)}{1273\ \ MW\ \ coal\ \ feed}$$

The single cathode air compressor system was run over a range of operating pressures using both the standard Brayton cycle and the recuperated Brayton cycle configurations. A comparison of the system efficiencies is shown in Fig. 6. In these results the fuel utilization factor was 70%. The results show the classic behavior difference between a standard Brayton cycle and a recuperated Brayton cycle, namely that the recuperator is very helpful at low pressure ratios and becomes less effective with increasing pressure ratio.

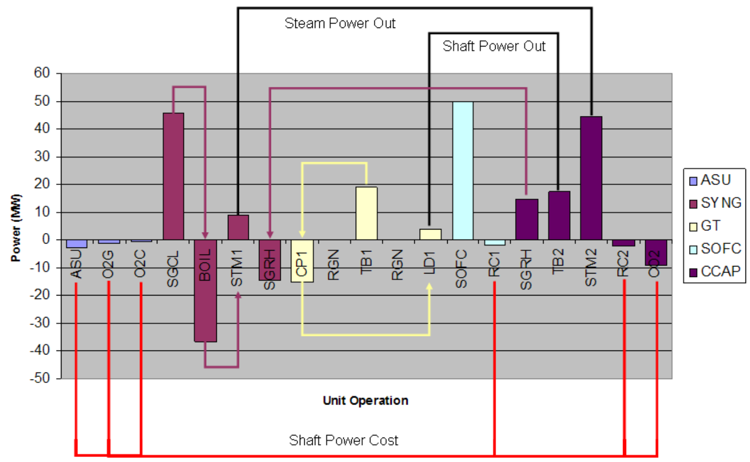

FIGURE 5. POWER BUDGET WITH SOFC FUEL UTILIZATION OF 70%

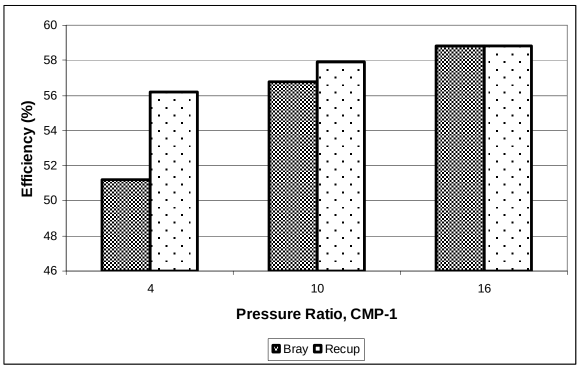

FIGURE 6. DIMINISHING IMPACT OF THE RECUPERATOR ON SYSTEM EFFICIENCY

The effect of the SOFC fuel utilization factor on the system efficiency for the system operating with a standard Brayton cycle and a pressure ratio of 8 is shown on Table 3. The results show that for every percentage point increase in fuel utilization, a 0.38 percentage point increase is gained in system efficiency.

Table 3. Effect of fuel utilization on system efficiency with Pressure Ratio = 8.

Fuel Utilization (%)	System Efficiency (%)
66	52.84
68	53.22
70	53.60
71	53.77

For this system the fuel utilization factor could not be increased over 71 %. Beyond this point the system model was

Downloaded From: https://proceedings.asmedigitalcollection.asme.org on 06/30/2019 Terms of Use: http://www.asme.org/about-asme/terms-of-use

unable to achieve a converged solution. As was previously mentioned the fuel utilization for this configuration must be maintained at a low value in order to maintain all the thermal operations in the post combustion anode stream.

3.2 High cost of compression for Brayton cycle.

By examining the energy budget for this system shown in Fig. 5 it can be seen that the cost of compressing the cathode air stream to the elevated operating pressure of the SOFC is greater than the cost of compressing the CO_2 stream. This situation exists because the mass flow rate of the cathode air exceeds the mass flow rate of the CO_2 stream by a ratio of greater than 3 to 1. So although the pressure of the CO_2 compression is high at approximately 2000 psi, the actual power expended to move the mass of air through the hybrid system is greater.

A hybrid system previously proposed by the authors that is similar to the present system showed the same high cost for cathode air compression. The previous system was originally used to calculate the cost of carbon capture in a coal fired gas turbine hybrid system [7]**.** The calculation results that were presented in this study showed that the fuel utilization factor did have an effect on the system performance. However, these calculations did not directly include the gasification system, or the air separation unit. They therefore did not directly calculate the cost of reheating the syngas, or producing steam and oxygen for the gasification process. These costs were lumped into the gasifier efficiency which was held constant for all the calculations. Changes in the SOFC fuel utilization factor thus did not have the same impact on the gasification costs for these previous studies as they do in the present studies, as they were decoupled from the system model.

In the present system both the gasifier and the air separation unit are integrated with the hybrid system model. The way in which these components are integrated gives rise to a greater effect that the SOFC fuel utilization has on system performance. One effect is that in the present studies because of the syngas reheat operation we must use a substantially reduced fuel utilization factor. The results of these previous calculations are useful however because the gas turbine hybrid system that was used in these previous studies is basically the same as in the present case, and so the calculation results indicate the relative magnitudes of power flow between the various components in the hybrid system. For this reason selected results from these studies are shown here.

The power producing components of the system are shown in Fig. 7. These are the anode turbine TRB-2, heat for the bottoming steam cycle STM-2 and the load LD-1 which is the net power produced by the cathode turbine TRB-1 minus the power required by the cathode air compressor CMP-1. It has been assumed that the heat that can be used in a steam cycle at an overall efficiency of 30%. It is interesting to note that there is more power produced by the anode turbine than by the net load from the cathode compressor-turbine pair. The cathode compressor and turbine thus serve primarily to move air through the system, and they use residual heat from the SOFC to do it.

In Fig.8 the relative magnitudes for the power requirements of the cathode air compressor CMP-1 and the CO_2 compressor CMP-2 in the hybrid system are compared with the power required by the recirculation pumps. It can be easily seen that the largest power requirement is for the cathode air compression. The carbon capture compression requires less than half of the power of the cathode air compression.

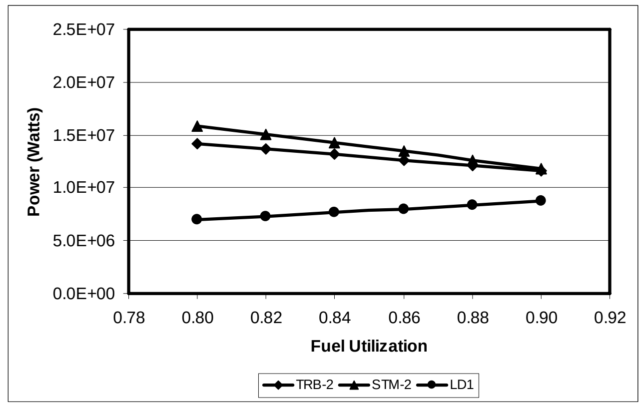

FIGURE 7. COMPONENT POWER OUTPUTS

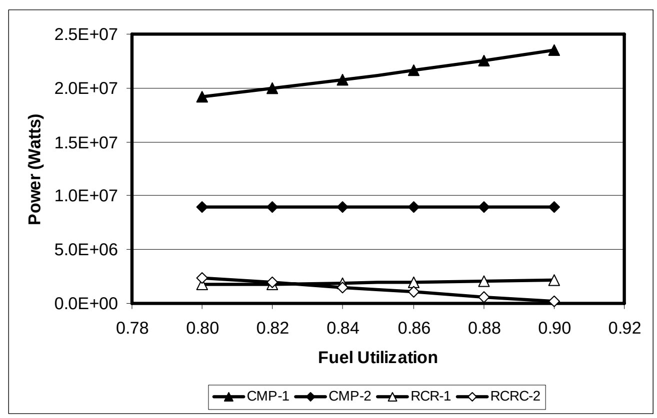

FIGURE 8. COMPONENT POWER REQUIREMENTS

4.0 IMPLEMENTATION OF STAGED COMPRESION FOR CATHODE AIR

In light of the previous results, in order to reduce the internal energy cost of the cathode air compression the single compressor CMP-1 of the hybrid system shown in Fig. 1 was replaced by two compressors CMP-A and CMP-B with an intercooler in between them. The change in the system diagram is as shown in Fig. 9. Staging compression in this way has long been used to reduce the work that is required to compress a gas.

Downloaded From: https://proceedings.asmedigitalcollection.asme.org on 06/30/2019 Terms of Use: http://www.asme.org/about-asme/terms-of-use

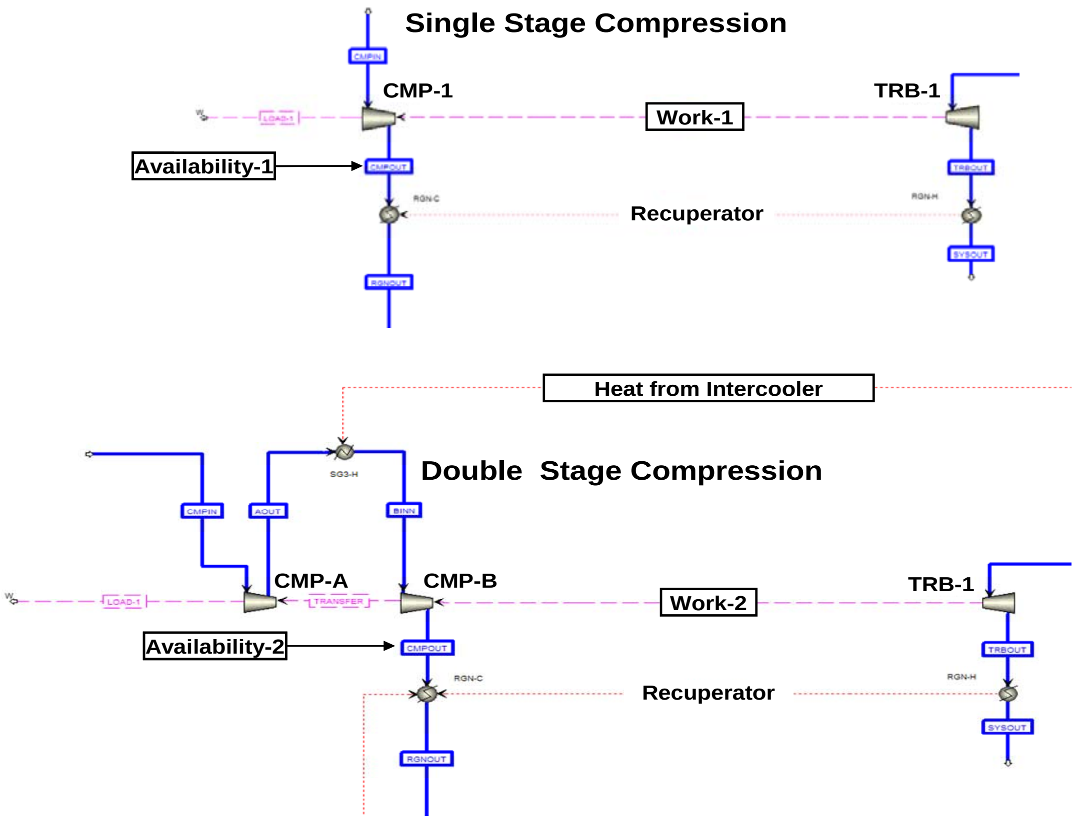

FIGURE 9. IMPLAMENTATION OF STAGED COMPRESION IN HYBRID SYSTEM

A direct comparison between the compression costs for the two systems is shown in Figs. 10 and 11. When the single cathode air compressor CMP-1 operates with a pressure ratio of 16 and a mass flow rate of 50 kg/sec, which are typical of our hybrid system, is replaced by two compressors in series, CMP-A and CMP-B, operating together with the same mass flow rate and total pressure ratio the range of different possibilities for the pressure ratios of the two individual compressors is shown in Fig. 10.

Assuming that enough heat is removed from the air stream between the compressors using an intercooler so that the temperature of the inlet stream for the second compressor is the same as the temperature for the inlet stream of the first compressor the resulting work requirement and the availability analysis for the output stream of the two stage system are compared to the single stage system in Fig. 11. Each curve is normalized by the work requirement and the output stream availability of the single stage system.

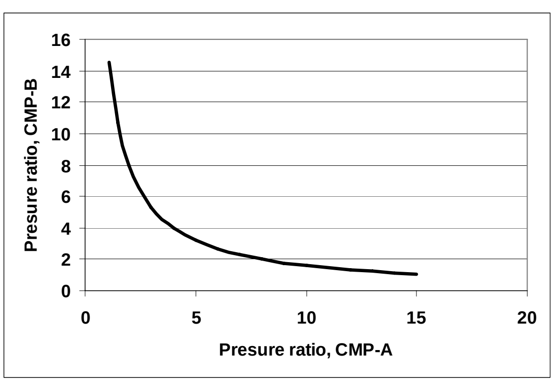

FIGURE 10. PRESURE RATIOS FOR EACH STAGE OF TWO COMPRESSORS OPERATING WITH A TOTAL PRESURE RATIO OF 16

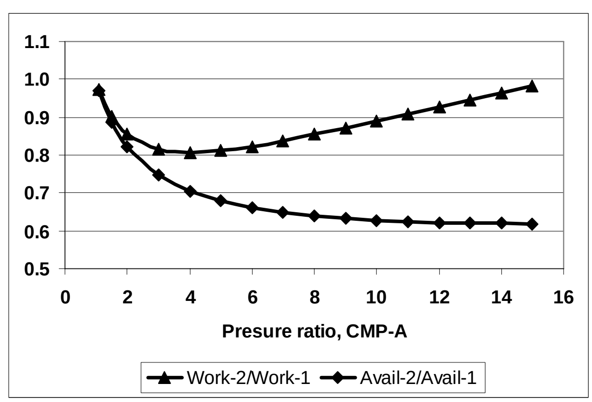

FIGURE 11. WORK AND AVAILABILITY OF COMPRESION OUTLET STREAMS

Downloaded From: https://proceedings.asmedigitalcollection.asme.org on 06/30/2019 Terms of Use: http://www.asme.org/about-asme/terms-of-use

It is clear from this analysis that if the pressure ratio of the first stage compressor is maintained at 4 to 1, then the total work requirement for the two stage compression process can be reduced by 20%. It is also clear that because of the intercooler, the availability of the outlet stream of the two stage system at this point decreases to 73% of that for the single compressor system. However, there is the additional heat source now available from the intercooler.

Implementation of the two stage compression for the cathode air thus gives rise to this additional low grade heat source. When this heat is used as a pre-heater for the syngas reheat operation there is a reduced requirement on the post combustion reactor to provide heat for all the process that follow in the carbon capture loop. The fuel utilization factor for the SOFC can thus be increased beyond the 70% limit that was realized for the single compressor system.

The results of the above analysis indicate a more favorable outcome than a practical system would allow. In a real system the inlet temperature for the second compressor can not be reduced to the inlet temperature of the first compressor. This is because the syngas stream is generally hotter than the inlet temperature of the first compressor. The heat from the intercooler must be integrated into the syngas preheat using the same heat exchanger effectiveness calculation technique that was used for the recuperator. This ensures that the heat transfer process can occur, and that there are no temperature anomalies present, but the outcome is that the inlet temperature for the second compressor is higher than the inlet temperature for the first compressor. The value used for the heat exchanger effectiveness for this process was 0.86, the same value that was used for the recuperator.

5.0 RESULTS

With the implementation of the two stage cathode air compression in our model the efficiency was calculated for both recuperated and non recuperated system configurations. The results are shown in Fig. 12 for a total system pressure ratio of 10, and Fig. 13 for a total system pressure ratio of 16. In all cases the SOFC fuel utilization was 70%. In the figures the calculation results for two stage cathode air compression with no recuperator are noted as “Bray-2”, and for two stage cathode air compression with recuperation as “Recup-2”. These are compared with the same results for the single stage compression which are noted as “Bray-1” and “Recup-1”. The results are plotted as functions of the pressure ratio of the first compressor in the series. Strictly speaking, with the addition of multiple compressors in the compression leg of the cycle we can no longer regard the system as being either a Brayton cycle, or a recuperated Brayton cycle. They are named this way in the figures for comparison purposes only.

The results show several things. The first is that the staged compression system does generally have higher system efficiency than the single compressor system. This is true for both recuperated and non-recuperated systems.

The system efficiency generally increases with the pressure ratio of the first compressor CMP-A in the series. This is probably due to the fact that as the pressure ratio for the first stage compressor increases, so does the temperature of the intercooler inlet stream, which is the hot side of the syngas pre-heater. This indicates that it may not be the reduced work requirement of the staged compression which is increasing the system efficiency, but it may simply be the transfer of heat from the cathode stream to the anode stream.

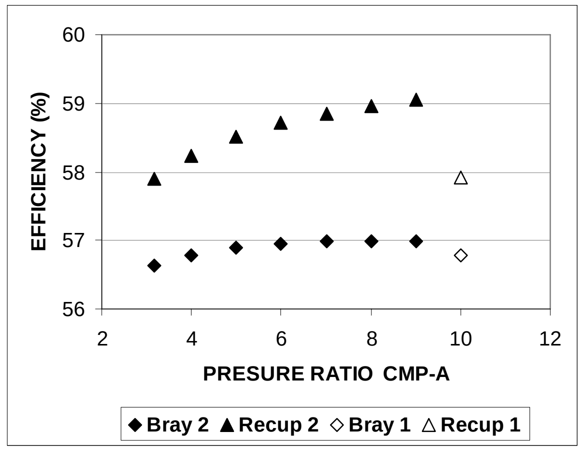

FIGURE 12. SYSTEM EFFICIENCY FOR PRESSURE RATIO OF 10

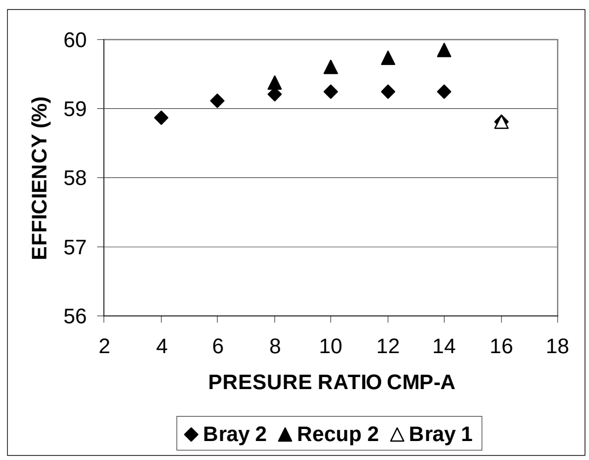

FIGURE 13. SYSTEM EFFICIENCY FOR PRESSURE RATIO OF 16

In a single stage system the results presented in Fig. 6 showed how the recuperator loses impact with increasing pressure ratio. With staged compression of the cathode flow this trend is still present. Comparing Fig. 12 to Fig. 13 shows that the effect that heat recuperation has on increasing the system efficiency is greater for the lower pressure system than it is for the higher pressure system. Previous calculations have shown that for single compressor systems the recuperator has lost

Downloaded From: https://proceedings.asmedigitalcollection.asme.org on 06/30/2019 Terms of Use: http://www.asme.org/about-asme/terms-of-use

most of its impact at a pressure ratio of approximately 10. In these calculations with staged compression this upper limit is extended. This is because the cathode inlet air stream still requires pre-heating to achieve the 973 K SOFC inlet temperature. With the reduced temperature in the second stage compressor outlet stream caused by the intercooler there is an increased flow of heat from the recuperator at the higher pressure ratios. Thus the recuperator becomes active again at the higher pressure ratio for the staged compression system.

Specifically, at a pressure ratio of 10, going from single stage to double stage compression of the cathode air flow of the non-recuperated system increased the system efficiency from 56.78% to 56.98% which is a 0.35% gain. For the recuperated system the system efficiency increased from 57.91% to 59.06% which is a 1.99% gain. At a pressure ratio of 16, going from single stage to double stage compression of the cathode air flow of the non-recuperated system increased the system efficiency from 58.82% to 59.24% which is 0.71% gain. For the recuperated system the system efficiency increased from 58.79% to 59.85% which is a 1.80% gain. These results are summarized on Table4.

Table 4. Effect of staged compression on system efficiency.

Pressure Ratio	Recuperator	Single Stage	Double Stage	Percent Increase
10	No	56.78	56.98	0.35
10	Yes	57.91	59.06	1.99
16	No	58.82	59.24	0.71
16	Yes	58.79	59.85	1.80

The data presented on table 2 shows that the benefit of using staged compression for the cathode air flow decreases with increasing pressure ratio for the recuperated system, but for the non-recuperated system the benefit actually increases with increasing pressure ratio. It is not hard to extrapolate this data and see that for the non-recuperated system this benefit may continue to increase with increasing pressure ratio. If this is the case then it may be beneficial to run hybrid systems with multiple compressors for the cathode air flow at much higher pressure ratios. Staged compression is a technique that is normally used for power systems that operate at very high pressure ratios. Since there were efficiency gains realized for these hybrid systems operating at the relatively low pressure ratios of 10 and 16, it is reasonable to assume that at higher pressure ratios these gains could be significantly improved.

Figure 14 shows the calculation results for (1) single stage compression, and (2) two stage compression of the cathode air flow of the non-recuperated hybrid system configuration with SOFC fuel utilization factors of 70% and 75%. It can be seen that when the intercooler is used as a syngas pre-heater for the syngas reheat operation there is a smaller burden placed on the anode post combustion reactor. The fuel utilization can thus be increased beyond 70% diverting more fuel into the SOFC. This causes more heat to be processed by the hybrid system on the cathode stream, and less heat to be processed by the anode stream. By increasing the fuel utilization factor we effectively divert fuel from a less efficient power production process, i.e. the post combustion - anode turbine expansion - bottoming steam cycle, to a more efficient power production process, i.e. the SOFC hybrid. For the configuration with two stage compression of the cathode air this increased the efficiency to 60.12% giving a total increase from the single stage system with low fuel utilization to the double stage system with high fuel utilization of 2.21 %.

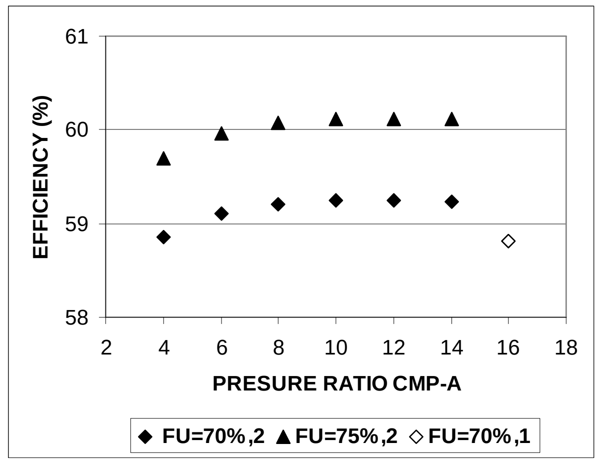

FIGURE 14. BRAY, PR=16, FU=70% AND 75%

6.0 SUMMARY AND CONCLUSIONS

The results reported here are consistent with basic principles of non-recuperative and recuperative cycle operation in spite of the presence of a recycle loop which is something unique for fuel cell operation vs. standard gas turbine operation. Specifically, it is shown that for a power generation system of this size with low pressure ratio operation, recuperated hybrid systems have greater efficiency for both single stage and double stage compression of the cathode air stream. We have shown that using staged compression to pressurize the cathode air flow can increase the system efficiency.

In our particular system the implementation of two stage compression gave rise to a low grade heat source which was used to partially reheat the syngas stream. This allowed us to increase the fuel utilization factor beyond the 70% limit that was realized for the single stage compression system thus increasing system efficiency.

REFERENCES

1. Surdoval, W., "U.S. DOE Fossil Energy Fuel Cell Program," SAE 2007 Conference, paper no. 2007-01-3867.

Downloaded From: https://proceedings.asmedigitalcollection.asme.org on 06/30/2019 Terms of Use: http://www.asme.org/about-asme/terms-of-use

2. D.Tucker, J.G.VanOsdol, E.A.Liese, L.O.Lawson, S.E.Zitney, R.S. Gemmen, J.C.Ford, C. L.Haynes, "Thermal Management in a coal-Based SOFC Hybrid Through Numerical Simulation," 7th Annual SECA Workshop and Peer Review, Philadelphia, PA, September 12-14, 2006.

3. Bove, R., Ubertini, S. (Eds.), Modeling Solid Oxide Fuel Cells · Methods, Procedures and Techniques, 2008, Springer Verlag, ISBN 978-1-4020-6994-9, Hardcover, Due: March 2008.

4. John G. VanOsdol, Randall Gemmen and Eric Liese, "Examination of the effect of system operating pressure and heat recuperation on the efficiency of a coal based gas turbine fuel cell hybrid power generation system with CO_2 capture," Fuel Cell 2008-65083, 6th International Fuel Science & Technology Conference, June 16-18, 2008, Denver, Colorado

5. D.Tucker, J.G.VanOsdol, E.A.Liese, L.O.Lawson, S.E.Zitney, R.S. Gemmen, J.C.Ford, C. L.Haynes, "Evaluation of Methods for Thermal Management in a Coal-Based SOFC Turbine Hybrid Through Numerical Simulation," International Colloquium on Environmentally Preferred Advanced Power Generation, Irvine, California, ICEPAG2006-24022, September, 2006.

6. John VanOsdol, Eric Liese, David Tucker, Randall Gemmen, Robert James, "Scaling a SOFC Gas Turbine Hybrid System to Meet a Range of Power Demand" 5th International Conference on Fuel Cell Science, Engineering and Technology, June 18th 2007, New York, USA

7. "Calculating the Cost of CO_2 Removal in a Coal Based Gas Turbine Fuel Cell Hybrid Power Generation System," J.G.VanOsdol, R.S. Gemmen, E.A.Liese, (Paper and presentation, *Coal Based Fuel Cell Technology: Status Needs, and Future Applications, West Virginia University, Morgantown, WV, October 11-12, 2007*).

8. "Novel Concepts in Compression of Large Volumes of Carbon Dioxide," J. Moore, Marybeth G. Nored, Ryan S Gernentz, Klaus Brun, Final Report, September 28, 2007, Southwest Research Institute, DOE Award No. DE-FC26-05NT42650.

9. North American Combustion Handbook, Second edition, Copyright 1978, North American Mfg. Co., ISBN 0-9601596-1-4.

10. "Process description for the Manufacture of Oxygen and Nitrogen from Atmospheric Air," Universal Industrial Plants Mfg. Co., Product literature, http://www.air-seperation-plants.com/oxygen-producing-equipment.html, January 16, 2008

11. "Technical Specification of Oxygen Nitrogen Plant," Universal Industrial Plants Mfg. Co., Product literature, http://www.air-seperation-plants.com/technical-specifications.html, January 16, 2008

12. "Second law comparison of oxy-fuel combustion and post-combustion carbon dioxide separation," Adam P. Simpson and A. J. Simon, Energy Conversion & Management, Vol. 48 (2007), pp. 3034-3045.

13. "Oxygen transfer across composite oxygen transport membranes," Bart A. van Hassel, Solid State Ionics Vol. 174 (2004), pp. 253-260.

14. Steam, its generation and use, 40th ed., Babcock and Wilcox, 1992, pp. 17.1-17.17

Downloaded From: https://proceedings.asmedigitalcollection.asme.org on 06/30/2019 Terms of Use: http://www.asme.org/about-asme/terms-of-use