A Thermodynamic Analysis of Tubular Solid Oxide Fuel Cell Based Hybrid Systems

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The goals of a research program recently completed at the University of California, Irvine were to develop analysis strategy for solid oxide fuel cell (SOFC) based systems, to apply the analysis strategy to tubular SOFC hybrid systems and to identify promising hybrid configurations. A pressurized tubular SOFC combined with an intercooled-reheat gas turbine (SureCell™ cycle) is chosen as the base cycle over which improvements are sought. The humid air turbine (HAT) cycle features are incorporated to the base cycle resulting in the SOFC-HAT hybrid cycle which shows an efficiency of 69.05 percent while the base cycle has an efficiency of 66.23 percent. Exergy analysis identified the superior efficiency performance of the SOFC component. Therefore, an additional cycle variation added a second SOFC component followed by a low pressure combustor in place of the reheat combustor of the gas turbine of the SOFC-HAT hybrid. The resulting dual SOFC-HAT hybrid has a thermal efficiency of 75.98 percent. The single SOFC-HAT hybrid gives the lowest cost of electricity (3.54¢/kW-hr) while the dual SOFC-HAT hybrid has the highest cost of electricity (4.02¢/kW-hr) among the three cycles with natural gas priced at \$3/GJ. The dual SOFC-HAT hybrid plant cost is calculated to be significantly higher because the fraction of power produced by the SOFC(s) is significantly higher than that in the other cases on the basis of \$1100/kw initial cost for the SOFC. The dual SOFC-HAT hybrid can only be justified in favor of the single SOFC-HAT hybrid when the price of natural gas is greater than \$14/GJ or if a severe carbon tax on the order of \$180/ton of CO_2 *is imposed while natural gas price remains at \$3/GJ.* [DOI: 10.1115/1.1499728]

Introduction

The majority of electricity in the U.S. is generated by the combustion of fossil fuels to heat either steam or ''air'' for use in Rankine or Brayton cycles. Until recently, the industry has operated these power plants under regulations that have guaranteed a reasonable return on investment. In the past decade, however, a number of factors have coalesced influencing the manner in which power will be generated in the years to come.

Potential for Regulation on Greenhouse Gas Emissions. Due to the projected increases in fossil fuel usage world wide, emissions of carbon dioxide (CO_2) to the atmosphere are expected to increase by about 60 percent over the 1990 level by 2015. CO_2 is the primary constituent in the earth's atmosphere that contributes to the greenhouse effect. The greenhouse effect is the entrapment of heat by the earth's atmosphere by gases such as CO_2; the sun's radiation falling on the earth's surface is reradiated as infrared heat which is absorbed by the greenhouse gases. It should be noted that the CO_2 generated from a given fuel per unit of power produced is inversely proportional to the thermal efficiency of a power plant, assuming complete utilization of the fuel. Thus, the CO_2 emissions may be reduced by increasing cycle efficiency.

Concern Over Emissions From Coal-Fired Plants. In addition to CO_2, pollutants such as oxides of sulfur, oxides of nitrogen, carbon monoxide, and unburned hydrocarbons are introduced into the atmosphere when traditional power generation technologies relying on combustion are used. The amount of pollutants emitted to the atmosphere depend on the degree of pollution abatement measures incorporated; these pollution abatement measures, however, tend to increase the plant operating and capital costs significantly in case of coal fired plants.

Deregulation. The breakup of the historic vertically integrated electric utility by deregulation is resulting in the appearance of merchant power producers selling in a market driven atmosphere. This is creating the marketplace for distributed power generation which is gaining much attention from industry and could be a major market for fuels cells if configurations can be identified that are efficient and simple so that the plant capital cost and process controllability are not compromised.

Thus, these factors have now made it a propitious time for a new approach to power generation; an approach that will change the way the fossil fuels are used by introducing advanced technologies that efficiently produce electricity while minimizing the environmental impact; fuel cells hold this promise.

Analysis Tools

Existing solid oxide fuel cell (SOFC) models do not fully integrate the heat and mass transfer with the electrochemistry while existing system models do not include simulation capabilities for the required power cycle equipment (e.g., SOFC). Thus, the capabilities required to perform tubular SOFC-based hybrid cycle analysis have been developed (Rao and Samuelsen [1]) which include analytical models for the tubular SOFC as well as the secondary equipment such as a gas turbine, reformer or partial oxidation reactor, shift reactor, humidifier, steam turbines, compressor, gas expander, heat exchangers, and pump. In addition to these equipment models, modules for functions such as separating a component from a stream, splitting a stream or combining streams and ''controller'' to automatically iterate in order to meet the desired design criteria are incorporated. Another important capability that is included is to be able to arrange the various components or modules as defined by the user in order to configure different hybrid systems.

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The system model may be used by cycle analysts from industry (e.g., equipment manufacturers, engineering and consulting firms, electric utility companies) for verifying performance of proposed cycles, as well as for developing new cycles.

Exergy Analysis

Exergy analysis may be applied to point the direction towards making changes to the system configuration in order to improve the thermal efficiency. It also allows a quantitative understanding of the dependence of the thermal efficiency on cycle operating parameters such as the pressure ratio, and provides means for quantitatively verifying the superiority of one cycle over another with respect to the thermal efficiency. The analysis consists of calculating the maximum work potential of each of the streams in the system as the stream is brought in thermodynamic equilibrium with the environment. The amount of this work potential destroyed across each major equipment within the system is also determined. Unlike the conventional definition of exergy, the maximum work potential is being defined to also include the work that may be produced from a stream when its temperature is lower than the ambient temperature. In such cases, a heat engine is hypothesized using the environment as its heat source and the stream as its heat sink. In this manner, the refrigeration potential of streams such as liquefied natural gas (when supplied to a power plant as fuel) may be taken into account. A potential use of the refrigeration potential of liquefied natural gas may be to cool the inlet air of a gas turbine in order to reduce the compressor work and thus increase the thermal efficiency (and the net power output) of the engine.

When the kinetic and potential energy effects may be neglected, exergy (χ) is defined as (Vogler and Weissman [2]):

$$\chi = W_{\text{sensible}} + W_{\text{expansion}} + W_{\text{concentration}} + W_{\text{chemical}}$$

where W_{sensible} is the reversible work that may be obtained by a heat engine taking heat from the stream (at temperature T) and rejecting heat to the environment (at temperature T_o), $W_{\text{expansion}}$ is the reversible work that may be obtained from the stream at pressure P by expansion (after conversion of the sensible heat) to the pressure of the environment (P_o), $W_{\text{concentration}}$ is the additional work that may be obtained by reversibly diffusing a noncombustible component i within the stream at partial pressure P_i through a membrane to the environment where it may be at a partial pressure of P_{oi}, and W_{chemical} is the work (after cooling and expansion) that may be produced by oxidation of the combustibles that may be present in the stream with enough excess air such that the partial pressure of the CO_2 corresponds to that in the ambient. Thus,

$$\chi = -\int (1 - T_o/T) C_p dT + RT\left[\ln(P/P_o) + \sum \ln(P_{io}/P_i)\right] - \Delta G_{\text{reax}}$$

where the integral in the first term on the right-hand side of the above equation is evaluated from the initial to the final temperature of the stream, C_p is the specific heat of the stream, ΔG_{reax} is the Gibbs free energy change for the oxidation reaction of the combustibles at the temperature of the environment. The first term on the right-hand side of the equation above (within the integral) defines the maximum work that may be obtained based on the Carnot cycle efficiency. For systems containing an electrochemical device such as a fuel cell and for systems where streams leaving the system have compositions very different from that of the ambient air, the Carnot cycle efficiency does not suffice.

This first term in the above equation as defined in Vogler and Weissman [2] is modified to include the work potential of streams that contain water in the form of vapor which could undergo a phase change when equilibrated with the environment, and is also applied to streams that are colder than the environment. This term (W_{heat}) is thus redefined as

$$W_{\text{heat}} = -\int (1 - T_o/T) dH$$

where H is the enthalpy which may include both sensible as well as latent heats. When $T < T_o$, it may be shown that the expression $W_{\text{heat}} = -\int (1 - T/T_o) dH$ still applies where dH is now the heat rejected by the reversible heat engine to the stream.

The second term is also modified in order to be able to handle streams that contain water as a vapor or as a liquid and may undergo phase change:

$$W_{\text{expansion}} = -\Delta G_{\text{expansion}}$$

where $\Delta G_{\text{expansion}}$ is the Gibbs free-energy change of the stream as its pressure is reduced to that of the environment. Note that for a reversible process occurring at constant temperature T_o,

$$\Delta H = T_o \Delta S - W_s$$

or

$$W_s = -\Delta H + T_o \Delta S = -\Delta G$$

where ΔH, ΔS, and ΔG are the enthalpy, entropy, and Gibbs free-energy changes while W_s is the shaft work.

The proposed next step in the path for the stream to equilibrate with the environment is the reversible isothermal oxidation reaction at T_o of the combustibles present in the stream utilizing the ambient air:

$$W_{\text{chemical}} = -\Delta G_{\text{chemical}}.$$

The proposed final step in the path for the stream to equilibrate with the environment is the reversible isothermal expansion at T_o of component i through a hypothetical reversible membrane to its partial pressure in the ambient air (by allowing the component to reversibly exchange through a selective membrane between the stream and a chamber, and similarly between the ambient air and a second chamber, the two chambers being connected by a turbo-expander operating reversibly between the two pressures):

$$W_{\text{concentration}} = -\Delta G_{\text{concentration}}.$$

The components considered for this type of expansion are water vapor and carbon dioxide. The oxygen and nitrogen could also be expanded but in the reverse direction while producing work, since a concentration gradient may exist for these components between the system and the environment (the concentration in the environment being typically higher). Such considerations would, however, lead to misleading results or provide impractical guidance for cycle improvements.

Hybrid Systems Analysis

Systems identified for analysis and the results obtained by the application of the model are presented in the following.

Base Cycle—Westinghouse SureCell™ Configuration. A fuel cell based hybrid cycle consists of combining a fuel cell with a heat engine to maximize the overall system efficiency. One example of such a Hybrid cycle is the SureCell™ system as proposed by Westinghouse and depicted in Fig. 1 (Bevc and Parker [3]).

The system consists of an intercooled/reheat gas turbine integrated with a pressurized tubular solid oxide fuel cell (SOFC). Atmospheric air is compressed in an intercooled compressor, comprised of a low-pressure (LP) compressor and a high-pressure (HP) compressor. The discharge air from the HP compressor is preheated against the turbine exhaust in a recuperator and then provided to the SOFC as its oxidant. Fuel is also preheated in the turbine exhaust, supplied to the SOFC (after desulfurization) and to the gas turbine reheat or LP combustor. The exhaust from the SOFC, consisting of the depleted air and the depleted fuel, is supplied to the HP combustor of the gas turbine. The exhaust from the HP combustor enters the HP expander where it is expanded to

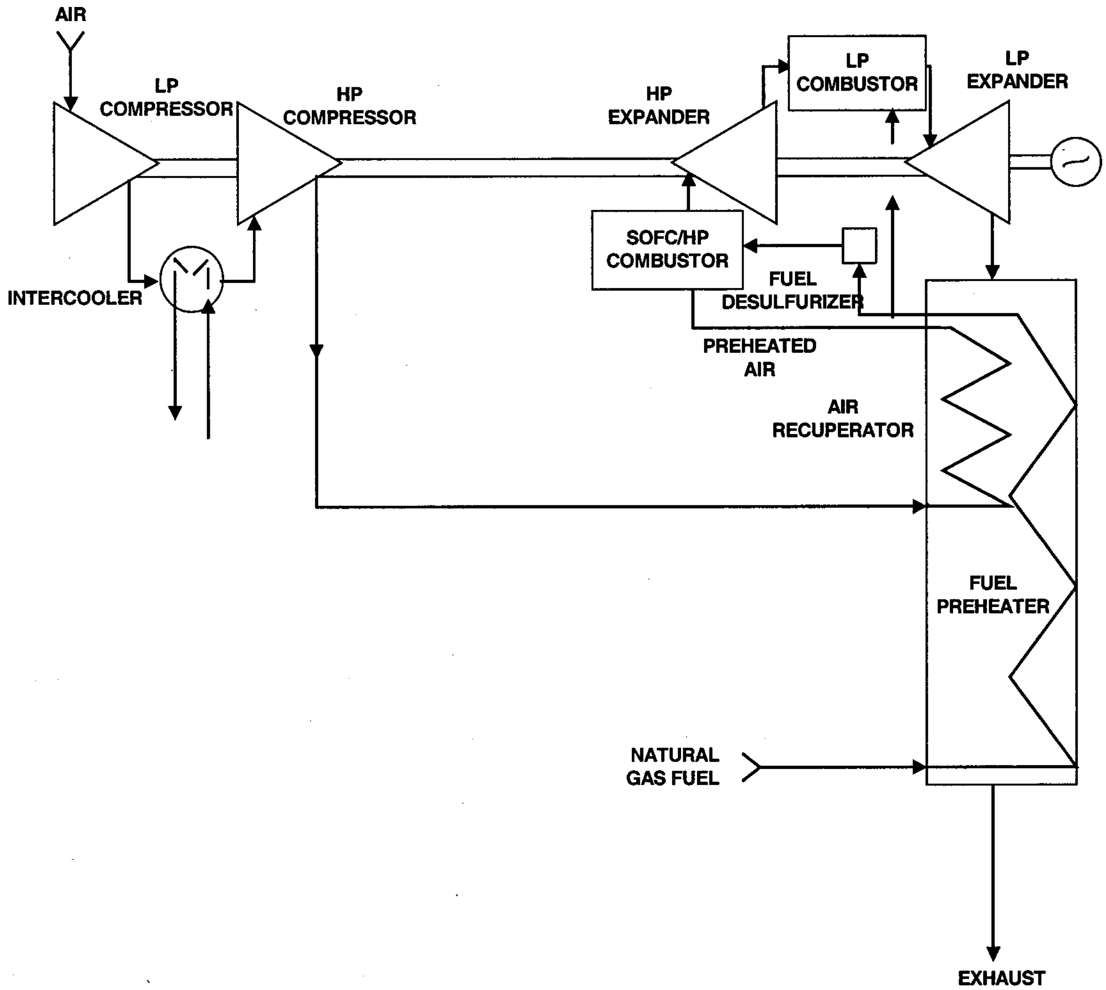

Fig. 1 Base cycle-SureCell™ system as proposed by Westinghouse (Bevc and Parker [3])

a pressure which is higher than atmospheric and then supplied to the LP combustor where the additional fuel is fired. Additional air and/or fuel may also be fed to the HP combustor. The hot exhaust from the LP combustor is then expanded in the LP expander to near atmospheric pressure and then supplied to the heat recovery unit. The power developed by the expanders drives the compressors and the electric generator.

The cycle thermal efficiency for this base cycle is developed for various pressure ratios. The cycle thermal efficiency is not a strong function of pressure ratio. The thermal efficiency of the cycle increases from 65.5 percent to 66.59 percent on a lower-calorific value of the fuel as the pressure ratio is decreased from 15 to 6.5. In order to explain this trend the cycle configuration is further analyzed by developing the exergy changes across each of the components of the system at three different pressure ratios. The results are summarized in Table 1 as relative exergies, that is, these exergies are presented as percentage of the exergy contained in the total fuel stream (entering the SOFC and the low pressure (LP) combustor). The exergy contained in the stack gas is also included in this table. The remaining two streams crossing the system boundary are the ambient air (LP compressor inlet) whose exergy is zero (the dead state) and the fuel which has the relative exergy of 100 percent. As seen by the data, the total exergy loss for the case with a pressure ratio of 6.5 is the lowest verifying the thermal efficiency trend.

As the cycle pressure ratio is reduced, the exhaust temperature from the LP turbine increases which in turn increases the temperature of the preheated air supplied to the SOFC. This increase in temperature more than offsets the decrease in efficiency of the SOFC operating at a lower pressure in the range of pressure ratios investigated. Furthermore, the irreversibilities in the LP combustor are reduced at the lower pressure ratio because the temperature of the oxidant stream entering this combustor increases as the expansion ratio of the high pressure (HP) turbine decreases. Also, the contribution to exergy loss by the intercooler is reduced as the cycle pressure ratio is decreased since less heat is rejected in the intercooler as the compression ratio of the LP compressor is reduced.

A pressure ratio of 8.8 is chosen for this base cycle (and not a lower pressure ratio) based on the constraint of limiting the tur-

Table 1 Base cycle—exergy destruction data (without generator/inverter losses)

Pressure Ratio	6.5	8.8	15
Component	**Exergy, % of Total Fuel Input**		
LP compressor	0.83	0.86	0.87
Intercooler	1.58	2.09	2.63
HP compressor	0.82	0.80	0.80
Recuperator+fuel preheater	2.53	2.05	1.43
SOFC	11.57	11.44	11.63
HP combustor	3.18	3.19	3.14
HP expander	0.81	0.86	0.84
LP combustor	9.77	10.14	10.54
LP expander	1.10	1.08	1.10
Stack gas	5.64	5.54	6.00
Total	31.33	29.25	23.98

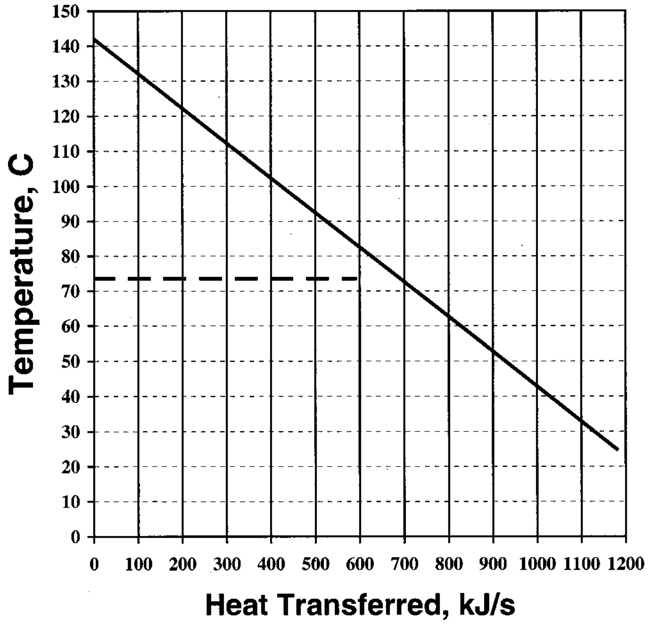

Fig. 2 Heat transfer from a gas to generate steam

bine exhaust temperature to a maximum of 635°C as set by the chosen design basis for this evaluation. The pressure ratio of 8.8 is also consistent with the pressure ratio touted for the SureCell™ hybrid by Westinghouse (Bevc and Parker [3]).

Enhancement of the thermal performance of the cycle may be accomplished by minimizing the exergy losses due to the intercooler and the stack gas. Modifications aimed at these components of the cycle are next attempted in order to maximize the cycle efficiency. The modifications however, should be such that the resulting cycle is not complex, thus not compromising its controllability and cost.

Conventional approach to recovery of heat has been via a Rankine cycle by generating steam. Inspection of the temperature of the heat available in the intercooler and in the stack gas indicates that only low pressure steam may be generated, the quantity and the pressure being limited by the saturation temperature of the steam corresponding to its pressure. Figure 2 depicts the heat transfer if steam were generated by half of the heat rejected by the air in the intercooler (for the case with a pressure ratio of 8.8).

As can be seen from the figure, the temperature of the gas (represented by the solid line) decreases as heat is transferred while the water/steam (represented by the dashed line) remains at a constant temperature being a single component. Thus, when as much as half of this heat is utilized for steam generation, the pressure of steam that may be generated corresponding to the saturation temperature of 73.5°C (allowing a 10°C temperature difference in the heat exchanger) will be only 0.34 bar, a pressure that is too low to generate power in a steam turbine economically. Another disadvantage with steam generation in addition to the above is that due to the diverging temperature difference between the gas and the steam/water mixture, the exergy loss in heat transfer is increased. If, however, a fluid that has a variable boiling point is utilized to recover the low temperature heat rejected in the intercooler, the quantity of heat recovered as well as the exergy destruction may be reduced.

The humid air turbine (HAT) cycle (Rao [4]) which utilizes generation of "steam" by directly contacting pressurized air with hot water in a countercurrent humidifier and circulating the water leaving the humidifier to recover heat rejected in the intercooler and from the stack gas could potentially be applied in this hybrid system to enhance the overall cycle efficiency.

The humidifier, by introducing water vapor into the combustion air would increase the amount of motive fluid available for expansion in the turbines, while recovering the low temperature heat from the intercooler and the stack gas. Within the humidifier, the water evaporates at successively higher temperatures as the air moves up the humidifier column (as its water vapor content increases) with hot water flowing countercurrently downwards exchanging mass and heat with the pressurized air stream. Furthermore, the water evaporates at temperatures much lower than the boiling point or saturation temperature of pure water since the phase change occurs within the humidifier in the presence of air (at the prevailing partial pressure of water vapor in the air stream). This combined humidifier and water circulating subsystem makes it possible to recover low temperature heat without being constrained by the boiling temperature of pure water while reducing the exergy destruction during heat transfer.

Single Solid Oxide Fuel Cell–Humid Air Turbine (SOFC-HAT) Hybrid. The resulting hybrid cycle as depicted in Fig. 3 incorporates humidification of the air before it is preheated in the recuperator and fed to the SOFC. The air leaving the compressor is first cooled in an aftercooler and then introduced into the humidifier column where it comes into countercurrent contact with hot water. A portion of the water is evaporated into the air stream, the heat required for the humidification operation being recovered from the intercooler and the stack gas by circulating water leaving the humidifier.

A potential disadvantage with this cycle is that the partial pressure of the oxygen in the air stream entering the SOFC is reduced which decreases the mass transfer rate of the oxygen to the cathode surface and through the cathode while increasing the cathode concentration and activation polarizations. On the other hand, the cycle may optimize at a high pressure ratio such that it off-sets the reduction in the concentration of the oxygen in the air stream with the net effect that the partial pressure of the oxygen is not significantly effected.

The efficiency of this hybrid cycle is determined to be also a weak function of the pressure ratio but increases with pressure in direct contrast to the SureCell™ configuration. The optimum efficiency of the cycle may lie beyond the maximum pressure ratio of 15 for the SOFC as constrained by the chosen design criteria for this investigation. The efficiency of the cycle at a pressure ratio of 15 is 69.05 percent based on the lower calorific value of the fuel to the system. The exergy destruction in each of the components of the cycle for the maximum efficiency case is compared to exergy destruction of the base cycle at the pressure of 8.8 in Table 2.

The SOFC-HAT hybrid has significantly less exergy destruction which verifies its significantly higher thermal efficiency as compared to the base cycle. The fuel consumption of the SOFC-HAT case is higher than the base cycle per unit of inlet air flow because of the high concentration of water vapor in the combustion air. Thus, the exergy destruction in the various components of the system of the SOFC-HAT hybrid are reduced per unit flow of fuel to the system. Additionally, in the case of the SOFC-HAT hybrid, the exergy destruction is reduced by the incorporation of recovery of heat from within the cycle and utilizing this heat for the humidification operation as can be seen by the data presented in Table 3 which also explains the relationship of the overall thermal efficiency of this case and the pressure ratio.

As the pressure ratio increases, more heat is removed from the air in the intercooler but since this heat is recovered for the humidification operation, the cycle is not penalized as is the base case cycle. Furthermore, the power developed by the expanders is increased by a much more significant amount than the power consumption of the air compressors as compared to the base case since additional motive fluid (water vapor) is added to the expanding fluid.

The performance of the SOFC in the base case and in the SOFC-HAT is compared in Table 4. The thermal efficiency of the fuel cell is slightly lower for the SOFC-HAT than that in the base

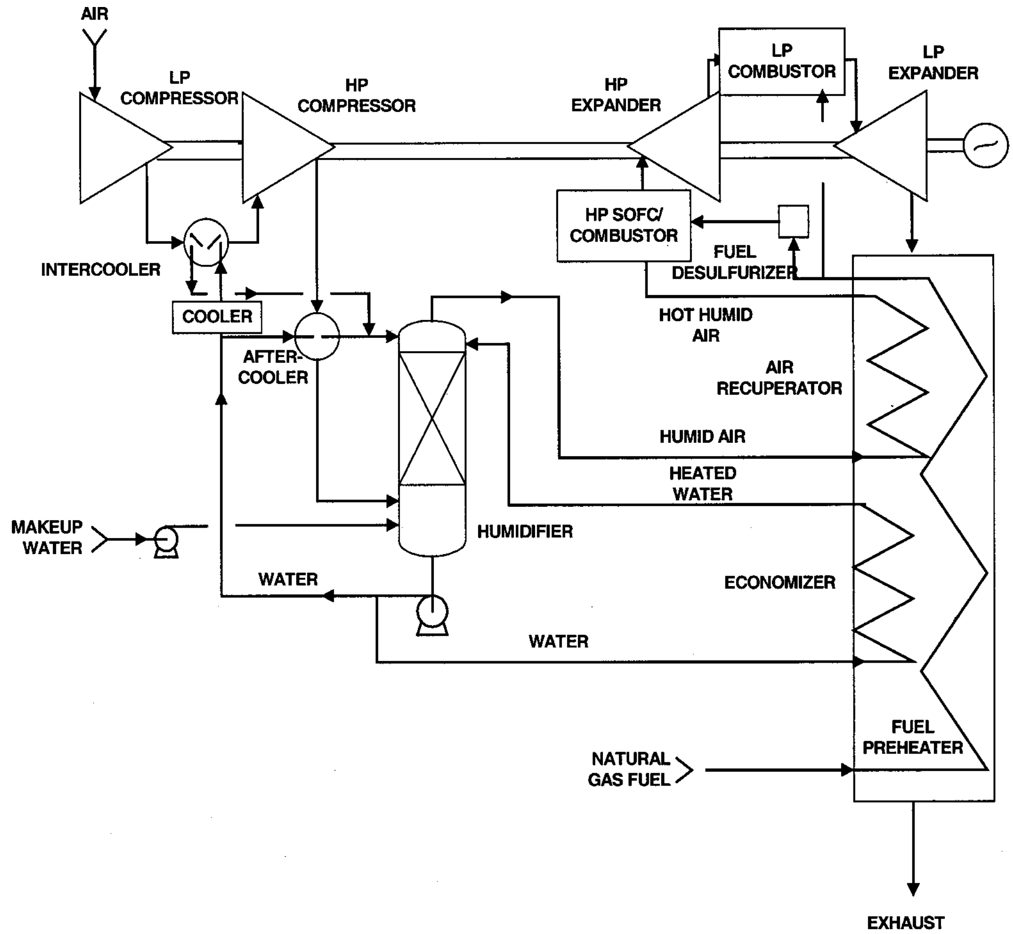

Fig. 3 Single SOFC-HAT hybrid

case. For a given operating pressure of the SOFC in the HAT-based system, as pointed out previously the lower concentration of the oxygen in the air stream entering the SOFC tends to decrease the mass transfer rate of the oxygen to the cathode surface and through the cathode itself which has the effect of decreasing the capacity of the cell as well as in increasing the cathode concentration and activation polarizations. However, the higher operating pressure of the SOFC in the HAT-based system more than compensates these effects such that the capacity of the SOFC is actually increased while the thermal efficiency is only slightly compromised over the SOFC in the base case.

Based on the exergy destruction data as presented in Table 2, it appears that the SOFC and the LP combustor destroy about the same amount of exergy when expressed as a fraction of the total fuel input to the cycle. However, when the exergy destruction by

Table 2 Exergy destruction in SOFC hybrid cycles as percent of total fuel input

	Base Cycle	Single SOFC-HAT Hybrid
LP compressor	0.86	0.7
Intercooler	2.09	0.58
HP compressor	0.80	0.72
Aftercooler	⋯	0.30
Humidifier	⋯	0.16
Economizer	⋯	0.24
Cooler	⋯	0.29
Recuperator and fuel preheater	2.05	1.71
HP SOFC	11.44	11.51
HP combustor	3.19	2.87
HP expander	0.86	0.81
LP combustor	10.14	10.19
LP expander	1.08	1.09
Stack gas	5.54	4.54
Total	38.05	35.71

Table 3 Reduction in exergy destruction by humidification as percent of total fuel input

	Base Cycle	Single SOFC-HAT Hybrid
Intercooler	2.09	0.58
Aftercooler	⋯	0.30
Humidifier	⋯	0.16
Economizer	⋯	0.24
Cooler	⋯	0.29
Stack gas	5.54	4.54
Total	7.63	6.11

Table 4 SOFC performance comparison

	Base Cycle	Single SOFC-HAT Hybrid
Current density mA/cm^2	295.7	304.9
Power per tube, Watts	193.7	198.9
Thermal efficiency, % fuel energy to SOFC (lower calorific value)	47.35	47.28

Table 5 Exergy destruction in SOFC versus LP combustor for SOFC-HAT hybrid

	% of Exergy Entering SOFC or LPCombustor
SOFC	10.62
HP combustor	2.65
Subtotal (SOFC and HP combustor)	13.27
LP combustor	16.03

these components is expressed as a percentage of the total exergy entering that component (Table 5), the result reveals that the SOFC is a much more efficient component. Thus, further gain in efficiency may be expected by minimizing combustion by adding an LP SOFC.

Dual Solid Oxide Fuel Cell–Humid Air Turbine (SOFC-HAT) Hybrid. The resulting hybrid is depicted in Fig. 4 and is similar to the previous case incorporating humidification of the compressed air before it is preheated in the recuperator. However, the system consists of the additional SOFC followed by an LP combustor in place of the reheat combustor of the gas turbine. The cycle thermal efficiency as developed for various pressure ratios indicates that for this cycle also the efficiency is essentially independent of the pressure ratio. It shows an efficiency of 75.98 percent at a pressure ratio of 15 which is slightly higher than that obtained at a pressure ratio of 8.8. Once again, the pressure ratio of the cycle is limited to 15 based on the design basis established for this investigation. The exergy destruction in each of the components of the cycle for this maximum efficiency case is compared to the corresponding exergy destruction of the previous two cases in Table 6 which verifies the higher efficiency of this dual SOFC-HAT case.

Table 6 Exergy destruction in SOFC hybrid cycles as percent of total fuel input

	Base Cycle	Single SOFC-HAT Hybrid	Dual SOFC-HAT Hybrid
LP compressor	0.86	0.7	0.52
Intercooler	2.09	0.58	0.43
HP compressor	0.80	0.72	0.54
Aftercooler	⋯	0.30	0.22
Humidifier	⋯	0.16	0.11
Economizer	⋯	0.24	0.17
Cooler	⋯	0.29	0.22
Recuperator and fuel preheater	2.05	1.71	1.22
HP SOFC	11.44	11.51	8.55
HP combustor	3.19	2.87	2.09
HP expander	0.86	0.81	0.61
LP SOFC	⋯	⋯	7.91
LP combustor	10.14	10.19	1.54
LP expander	1.08	1.09	0.78
Stack gas	5.54	4.54	4.20
Total	38.05	35.71	29.11

Results and Discussions

The overall performance of the three hybrid cycles is compared in Table 7. The current density of the SOFC in each of the cases is compared. The current density of the dual SOFC-HAT hybrid's LP

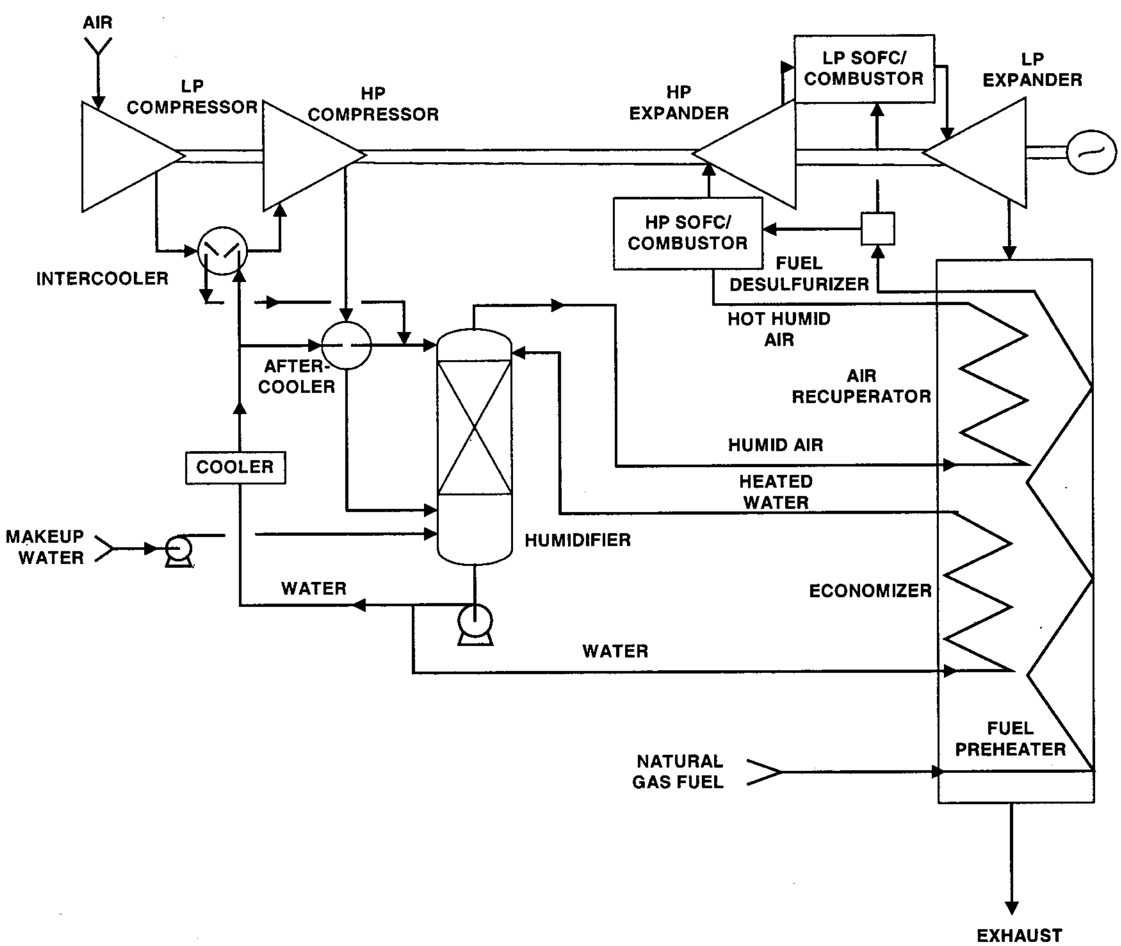

Fig. 4 Dual SOFC-HAT hybrid

Table 7 Performance comparison of SOFC hybrid cycles

	Base Cycle	Single SOFC-HAT Hybrid	Dual SOFC-HATHybrid
Cycle pressure ratio	8.8	15.0	15.0
SOFC power, % of total	56.5	53.7	68.4
Gas turbine power, % of total	43.5	46.3	31.6
SOFC current density, mA/cm^2	193.7	198.9	198.6/161.1
Specific power output. kW/kg/s	665.3	969.5	1431.8
Exergy destroyed, % of total fuel input	38.05	35.71	29.11
CO2 emissions, kg/MW-hr	0.08994	0.08627	0.07840
Thermal efficiency, % fuel (lower calorific value)	66.23	69.05	75.98

SOFC is significantly lower than that in the other SOFCs because this SOFC operates at a much lower pressure while the concentration of diluents (water vapor and carbon dioxide) in the oxidant stream to the SOFC is high. The fraction of the total power developed by the SOFC(s), however, remains to be the highest with the dual SOFC-HAT hybrid while it is the lowest with the single SOFC-HAT hybrid. The specific power output defined as the net power developed by the cycle per unit of air entering the system (which has an inverse relationship to the size of the turbomachinery required to generate a unit of power) is significantly increased by combining the SOFC with the HAT cycle; as much as a 46 percent increase is realized. This increase is due to the introduction of water vapor into the pressurized air stream which increases the working fluid for the expanders as well as the higher operating pressure of the cycle. Thus, power developed by the gas turbine as a fraction of the total power generated is increased when the HAT cycle is incorporated into a single SOFC-based hybrid. Further increase in the specific power is realized by including the second SOFC, the specific power output being more than doubled over the base case. However, the fraction of total power generated by the SOFCs is increased.

The greenhouse gas emissions of CO_2 are significantly reduced as the system thermal efficiency is increased, these emissions being inversely proportional to the efficiency.

The exergy losses through the stack gas for the three cases are presented in Table 8. The loss of exergy due to the large amount of moisture carried by the stack gas in the HAT based hybrids is, however, not significantly higher than that in the base case. Thus, only small gain in efficiency may be expected if a cycle is devised to recover the remaining exergy in the water vapor. Recovery of this water for recycle and recovery of the latent heat for cogeneration (production of hot water for district heating) purposes may, however, be considered.

The relative plant costs expressed as $/kW and economics of the three cases are summarized in Table 9. The base cycle cost of $1000/kW is based on the projected cost by Siemens Westinghouse when full manufacturing and production occurs. The cost of the HAT-based hybrids were estimated based on the relative difference in cost of the turbomachinery, the heat exchange, the humidifier, and water treatment equipment derived from the Gas Research Institute Report [5]. Natural gas is assumed to cost $3/GJ on a lower calorific basis and the plant on-stream factor of 0.9 is utilized to calculate the cost of electricity. The total capital requirement, and the operating and maintenance (O&M) costs are estimated as fractions of the plant cost based on projected values taken from the Electric Research Institute's Technical Assessment Guide [6].

The single SOFC-HAT hybrid results in the minimum cost of electricity while the dual SOFC-HAT hybrid has the maximum cost of electricity among the three cases. The plant cost of the dual SOFC-HAT hybrid is significantly higher because the fraction of power produced by the SOFC(s) is significantly higher than that in the other cases. The cost of the SOFC per unit of power produced by the SOFC is significantly higher than that of the gas turbine. Also as pointed out previously, the power density of the LP SOFC is significantly lower which also contributes towards increasing the plant cost. The dual SOFC-HAT hybrid can only be justified in favor of the single SOFC-HAT hybrid when the cost of natural gas is greater than $14/GJ or if a severe carbon tax is imposed on power plants.

The plant cost of the single SOFC-HAT hybrid is lowest because the fraction of power produced by the SOFC is significantly lower than that in the other cases. This case represents a healthy tradeoff between efficiency and plant cost.

The cost of the SOFC module(s) in the HAT-based hybrids is derived from the projected cost of Siemens Westinghouse which is

Table 8 Exergy loss in stack gas as percent of fuel input

	Base Cycle	Single SOFC-HAT Hybrid	Dual SOFC-HAT Hybrid
Due to temperature	4.07	2.98	2.52
Due to partial pressure of H_2O and CO_2	1.47	1.56	1.68
Total exergy lost	5.54	4.54	4.20

Table 9 Relative plant costs and cost of electricity with natural gas at $3/GJ

	Base Cycle	Single SOFC-HAT Hybrid	Dual SOFC-HAT Hybrid
Plant cost, $/kW	1000	960	1240
Total capital requirement[1], $/kW	1074	1031	1332
Thermal efficiency, % Fuel (lower calorific value)	66.23	69.05	75.98
Capital charge, ¢/kW-hr	1.53	1.47	1.90
Fuel cost, ¢/kW-hr	1.47	1.41	1.28
Fixed O&M costs[2], ¢/kW-hr	0.08	0.08	0.1
Variable O&M costs[3], ¢/kW-hr	0.60	0.58	0.74
Cost of electricity, ¢/kW-hr	3.68	3.54	4.02

[1]1.074 percent of plant cost

[2]0.08×10^{-3} of plant cost

[3]0.6×10^{-3} of (plant cost)×(on-stream factor)

$1100/kW. With the single SOFC-HAT hybrid, the cost of electricity remains less than the competitive 5¢/kW-hr even when the cost of the SOFC is 50 percent higher than this projected value.

Summary and Conclusions

The Westinghouse SureCell™ hybrid configuration is chosen as the base cycle over which improvements are sought. The SureCell™ hybrid combines a pressurized tubular SOFC with an intercooled-reheat gas turbine. One variation considered applies HAT cycle features to an SOFC hybrid design. Generation of ''steam'' by directly contacting pressurized air with hot water in a countercurrent humidifier and circulating the water leaving the humidifier to recover heat rejected in the gas turbine intercooler and the stack gas is applied. The resulting SOFC-HAT hybrid cycle shows an efficiency as high as 69.05 percent based on the fuel lower calorific value at a pressure ratio of 15 while the base case has an efficiency of 66.23 percent at the pressure ratio of 8.8. The efficiency of the base case corresponding to a pressure ratio of 8.8 is chosen for the comparison because the efficiency of the cycle at this pressure is higher than that at a pressure ratio of 15 (the efficiency of this hybrid configuration decreases as the pressure ratio is increased; at pressure ratios below 8.8, the efficiency increases slightly but at the lower pressure ratios, the turbine exhaust temperature increases beyond the temperature limit of 635°C which is set by strength of the last stage turbine blades). The pressure ratio of 8.8 is also consistent with the pressure ratio touted for the SureCell™ hybrid by Westinghouse that forms the basis for the configuration of the base case).

Exergy destruction data, which quantifies the amount of lost work due to thermodynamic irreversibilities, were developed for all the components within the system and identified the superior efficiency performance of the SOFC component. Therefore, an additional cycle variation added a second SOFC component followed by a LP combustor in place of the reheat combustor of the gas turbine of the SOFC-HAT hybrid. The resulting dual SOFC-HAT hybrid cycle has a thermal efficiency as high as 75.98 percent.

Assuming a natural gas cost of $3/GJ, the single SOFC-HAT hybrid gives the lowest cost of electricity (3.54¢/kW-hr) while the dual SOFC-HAT hybrid has the highest cost of electricity (4.02¢/kW-hr) among the three cycles analyzed. The plant cost of the dual SOFC-HAT hybrid is calculated to be significantly higher because the fraction of power produced by the SOFC(s) is significantly higher than that in the other cases on the basis of $1100/kw initial cost for the SOFC. The dual SOFC-HAT hybrid can only be justified in favor of the single SOFC-HAT hybrid when the cost of natural gas is greater than $14/GJ or if a severe carbon tax is imposed on power plants (on the order of $180/ton of CO2 emitted with natural gas priced at $3/GJ).

The plant cost of the single SOFC-HAT hybrid is lowest of the three cycles because the component of power produced by the SOFC is significantly lower than that in the other cases. This case represents a healthy tradeoff between efficiency and plant cost.

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