HYBRID CYCLES EMPLOYING GASIFIER & SOFC: TOWARDS CLEANER AND MORE ENERGY-EFFICIENT POWER

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Abstract With increasing concern about fossil fuel resource depletion and environmental degradation, more and more attention is being put into the methods of energy conversion with an aim to develop systems that will deliver useful energy in more efficient and environment friendly manners. Integrated Gasification Combined Cycle (IGCC) was a development in that direction and electric power plant based on such cycle is now a reality. Fuel Cells, particularly the Solid Oxide Fuel Cells (SOFC) are considered to be viable and effective additions to these cycles. Expectations are that incorporation of SOFC in IGCC will cross the 70% efficiency mark on the whole. But in which ways the fuel cells can be suitably integrated in the combined cycle and how are they going to affect the overall cycle performance remain the matters of scientific studies. This paper deals with these very issues and also discusses the environmental benefits which these hybrid cycles are expected to offer.

Keywords: IGFCC,IRSOFC, Efficiency and Environment.

SYMBOLS & ABBREVIATIONS

A-Anode, AC – Air Compressor, ASU–Air Separation Unit, C-Cathode, CC – Combustion Chamber, D-Drum, G – Gasifier, GC-Gas Cooler, GT – Gas Turbine, HRSG – Heat Recovery Steam Generator, NG – Natural Gas, RECUP – Recuperator, SRU – Sulfur Removal Unit, ST – Steam Turbine,.

INTRODUCTION

The search for alternative energy sources began decades back when the primary concern was the impending shortages of fossil fuel reserves as predicted by the energy analysts. In the recent years another factor, and probably the more important one, has been added – the environment. Even if the reserves are sufficient enough (recent studies indicate that there indeed are enough primary fossil fuel reserves viz. coal and lignite, to support primary energy needs for centuries together although the reserves for petroleum oil are very limited), the environmental concern and future regulations will hardly permit the use of such reserves unless we change the modes of realization of energy contained therein. So the power engineers and energy scientists are looking for methods of energy conversion that will have the least impact on the environment. Another driving force behind this all out search is the realization of the fact that most of the present energy conversion systems are miserably inefficient, particularly when it comes to bulk power generation. A conventional thermal power plant hardly operates beyond 35% overall efficiency. Combined cycles and IGCC have considerably increased this figure and today's advanced designs of Combined Cycles incorporating suitable steam cycle at the bottom can deliver power at 50-55% efficiency range or even beyond (Winterbone,2000).

The fuel cells, operating in isolation, are proved to be very efficient, drawing power from the enthalpy change (ΔH) accompanying the electrochemical reaction. Hence, they are not subjected to the Carnot cycle limitations and ideally they can deliver a maximum work equivalent to the change in Gibb's energy (ΔG) although practical considerations limit the actual output. Different types of fuel cells, their operating temperatures ranging from 60^o to about 1000^o, can be used for the purpose of producing electrical work efficiently. Out of them, only Molten Carbonate (MCFC) and Solid Oxide (SOFC) cells operate at higher temperature and SOFC, operating in the range of 850^oC-1050^o C, enjoys the maximum advantage of integration in a topping cycle. In the foregoing sections some models are being presented and discussed where SOFC s have been considered as the main power producing components, keeping in mind at the same time that the SOFC technologies are yet to be developed to the scale and level as presented herein.

POWER CYCLE DESCRIPTION AND ANALYSIS

The basic IGCC consists of a Gasifier, Scrubber & Gas Cooler and Sulfur Removal Unit (SRU) placed in the

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topping cycle with Gas Turbine-Compressor assembly. The gasifier, operating at elevated temperature and moderate to high pressure, burns carbonaceous fuels (bio-fuels and municipal wastes in bio-gasification) in an oxygen-deficient enclosure to produce fuel gas or synthetic gas of varying heating values. Major constituents of such gas include CO, H_2, CH_4 and CO_2.

In SOFC, the predominant electrochemical reaction responsible for power output is that between O_2 and H_2 and ion transfer within the cell between them happens through a thin layer of solid oxide (for example Yittria-Stabilized Zirconia or YSZ). In fact, any Hydrogen containing gaseous fuel (like producer gas or coal gas) can be used instead of H_2, making up the anode stream while air can effectively replace oxygen as the cathode gas. And, this gives the linkage between the Gasifier and the fuel cell. To increase the effectiveness and to help maintain the operating cell temperature the fuel gas needs to be reformed and shifted, increasing the H_2 concentration. These reactions are described by:

$CH_4 + H_2O(steam) \rightarrow CO + 3H_2$ (Reforming)

$CO + H_2O(steam) \rightarrow CO_2 + H_2$ (Shifting)

While the net electrochemical reaction can be shown by:

$$H_2 + (1/2)\, O_2 \rightarrow H_2O$$

An external reformer may be used for this purpose prior to the SOFC but, given the high operating temperature of SOFC that suits the reforming, we can do away with the external reformer and, instead, consider the cell itself to be Internal Reforming type (IRSOFC) (Massardo & Lubelli,2000).

With this understanding we can now consider a power cycle that may be called an Integrated Gasification Fuel Cell Combined Cycle (IGFCC) which takes the shape as shown in Fig.1.

A number of Gasifiers are available to chose from but the preferred ones will be the pressurized, entrained-bed, oxygen-blown gasifiers which produce high temperature, high heating value syngas and at the same time give higher H_2 concentration.

As far as SOFC s are concerned, the planar type stacks have good prospect in bulk power application although they are yet to be developed to MW level.

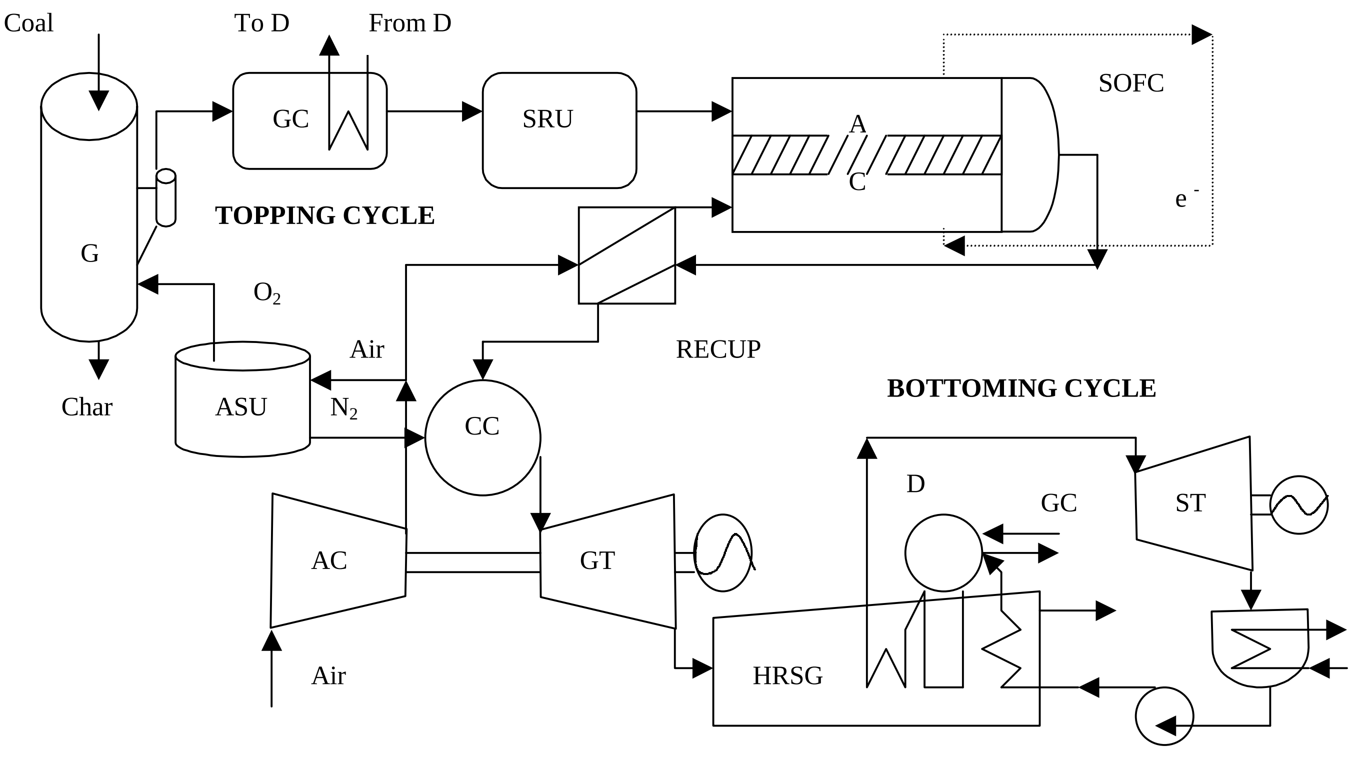

Fig.1: Proposed Combined Cycle incorporating Pressurized Gasifier, SOFC, Gas Turbine and HRSG

Major parameters for such a combined cycle may be as indicated below:

Operating Pressure for the topping cycle: 10bar to 35 bar,
Gasifier exit raw gas temperature : 1000 ^{o}C –1500^{o}C,
SOFC operating temperature : 850 ^{o}C - 1050^{0}C,
GT inlet temperature : 1000 ^{o}C –1250^{o}C,
GT outlet temperature: 475 ^{o}C – 850^{o}C,
Maximum steam temperature: 550^{o}C.

A suitable bottoming steam cycle with varying Superheat & Reheat temperature and with or without regenerative heaters can be employed.

Thermodynamic analysis of such a hybrid cycle was carried out by the authors which considered a syngas composition typical of an oxygen-blown Schwarze Pumpe (Todd,2000) gasifier (61.9%H_2, 26.2% CO, 6.9% CH_4, 2.8% CO_2) and maximum Gas Turbine inlet temperature of 1250^{o}C. Bituminous type coal was considered with HHV of 23 MJ/Kg. The SOFC was considered to be self-reforming or internal reforming one and the cell equilibrium analysis was done using reaction kinetics data in line with that suggested by Massardo & Lubelli (2000). The steam cycle was of single pressure non-reheat type.

The power and efficiency variation of the cycle with pressure are presented in Fig.2 and Fig.3.

While outputs from the individual components viz. SOFC, GT and ST were varying to some extent with varying pressure ratio and SOFC operating temperature, combined output appeared to be more or less steady even at low pressure ratio. The results also suggested that this cycle can effectively convert 65-68% of the heating value of fuel (HHV basis) into electrical energy – fuel cell, gas turbine and steam turbine added together. A very simple steam cycle with moderate boiler pressure and superheating, and with no reheating or regenerative feed heating, was considered as the bottoming cycle. Auxiliary power requirements like that for ASU were however neglected.

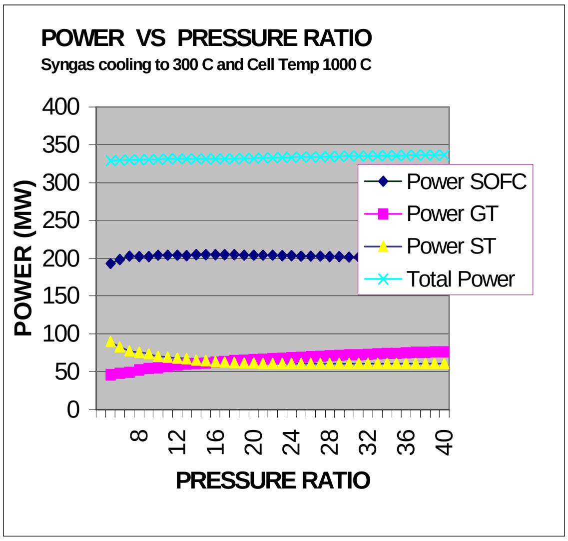

Fig. 2. Variation of Power With Pressure Ratio.

While sufficient information is not available in the literature on analysis of IGFCC using gasifiers, SOFC, GT and ST in combined cycle, there are a number of references available on cycles incorporating SOFC and GT in topping cycle and ST in the bottoming cycle. Winterbone(2000) has nicely described the status of research and development in fuel cell technology and made comparisons with other engines. Watanabe(1997) has shared valuable information on the fuel cell development status in Japan. Massardo & Lubelli (2000) have reported thermodynamic analysis of a number of SOFC-GT cycles for some of which overall efficiencies well exceeded 70%.

A cycle considered by Fry et al (1997) using air and Natural Gas was reported to have an overall LHV efficiency of 60%. It didn't employ a GT since the air and fuel stream pressure were considered low (1.6 bar for air and 1.97 bar for NG at respective inlets). But it did consider a single pressure steam cycle at the bottom producing about 25% of the total net power, the SOFC producing the balance.

One high pressure system has also been discussed by them that considers a MCFC, operating at 8.8 bar, and a GT receiving the anode and cathode gas mix through an afterburner and feeding a dual pressure steam cycle. Here, about two-third of the gross power was being developed by MCFC. The overall efficiency was 61%.

Both these cycles considered fuel (as well as air) to be preheated using heat in fuel cell exit gas/air streams.

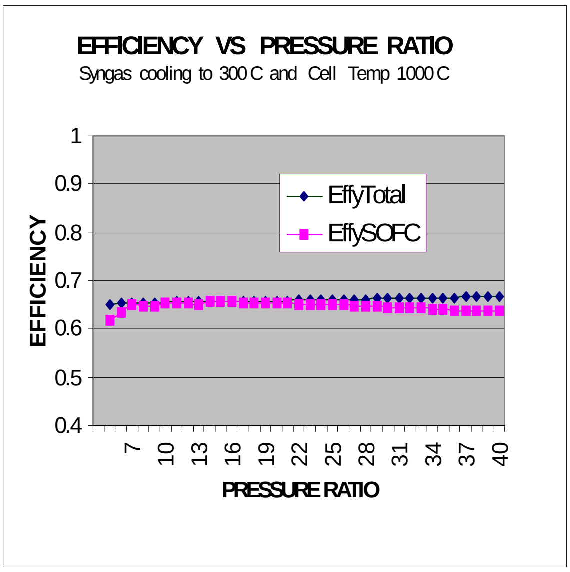

Fig.3. Variation of Efficiency of The SOFC & The Cycle.

Integration of a gasifier in the topping cycle will obviously save some of the preheating load. Moreover, a considerable amount of heat can be recovered from hot syngas by employing HRSG feed water heating (or evaporation of water). The power cycle in Fig.1 considers evaporation of saturated water at boiler pressure in the gas cooler and economizing of feed water and superheating in the HRSG. (Some more water is totally heated, including evaporation, in the HRSG depending on the extent of usable energy and temperature associated with the GT exhaust).

It may be noted that for effective sulfur removal SRU temperature was considered to be around 300^oC – 400^oC. Efforts are on all over the globe to make this happen at elevated temperature and if that becomes available possibly the preheating of the air using cell exit gas will not be necessary anymore and further gain in efficiency can be achieved.

Integration of another fuel cell operating at medium or low pressure can also be envisaged. Either a SOFC or a MCFC can be employed here, MCFC being suitable at lower temperature. A part of the high-pressure syngas may be expanded (expansion work may be utilized in compressing air required for this fuel cell) before sending to the low-pressure fuel cell. In fact such a dual pressure system using two SOFC s in an IGCC is projected by US DOE as one of the 21^{st} century power cycles (Vision21) in its report on development status of hybrid cycles (US DOE,2000).

ENVIRONMENTAL IMPACT

The IGGC technology is well known for reduced emissions. High pressure gasification process, specifically those employing oxygen only, like Texaco, British Gas-Lurgi or Schwarze Pumpe give twofold advantages. On the one hand they avoid Nitrogenous emissions (mainly NO_x) by separating out N_2 from air through ASU. On the other hand they generate low volume of Syngas which can be effectively cleaned.

The table below (Table 1) shows the emission data of some advanced IGCC facilities (Todd, 2000). Fuel Cells are clean power producing devices by virtue of their electrochemical reactions. However, they produce CO_2 as a consequence of shifting reaction. In the long run it would call for suitable CO_2 trapping mechanism to be employed with IGFCC. A Zero-Emission cycle has been suggested by Mathieu and Nihart (1999).

Table1: Emission Data For Some IGCC Facilities

Plants (Operating/Predicted)	NO_x PPM Volume
Cool Water-California (operating)	25
PSI – Wabash (operating)	<25
Tampa – Polk (operating)	<25
Sarlux – Italy (operating)	<30
Sierra Pacific (predicted)	<42
Exxon -Singapore (predicted)	42

CONCLUSIONS

Given this discussion, it is quite reasonable to expect that the proposed cycles as shown above will operate around 65% overall efficiency (based on HHV of input coal) even after taking into account the auxiliary consumption of ASU, AC etc. With further optimization of bottoming cycle and GT inlet temperature and development of high temperature gas clean-up system and high-pressure air separation units, the overall efficiency is expected to cross the 70% mark.

Both the IGCC and SOFC technologies are developing rapidly over the years, particularly in the US and Japan. US DOE has sponsored a number of developmental projects in gasification technology and also in fuel cell. Japan is also proceeding with its EAGLE and Sunshine projects. Some of the most advanced gasifications systems have already been put into commercial service. SOFC s so far could operate only on KW range and MW stacks are under development. While a lot depends on the success of such developmental projects, it is almost certain that the future power generation scenario will be largely governed by IGFCC technology.

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