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COMBINED CYCLE WITH CO_2 CAPTURE BASED ON THE PRE-COMBUSTION METHOD

Hanne M. Kvamsdal,
SINTEF Energy Research,
N-7465 Trondheim, Norway

Ivar S. Ertesvåg, **Olav Bolland**, and **Tor Tolstad**
Norwegian University of Science and Technology
N-7491 Trondheim, Norway

INTRODUCTION

In order to reduce the CO_2 emission from natural-gas based power-generation plants, three different main types of concepts have emerged as the most promising.

A) Separation of CO_2 from exhaust gas coming from a standard gas-turbine combined cycle (CC), using chemical absorption by amine solutions [1,2].

B) Oxy-fuel CC with a close-to-stoichiometric combustion with oxygen (97%+ purity) from an air-separation plant as oxidising agent, producing CO_2 and water vapour as the combustion products [3,4].

C) Decarbonisation, in which the carbon of the fuel is removed prior to combustion, and the fuel heating value is transferred to hydrogen. [5-7].

In the present work, focus is put on concept C; decarbonisation prior to combustion. The work is based on previous results published in [8-10]. Compared to previous work, the advance in this paper is a full implementation of the cycle model in PRO/II v.5.5 (SIMSCI Inc.). New parameter variations as variations in supplementary firing for preheating of the reformer streams, gas turbine pressure ratio and gas turbine inlet temperature (TIT), are carried out. The gas turbine model in the combined cycle (CC) is based on GTPRO (Thermoflow Inc.) simulations.

As in the work reported in [10], second-law analysis or exergy analysis has been performed in addition to first-order analysis in order to analyse this complex energy system more thoroughly.

PROCESS DESCRIPTION

The applied flowsheet was based on case 2 reported in [8-10]. The results of the simulations are compared to a standard combined cycle with no CO_2 capture.

Fig. 1 shows the present process configurations. The hydrogen-rich reformed gas is combusted in a gas turbine (GT), which is integrated with the decarbonisation process [9]. The gas turbine was modelled with units provided among the PRO/II standard unit models (a compressor unit, a Gibbs reactor and an expander). The gas turbine performance model reflects the General Electric 9351FA technology. This gas turbine represents modern technology of today, and it is used in a number of plants built in the last few years. The considered steam cycle; the heat-recovery steam generator (HRSG), the steam turbine (ST), and the seawater-cooled condenser (COND), is an advanced process with three pressure levels and steam reheat.

The reforming process is supplied with high-pressure air (8) and medium-pressure steam (2) from the gas turbine compressor and the HRSG, respectively. There is integration between the power plant and the reforming process with respect to preheating of feed streams for the reformers (auto-thermal reformer, ATR, and prereformer, PRE). This may require supplementary firing (SF) of the gas-turbine exhaust.

The required gas-turbine fuel-nozzle pressure is typically 25% higher than the pressure of the air extracted from the gas-turbine-compressor. Thus, an extra pressurisation of the fuel back to the gas turbine using a fuel compressor (FC) is required.

Natural gas (1), mixed with the medium pressure steam (2), is preheated to 500 °C in the HRSG unit prior to the pre-reformer (PRE). The steam-to-carbon ratio was set to 2 at the prereformer inlet. The air extracted from the gas-turbine compressor (8) and the prereformer products (5) are preheated by the exhaust gas stream upstream the ATR unit. Both the pre-reformer and the main reformer (ATR) are assumed equilibrium reactors. In the prereformer, most of the heavier hydrocarbon components (mainly C_2H_6) are converted to H_2 and CO, whereas the remaining methane is converted in the ATR unit. The ATR outlet temperature was set to 900 °C. The steam cycle takes advantage of the reforming process by utilising the cooling process of the reformer products downstream the ATR to generate additional saturated high-pressure steam (40, 41). The saturated steam (42) is superheated in the HRSG unit, and fed into the steam turbine (26). The produced CO is converted to CO_2 in the high- and low-temperature shift reactors (HTS, LTS). Most of the water (99%+) is removed in the water-removal unit (WR) by condensation at 25 °C. In the simulations, it was assumed that 90% of the CO_2 content is removed (22) in the absorber unit (ABS). The duty in the heat exchanger H5 is assumed to represent the necessary duty of the stripper boiler in the absorption/desorption section. Therefore, the temperature out of heat exchanger H4 (flow 17) was required to be above 130 °C. This, and the throttling of the CO_2 to 1 atm (flow 22), is assumed to give sufficient exergy for the CO_2 separation.

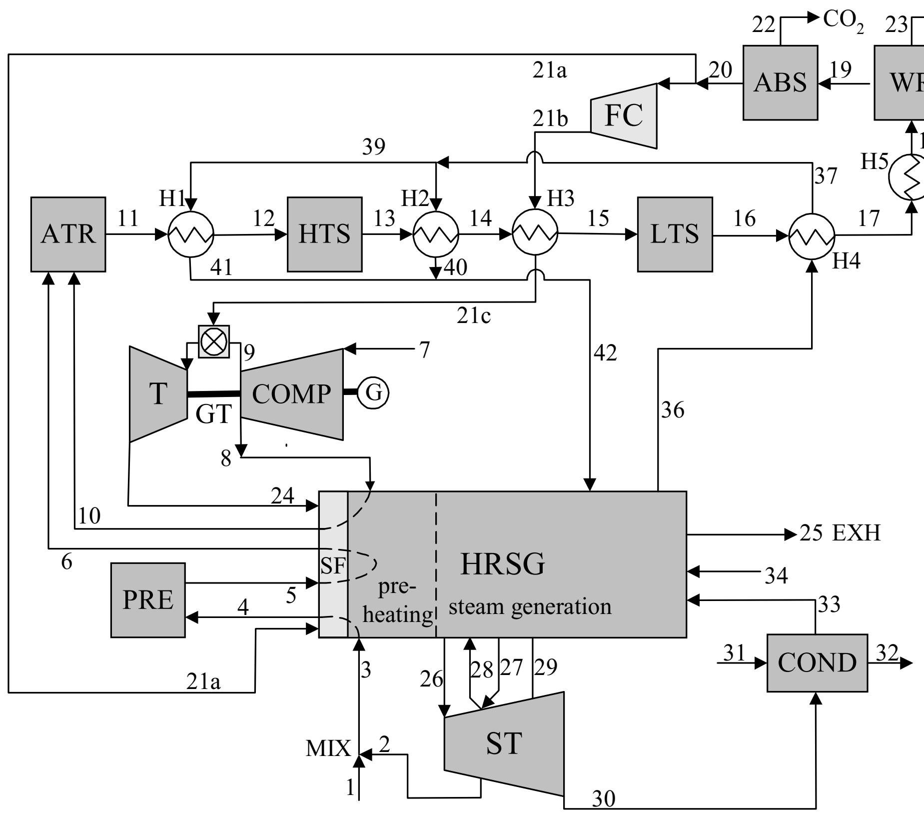

Fig. 1: Process flow diagram

The fuel (20) still contains small amounts of CO and hydrocarbons. A fraction (0-28.4%) of the resulting fuel is used for supplementary firing (21a) in the gas-turbine exhaust at the hot end of the HRSG. The remaining fuel (21b) is compressed (FC) to about 20 bar, heated by the feed stream (14) to the LTS, and then fed to the gas-turbine combustor (21c). By extracting air (8) from the gas turbine, there will be a significant reduction in the gas volume going into the gas turbine expander, and thus a reduction in the gas turbine pressure ratio. However, the fuel volumetric flow rate is such that it more or less replaces the lost volume caused by the air extraction. It is therefore possible to maintain the gas-turbine pressure ratio at about the same level as for a natural-gas-fired gas turbine without any air extraction. It was assumed a pressure drop of 3% in the pre-reformer, heat exchangers, and shift-reactors, whereas 6% pressure-drop was assumed for the ATR.

The generator efficiency was assumed equal to 98.6%, and the auxiliary power was assumed to 1% of the gross electric power production. In addition, some electric power (approx. 2,8% of the LHV) was used to compress the removed CO_2 from 1 atm to 80 bar for storage (not shown in Fig. 1).

METHODOLOGY

The flowsheet simulations provide data for species mass flows and energy flows. Furthermore, it provides the necessary data for calculating the physical (thermomechanical) exergy. Based on these data, the chemical exergy was calculated in a separate program according to the theory given in, e.g., [10] and [11]. The chemical exergies of the individual species of this study were taken from [11] and corrected to the ambient temperature of 8 °C according to the procedure given therein. The composition of the dry atmosphere was then defined by the molar fractions (%) N_2: 78.03, O_2: 20.99, Ar: 0.94, CO_2: 0.03. For the present simulations, the content of water vapor corresponds to a relative humidity of 82% at 8 ºC and 1 atm, which was chosen as the environmental temperature and pressure. This was the state of the air entrained into the system.

From this, the exergy of all streams were calculated. The irreversibility was then found from the exergy balance for each of the individual unit processes.

The generator losses, auxiliary power, and work for compressing the removed CO_2 to 80 bar, and hence, the net electric power production, were calculated separately after the termal-plant simulation.

RESULTS AND DISCUSSION

The following parametric variations have been carried out:

- supplementary firing for preheating of the reformer streams,
- gas turbine pressure ratio, and
- gas turbine inlet temperature (TIT).

The two latter variations were made for the system presented above, and for a corresponding conventional combined cycle without reforming and without CO_2 capture. Both variations were made without supplementary firing.

First, a series of simulations with a TIT of 1250 ºC and a pressure ratio of 15.6 was carried out with varying supplementary firing.

The calculated energy efficiencies are given in Fig. 2. As can be seen from Fig. 2, the efficiencies were (as expected) decreasing with increasing supplementary firing. However, the negative effect of increased combustion irreversibility was to some extent counteracted by the higher HP/MP steam temperature (see Table 1) until the maximum steam temperature was reached (560 ºC). This is indicated by the shift in curve gradient. The case with no supplementary firing showed an energy efficiency of 47,7% whereas the corresponding value for a natural-gas-fired combined cycle without CO2 capture was 58.4%.

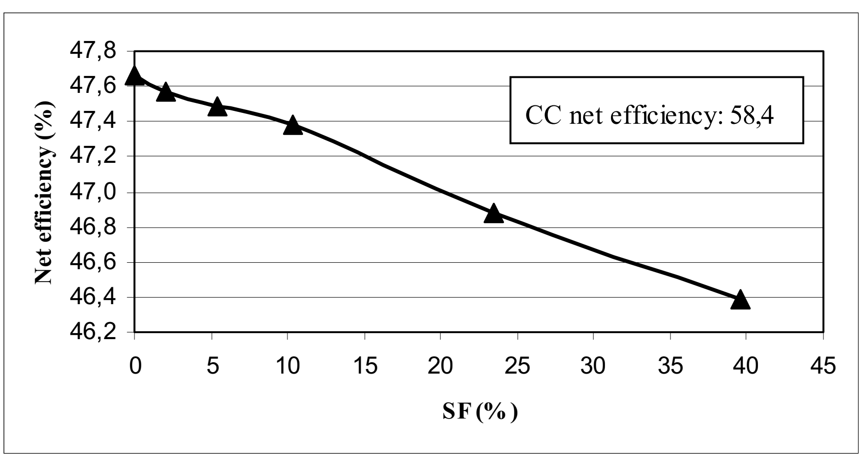

Fig. 2: Net energy efficiency (net electric power) for different cases with variation in supplementary firing (SF, as % of GT fuel).

Figure 3 shows those units that exhibited the significant changes in exergy losses. As seen from Fig. 3, the largest contributors to exergy losses are the combustor and ATR units, that is, the main units for chemical reactions. It is also seen that the reduction in the (relative) contribution of these two units was less than the increased contribution from the SF.
Furthermore, it can be noted that the single heat exchanger H1 had a considerable irreversibility, e.g., greater than that of the HRSG. H1 is a boiler in which high-pressure water is heated and vaporised to saturated steam (approx. 325ºC), and heated with the high-temperature products (900ºC) of the ATR. This thermodynamically "unwise" arrangement follows engineering practise and is due to the material problems that would occur in a high-temperature gas-gas heat exchanger, in particular when H_2 is present (metal dusting). The irreversibility of this unit was 25-30% of the exergy it transferred to the steam. With improved material technology, this may be utilised e.g. for superheating of steam.

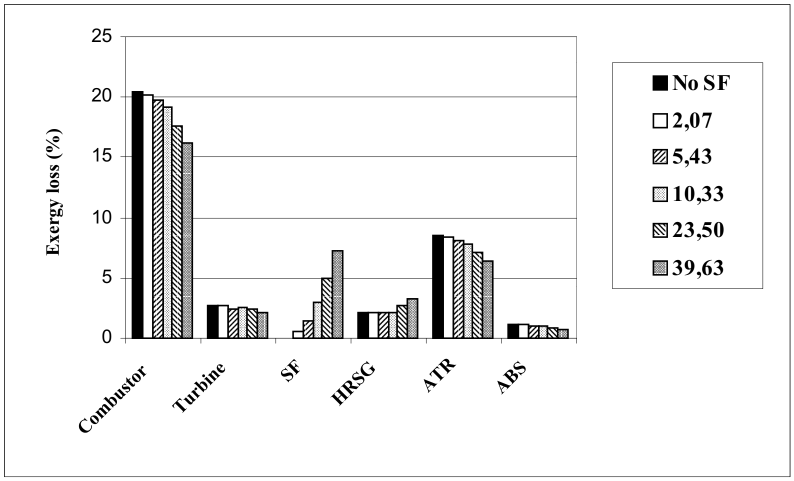

Fig. 3: Irreversibilities of selected units (% of fuel chemical exergy) with increasing supplementary firing (SF, denoted as % of the GT fuel).

Next, the influence of TIT and pressure ratio was investigated.
The energy efficiencies for the variations of gas-turbine compressor pressure ratio for 3 different TITs are shown in Figure 4 both for a decarbonised fuel power plant and for a corresponding conventional CC plant. The TITs were 1250ºC (ISO definition), 1350ºC, and 1450ºC, respectively, and the pressure ratios were 15.6, 20, 25, 30, and 40.
As expected, the efficiency increased with increasing TIT. Furthermore, for a conventional plant, the general tendency was that the efficiency increases with increased pressure ratio.
The corresponding irreversibilities are shown in Figs. 5 and 6. Here, the units of the plant are grouped into four groups. When details were inspected, it was observed that the changes in efficiency with higher pressure was a result of reduced irreversibility in the combustor and in the steam-cycle system (due to lower temperature of the exhaust inflow to the HRSG), counteracted by increased irreversibility in air compressor and turbine. In the high-pressure cases, the increased irreversibility outnumbered the reduction, and therefore the upper three curves in Figure 4 tend to flatten or turn slightly down.
These observations were also made for the plant with reforming and CO_2 capture. Here, the changes in irreversibility of turbine and compressor versus combustor more or less counteracted each other. However, the prominent effect in these variations was the irreversibility of the reforming process. In particular, the irreversibility of the ATR increased by approximately 1,0% (of the fuel chemical exergy) for all three TITs (from 8.5%, 8.0%, and 9.0%, respectively) as the pressure ratio was increased from 15 bar to 40 bar. An important reason for this was the reduced exhaust temperature from the gas turbine. To maintain the ATR outlet temperature at 900°C, more fuel was consumed in the ATR for thermal energy and thereby increasing the irreversibility.

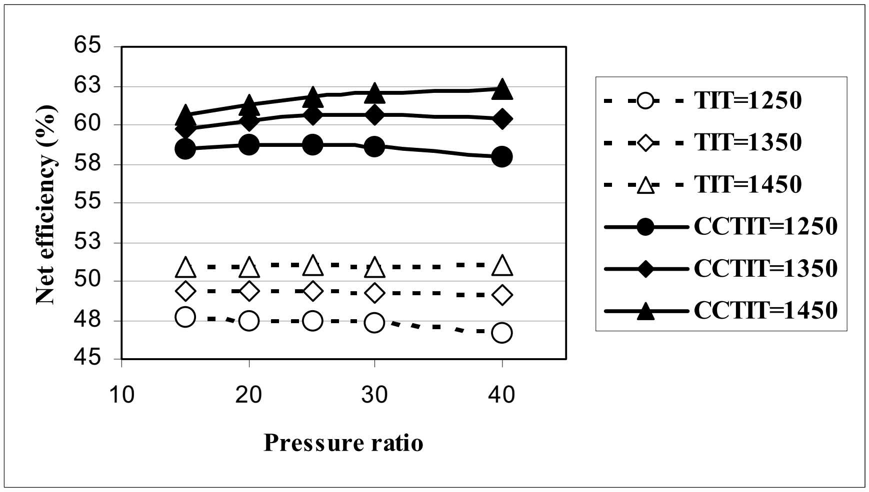

Fig. 4: Net efficiency – pressure ratio

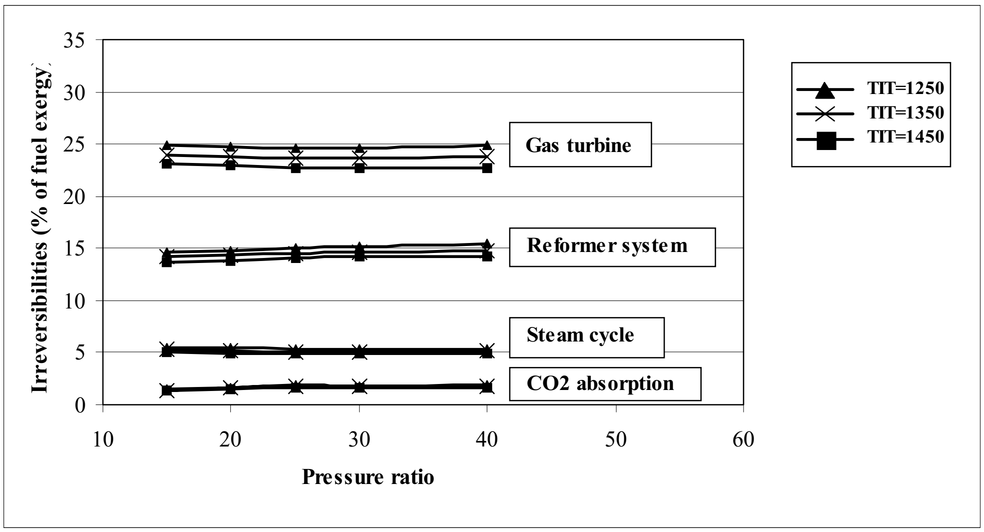

Fig 5: Irreversibilities for all units in groups (% of fuel chemical exergy) for variation in pressure-ratio and temperature (TIT). Fuel-reforming plant with CO_2 capture and no supplementary firing.

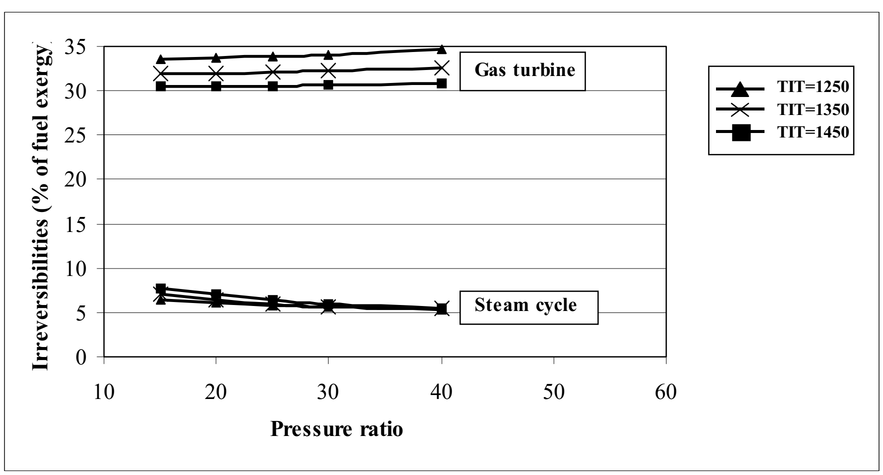

Fig 6:Irreversibilities for all units in groups (% of fuel chemical exergy), for variation in pressure-ratio and temperature (TIT). Conventional combined cycle with no CO_2 capture.

CONCLUSIONS

A parameter study of the pre-combustion method of CO_2 emission reduced gas power plant has been performed.

It has been shown that the exhaust gas can provide enough heat for reformer preheating without supplementary firing. Moreover, an increasing amount of fuel to supplementary firing increased the total irreversibility, and hence, reduced the net output from the plant. This was due to the higher irreversibility in the supplementary firing compared with that of the two other main reactors, the gas-turbine combustor and the auto-thermal reforming reactor.

Increasing the gas-turbine pressure ratio may improve the performance of conventional combined-cycle processes. This resulted from a reduced steam-cycle irreversibility due to reduced turbine-exhaust temperature. However, this was not the case for the process with fuel reforming and CO_2 capture. It was shown that at a certain turbine inlet temperature (TIT), a higher pressure ratio gave a slight reduction of the net efficiency. This resulted from an increased irreversibility of the reforming process, in particular that of the auto-thermal reforming reactor.

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