SIMULATION OF SEIZING CARBON DIOXIDE EMITTED FROM SIMPLE GAS TURBINE AND COMBINED CYCLES POWER PLANTS

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الملخص

يهدف هذا العمل إلى المساهمة في قضايا البيئة النظيفة عن طريق خفض إنبعاثات غاز ثاني اكسيد الكربون إلى المحيط الجوي، حيث يؤدي استخدام الوقود الأحفوري في محطات توليد الكهرباء إلى انبعاث الملوثات مثل غاز ثاني اكسيد الكربون الملوث الرئيسي للبيئة والذي يجب التقليل من انبعاثاته. يعد حجز الملوثات الناتجة من عمليات الإحتراق إحدى الطرق الممكنة لخفض انبعاثات ثاني اكسيد الكربون من المنشآت الصناعية، بما في ذلك محطات القوى، حيث يتم احتوائه ونقله وتخزينه بشكل آمن في عدد من الأماكن، بما في ذلك التكوينات الجيولوجية، وخزانات النفط والغاز المستنفدة. يستخدم محلول الأمين-الإيثانول الأحادي لإمتصاص ثاني اكسيد الكربون ثم فصله، وتعتبر هذه الطريقة الأبسط والأكثر استخداما. يتم في هذا العمل محاكاة دورة إزالة غاز ثاني اكسيد الكربون من غازات العادم المنبعثة من دورة غازية بسيطة واخرى مركبة. تم اختيار محطة قدرة غازية بقدرة 287.4 ميجاوات بكفاءة حرارية 28.98٪. اشارت محاكاة وحدة القدرة هذه إلى انبعاث 40.7851 كجم/ثانية من غاز ثاني اكسيد الكربون إلى المحيط الجوي، وبتوصيل دورة حجز غاز ثاني اكسيد الكربون بالدورة الغازية البسيطة والدورة المركبة، تم تخفيض معدل إنبعاث غاز ثاني اكسيد الكربون المنبعث إلى 0.3888 كجم / ثانية، وإلى 0.4085 كجم/ثانية على التوالي.

KEYWORDS: Carbon Dioxide Removal; Rich Amine; Lean Amine; Carbon Dioxide Loading; Absorbing Column; Stripping Column.

ABSTRACT

It is well known that carbon dioxide is one of the major pollutant agents to our environment, and its emission must be limited. Power plants mostly burn fossil fuel to generate electricity and hence produce a tremendous amount of pollutants such as CO_2. In this work, a simple gas-turbine cycle is connected with a steam cycle unit to form a combined gas-steam power unit and hence, improves its thermal performance. Since testing at large scale is so costly, it is likely to use process simulation software to evaluate such processes. Post-combustion removal is one possible way to lower CO_2 emissions from industrial plants, including power stations. Instead of discharging CO_2 which is contented in the exhaust gas to the atmosphere, the carbon dioxide can be seized, transported and stored securely in a number of places, including geological formations, and depleted oil and gas reservoirs. The most favorable method for CO_2 removal is by absorption in an amine-based solvent followed by desorption. The simplest and most used amine for CO_2 removal is MEA (Mono-Ethanol Amine). The net power output of the selected simple-gas turbine unit for the analysis is 287.4 MW with thermal efficiency of 28.98%. Modeling and simulating this power unit indicates 40.7851 kg/s of CO_2 is emitted to the atmosphere. The aim of this work is to reduce this amount and contribute to the clean environment issues. According to this study, the rate of the emitted CO_2 is reduced to 0.3888 kg/s, and to 0.4085 kg/s, when CO_2 removal cycle is connected to the simple gas turbine cycle and to the combined gas-steam cycle, respectively.

INTRODUCTION

Carbon dioxide concentrations in the atmosphere increased from of about 280 ppm in 1850 to 364 ppm in 1998 [1]. Nowadays the concentration of CO_2 in our environment exceeds 400 ppm and hence, it has been considered as the main contributor to the global warming phenomena [2]. Post-combustion carbon dioxide capture by absorption with aqueous amine solvents is expected to play an important role in climate change mitigation, by helping to reduce a significant fraction of CO_2 emissions from fossil fuel power plants. There are, however, a number of concerns with the large scale deployment of this technology, including energy requirements, solvent degradation and the environmental and health impact resulting from a potential loss of solvent and solvent degradation products [3].

Delays in organizing carbon capture and storage would necessitate advancing other means of stopping emissions, such as extensive moves away from gas heating, which is uncertain and expansive. On the other hand, post combustion CO_2 capture using liquid solvents is by far the most established and recognized process [4]. In order to alleviate CO_2 levels, it is crucial to deal with CO_2 emissions from power plants, and from all other sources. Part of the required reductions would be reached by enhanced energy efficiency and energy savings, and another portion could be reached by switching to non-fossil, renewable energy resources. High CO_2 removal efficiency at low costs is needed for carbon capture and storage technologies [1].

The issue of removing CO_2 from fossil fuel based power plants has got increased concern due to environmental causes. The main challenge recognized in the employment of post-combustion carbon capture is the high-energy requirement imposed by solvent regeneration, which brings down the net electrical efficiency by approximately 8 to 10% [5]. Hence, options for utilizing combined cycles to meet the energy demands have been considered in this work to offset the penalty of the reduction of the thermal efficiency and the net power output. Recently, more energy supplies (electricity) are required to fulfil the needs of the high living values and the population growth. Power stations count on the fossil fuel to generate electricity with the emission of considerable amounts of pollutant gases like carbon dioxide [5]. Furthermore, the IPCC (Intergovernmental Panel on Climate Change) has identified six gases with climate change potential: $\underline{CO_2}$,CH_4, N_2O, SF_6, CFC's (chlorofluorocarbons), and HFC's (hydro fluorocarbons) [6].

To contribute to the clean environment issues, carbon dioxide could be captured and stored for later use. One way to capture carbon dioxide from the exhaust gases is by absorbing it by using mono-ethanol amine (MEA) [7]. The process of removing carbon dioxide is an energy consuming process, for instance, for a combined cycle a 3.7 MJ of heat may be required to capture 1 kg of carbon dioxide from the exhaust gases [8].

Capturing CO_2 from the exhaust gases and natural gases has been the subject of many published papers for instance, to reduce CO_2 emission and to meet the liquefied natural gas standards [9], to test the capability of different amines for capturing CO_2 from coal-fired power plants, to simulate the absorption of CO_2 and H_2S into aqueous solutions of methyl di-ethanolamine (MDEA) and aqueous di-ethanolamine (DEA) [10], and introducing a novel amine-based solvent for post combustion capture of natural gas combined cycle [11].

MATERIALS AND METHODS

The combined power and amine cycle is shown in Figure (1). The combined power cycle consists of a simple gas turbine cycle with the three ordinary components, the compressor, the combustion chamber and the gas turbine, connected to a steam cycle. The steam cycle contains the heat recovery steam generator (HRSG), steam turbine, condenser and pump. The main components of the stripping cycle comprises an absorber, separator (stripper) with reboiler and condenser, heat exchanger, lean amine cooler and pumps. The thermodynamic package employed for the capture plant is the Acid Gas property package, which is based on the Electrolyte. An advanced software is employed for modeling and to estimate the material and energy balances simultaneously.

In the amine-based CO_2 capture, the flue gas is fed to the bottom of the absorber, and moves upward and contacts the liquid solvent which is cascades downward. The amine solvent reacts reversibly with the carbon dioxide and creates weak bonds resulting in the formation of water-soluble salts (rich amine). The rich amine mixture leaves the absorber from the bottom side to the separator. The sweet flue gas escapes to the atmosphere from the top of the absorber. The solvent (lean amine) is then regenerated in the separator and recycled to the top of the absorber .At the bottom of the separator, there is a reboiler to heat up the rich solvent and separate the CO_2 from the solvent and convert it to gas phase along with some H_2O. This gas mixture flows upward along the separator column. At the top of the separator column, there is a condenser to condense the H_2O back to the separator. The high CO_2 content gas stream leaves the top of the separator, which can be seized and stored for later use. The reactions of MEA and CO_2 are mainly occurred by electrochemical reaction in the aqueous solution. Typical reaction mechanism are as in the following equations [8].

$$\mathrm{2RNH_2 + CO_2 + H_2O \leftrightarrow (RNH_3)_2CO_3} \tag{1}$$

$$\mathrm{(RNH_3)_2CO_3 + CO_2 + H_2O \leftrightarrow 2RNH_3HCO_3} \tag{2}$$

$$\mathrm{2RNH_2 + CO_2 \leftrightarrow RNHCOONH_3R} \tag{3}$$

R stands for $\mathrm{C_2H_2OH}$.

The removal of CO_2 is not 100 %. The % CO_2 removal is limited both by low absorption and reaction rates and by the equilibrium conditions.

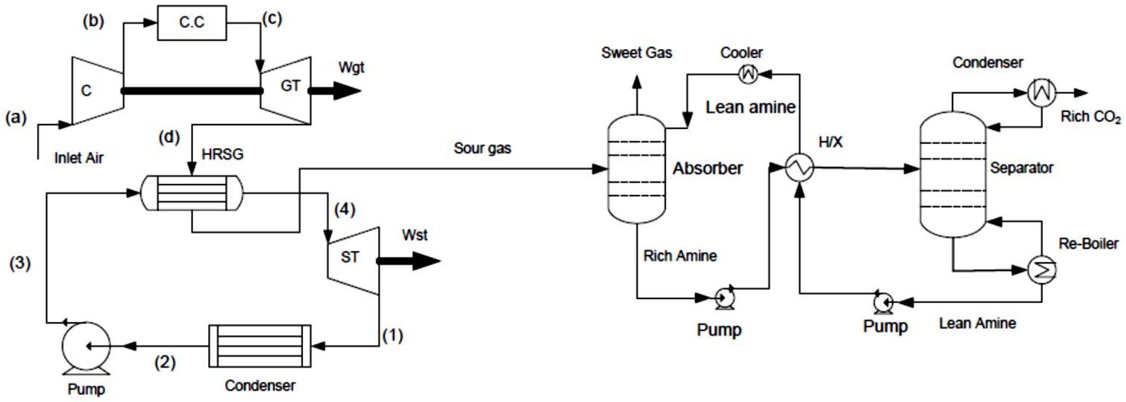

Figure 1: The combined cycle with CO_2 removal unit

Input data

The input data for the analysis are tabulated in Table (1), (2) and (3).

Table 1: Input data for the gas-turbine cycle

Inlet air Temperature Pressure Flow rate	 15 [° C] 1 [bar] 672 kg/s
Compressor Pressure ratio (PR) Efficiency	 17.5 87.468%
Combustion chamber (c. c)	$\Delta P = 0.0$
Gas turbine Inlet temperature Efficiency	 1242 [° C] 87.6 %

Table 2: Input data for CO_2 capturing cycle

Inlet gas temperature	40 [o C]
Inlet gas pressure	1.1 bar
Inlet gas flow	85000 kmole/h
CO_2 in inlet gas	3.73% (mole basis)
Water in inlet gas	6.71% (mole basis)
Lean amine temperature	40 [° C]
Lean amine pressure	1.1 bar
Lean amine rate	120 000 kmole/h
MEA content in lean amine	29% (mass basis)
CO_2 in lean amine	5.5% (mass basis)
Number of stages in absorber	10
Rich amine pump pressure	2 bar

Heated rich amine temperature	104.5 [^{o} C]
Number of stages in stripper	6(3+3)
Reflux ratio in stripper	0.3
Reboiler temperature	120 [^{o} C]
Lean amine pump pressure	2 bar
Minimum ΔT in heat exchanger	10 [^{o} C]

Table 3:The input data for the steam cycle

Designation	
T_4 [^{o}C]	500
P_4 [kPa]	600
P_1 [kPa]	7
Turbine efficiency	88 %
Pump efficiency	75 %

RESULTS AND DISCUSSIONS

The simulation reveals that, the net power output of the simple-gas turbine unit is 287.4 MW with thermal efficiency of 28.98%, and 40.7851 kg/s of CO_2 is emitted to the atmosphere. The mass flow rate of the exhaust gas (sour gas) is found equal to 691.820 kg/s. Additional data and results are tabulated in Table (4).

Table 4: Thermodynamic Results of the gas cycle

Designation	State: a	State: b	State: c	State: d	Fuel
Temperature [^{o}C]	15	412.030	1242	624.664	25
Pressure [kPa]	101.325	1773.187	1773.187	120	2773.187
Mass Flow [kg/s]	672	672	691.820	**691.820**	19.823

The composition of the gas turbine exhaust gas (sour gas) and the flow rate of each species are shown in Table (5). As can be shown, the mass flow rate of CO_2 is calculated as **40.7851 kg/s**, this amount should be reduced, which is the main task of this work.

For the amine cycle, the net power required to operate the pumps is calculated as 99.65 kW and the heat rate into the reboiler is found equal to 150 MW, hence the net heat supply to both cycles becomes 1142 MW, and the net power output drops to 263.5 MW with 8.32% drop in the net power output. It is found that, the combined thermal efficiency drops to 23.07%, hence the thermal efficiency is reduced by 20.39 %. A reduction in the range of 8 to 10 % for different operating conditions was reported by U. Ali et al. [5].

The amount of heat which is required to capture one kilogram of CO_2 is found equal to 3.713 MJ, this value is in excellent agreement with that given in the literature [8] and [12]. The CO_2 loading in lean amine is found as 0.2459 kgmole CO_2 per kgmole of lean amine, values between 0.165 and 0.204 was reported by M. Akram et al. [4]. The obtained results reveal that, the mass flow rate of the emitted CO_2 to atmosphere drops to 0.3888 kg/s that is 99 % of the CO_2 is removed from the sour gas.

Table 5: Sour gas composition and components mass flow rate

Designation	Mass fraction	Mole fraction	Flow rate kg/s
O_2	0.1405	0.1239	97.2161
N_2	0.74501	0.75020	515.4732
CO_2	0.05895	0.037781	**40.399**
H_2O	0.048264	0.075564	33.3902
CH_4	0.0072	0.0 12594	4.9559

To offset the reduction in the net power output and in the thermal efficiency, the gas cycle is combined with a steam cycle to improve the overall thermal performance. For the steam cycle the simulation reveals the steam turbine power is 103.20 MW, the pump power is 94.83 kW, and hence the net power is 103.10 MW. The steam flow rate is found equal to 117.8 kg/s, the heat recovered in the HRSG is 391 MW, and the rejected heat is 289.2 MW. Other data are tabulated in Table (6).

Table 6: Pressures and Temperature in the steam cycle

	Unit	**State :1**	**State: 2**	**State: 3**	**State: 4**
Temperature	ºC	57.02	39.02	39.09	500
Pressure	kPa	7	7	600	600

For the combined gas-steam cycle, the obtained result shows that the net power output is increased to 366.7 MW and the thermal efficiency to 36.97%, i.e. the net power is increased by 21.63 % and the thermal efficiency by 21.61 % over the simple gas turbine unit, respectively.

When the combined cycle is connected to the CO_2 capturing cycle, the thermal efficiency drops to 32.1%, and the net power output is almost fixed at 366.6 MW The mass flow rate of the captured CO_2 is found equal to 40.3461kg/s. The mole fraction of the CO_2 in the sweet gas is found as 0.0004 %, compared to 0.0012 % as reported by I. J. Otaraku [13]. The heat rate which is required to capture one kilogram of CO_2 is calculated as 3.718, this value is in good agreement with that given in the literature, where values between 3.97 and 6.63 were reported for different operating conditions by K. Lindqvist et al. [11], values between 3.02 and 3.26 were also reported by . E. Øi et al. [7], value of 3.7 was also reported by E. Øi et al. [8].

The composition and the flow rate of the sweet gas are shown in Table (7), as can be shown the mass flow of CO_2 which is rejected to atmosphere reduced tremendously to 0.4084 kg/s. The emission of CO_2 to atmosphere is reduced by 99%. The CO_2 loading in lean amine is calculated as 0.2459 kgmole CO_2 per kgmole of lean amine and in the rich amine as 0.4922 kgmole CO_2 per kgmole of rich amine, value of 0.496 was reported by J. Gervasi, L et al. [12] .

Table 7: The composition and the mass flow rate of the sweet gas

Designation	Mass fraction	Mole fraction	Mass flow rate kg/s
Oxygen	0.1496	0.1293	97.2102
Nitrogen	0.7932	0.7834	515.4754
CO_2	0.0006	0.0004	**0.4084**
H_2O	0.0565	0.0868	36.7108
ME amine	0.0001	0.0001	0.0740

The composition and the flow rate of the rich carbon dioxide gas flows from the top of the separator are shown in Table (8), as can be seen the CO_2 flow rate is **40.3461**

kg/s. This gas must be stored for later utilization for instance to enhance the oil recovery processes.

Table 8: The composition and the mass flow rate of the separated gas

Designation	Mass fraction	Mole fraction	Mass flow rate kg/s
Oxygen	0.0001	0.0001	0.0023
Nitrogen	0.0001	0.0001	0.0067
CO_2	0.7446	0.5441	**40.3461**
H_2O	0.2552	0.4557	13.8329

CONCLUSIONS

The objective of this work is to contribute to the clean environment concerns. With environmental issues, like pollution, and climate change, it is likely to look for techniques to reverse the damage to our planet and keep our environment clean. Emitting carbon dioxide to the atmosphere increases the greenhouse effect, where thermal energy is trapped by the atmosphere, causing the planet to become warmer than it would be naturally. Gas turbine engines emit large amount of exhaust gases with considerable amounts of carbon dioxide and must be reduced. In this work, Mono-Ethanol Amine is used as a CO_2 capturing agent. The results obtained showed that, the emitted CO_2 is reduced by 99% when a simple gas turbine cycle is connected to the carbon dioxide capturing unit with the penalty of reducing the net power output by 8.32% and the thermal efficiency by 20.39%. To overcome this deterioration, the gas turbine cycle is connected to steam turbine cycle to form a combined power cycle. For the combined gas-steam cycle, the obtained result shows the net power is increased by 21.63 % and the thermal efficiency by 21.61 % over the simple gas turbine unit, respectively. The mass flow rate of the removed carbon dioxide is found as 40.3461 kg/s.

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