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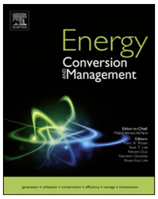

Thermoeconomic analysis of a CO_2 compression system using waste heat into the regenerative organic Rankine cycle

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ABSTRACT

The present paper deals with the thermoeconomic analysis of a CO_2 compression system using waste heat into the regenerative organic Rankine cycle. The compressor power required for CO_2 compression in the Carbon Capture and Storage has been supplied from a regenerative organic Rankine cycle which is used in thermal power plant. By using the turbine power supplied from the heat drawn and waste flue gas and the intercooler heat exchangers, 8% of the CO_2 separated from the waste flue gas compressed in the gas compressor. Thermoeconomic analysis of the system is performed by calculating thermodynamic and economic properties of the system. Energy and exergy efficiencies of cycle have been calculated as 17.2% and 51.6%. The average exergetic cost of waste heat flue gas as a fuel input in the integrated to the system is calculated to be 12.34 $/GJ or 947.5 $/h. The unit exergetic cost of electricity from the ORC system is calculated to be 17.47 $/GJ or 0.063 $/kWh. The unit exergetic cost of compressed CO_2 gas is calculated to be 84.9 $/GJ or 184.3 $/h at 310 K and 15,244 kPa. The cost of compressed CO_2 in the plant is calculated to be 18.36 $ per tonne of CO_2. The total exergy destruction cost rate of the plant and the most destructive component of the flue gas heat exchanger is calculated to be 297.8 $/h and 219.1 $/h, respectively.

1. Introduction

Climate change leads to the economic activities of mankind. Due to the mankind destruction, climate changes drastically impact the environment. The main challenge of these activities causing global warming is associated with the burning of fossil fuels. Therefore, any serious policy change has to stipulate the reduction or production regulation and fossil fuel consumption [1]. According to the Intergovernmental Panel on Climate Change (IPCC) the largest contributor to greenhouse gases resulting from human activities is CO_2 [2]. CCS is a process researched all over the world that can inspire hope for a future with low-carbon emission [3]. However, CCS is an energy intensive and costly process, increasing water consumption and reducing efficiency in power plants [4]. CCS consists of three main processes. These are the capturing of CO_2 from industrial sources producing emissions, its compression and permanent storage in geological repositories [5]. Compression of CO_2 during the CCS process is an energy-intensive process. CCS technology is still in the process of evolution and its initial costs and negative effects on the life-cycle and efficiency of the power plant is yet to be overcome [6]. Compression process in the Integrated Gasification Combined Cycle (IGCC) also decreases plant efficiency around 8–12% [7].

Carbon dioxide is known as a compound comprising a conveniently bonded molecule of carbon and two oxygen atoms found in the gaseous phase under normal conditions. The molecular weight of CO_2 is greater than air. Heavy molecular weight during the compression process is limiting the acceleration of the compressor rotor vanes. For this reason the compressor compression ratio is limited to certain numbers in single stage compressors [8,9]. CO_2 compression ratio in conventional turbo machines is approximately around 2. Therefore, multistage compressor chains are used for high pressure requirements. But as the number of stages increase, high levels of initial investment, operating and maintenance costs become a concern [10].

Growing energy needs which lead to serious environmental problems make technologies using low-temperature energy resources popular. Organic Rankine cycle (ORC), Kalina cycle and the Stirling cycle can be named as examples of these. ORC stands out among these cycles with its simple cycle configuration, low maintenance and repair costs and high durability [11]. Waste heat is recovered successfully with the ORC cycle in power plants [12]. At low temperatures

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Nomenclature

Symbols

c	specific cost (\$/GJ)
C	purchased equipment cost (\$)
$\dot{C}$	cost rate associated with exergy (\$/h)
CRF	capital recovery factor
ex	specific exergy (kJ/kg)
$\dot{E}x$	exergy flow rate (kW)
h	specific enthalpy (kJ/kg)
$\dot{I}$	irreversibility (kW)
$\dot{m}$	mass flow rate (kg/s)
$\dot{Q}$	heat transfer rate (kW)
s	specific entropy (kJ/kg K)
T	temperature (K)
W	work (kJ)
$\dot{W}$	power (kW)
η	efficiency
ε	effectiveness
$\dot{Z}_k$	total cost rate (\$/s)
τ	annual plant operation hours (h)
r_n	nominal escalation rate
$\dot{Z}^{\mathrm{T}}$	cost rate associated with the sum of capital investment and OMC (\$/h)
$\dot{Z}^{\mathrm{CI}}$	cost rate associated with capital investment (\$/h)
$\dot{Z}^{\mathrm{OM}}$	cost rate associated with OMC (\$/h)

Subscripts

FG	flue gas
HE	heat exchanger
in	inlet
p	pump
r	reversible
out	outlet
t	turbine
th	thermal
0	dead state
II	second law
OM	operation and maintenance cost
CI	capital cost of investment
i	inlet stream
F	fuel
e	exit stream
P	product

Acronyms

CCS	carbon capture and storage
CO_2	carbon dioxide
CRF	capital recovery factor
IGCC	integrated gasification combined cycle
MEA	monoethanolamine
OFWH	open feed water heater
ORC	organic Rankine cycle
WCC	water cooled condenser

(< 150 °C), the preferred technology is the organic Rankine cycle. In this cycle, organic fluid is used instead of water and high-pressure steam. High molecular weight liquids that can boil at lower temperatures compared to water are used in the ORC technology. Silicone-based fluid can be selected as working fluid and hydrocarbon or coolant-based liquids may be used for low temperatures [13]. Vapor extraction from the turbine and regeneration has a significant positive effect on the thermal efficiency of the ORC [14,15].

There are many studies in the literature about the application of CCS. According to Pei et al. [10] figure out that different types of CO_2 compression strategies and recovery of waste heat arising from these compression strategies. A compressor cycle with inter-cooling and a two-stage shock wave compression cycle were created theoretically and their energy consumption and potential waste heat recovery were determined. Waste heat recovery was performed with the organic Rankine cycle. As a result, when evaluated without waste heat recovery, the compressor cycle with inter-cooling consumed less specific energy compared to the two-stage shock wave compression cycle. The highest exergy loss has occurred in the evaporator. In their study, Guo et al. [16] investigated the effect of the use of different organic fluids on the system performance of ORCs generating electricity from waste flue gas. Analytical results suggest that the highest efficiency in the ORC using the compared mixtures of organic fluids is in the condenser. Franco [17] investigated that the exploitation of low temperature, water-dominated geothermal areas with a specific attention to regenerative ORC. In their study, Safarian and Aramoun [18] performed a theoretical energy and exergy analysis of three different types ORCs. As a result of their investigation they found that the maximum exergy loss has been observed in the evaporator and the loss appeared to increase with the rise of pressure. In their study Zhao et al. [19] used the waste heat from the organic fluid employed in an ORC, generating electricity from solar energy, in solvent regeneration in a CO_2 capture system with amine based chemical absorption. This combined system which has been designed theoretically in a 300 MW power plant, produced remarkable results in power generation and emission reduction. Alabdulkarem et al. [20] designed innovative CCS systems for liquefied natural gas plants using waste heat. They were able to produce a design 16.31% more efficient than conventional designs. Maalouf et al. [21] investigated that the two recovery processes using ORC. Net turbine power of ORC was reached to maximum using a direct contact water-vapor condensation. Campana et al. [22] represented the estimate of ORCs that can be installed in the twenty-seven countries of the European Union. Song et al. [23] carried out a one-dimensional analysis method for the ORC. It is shown that the inlet temperature of the heat source and the cooling water have an important influence on the ORC. The results show that the net power of the ORC system is 534 kW. In addition, the thermal efficiency of ORC system reaches 13.5%.

Exergoeconomic analyses provide important information that cannot be obtained by conventional thermodynamic calculations. There are many studies in the literature about economic analysis of CO_2 capture, liquefaction and transportation. Leeson et al. [24] conducted comparative cost analyzes for CCS systems of various sectors (the iron and steel industry, the cement industry, the petroleum refining industry and the pulp and paper industry). Also, the amounts of CO_2 captured were determined. Jakobsen et al. [25] investigated various alternatives for the nine different applications of CCS at a cement plant. Zahid et al. [26] studied techno-economic analysis of CO_2 liquefaction for ship transportation. Optimum localization of liquefaction facility was determined for post-combustion and pre-combustion of CO_2 capture. Petrakopoulou et al. [27] presented that three different oxy-fuel plants incorporated with CCS. The exergoeconomic analysis showed that an increase in the cost of electricity with according to the reference plant by more than 20%. Canepa and Wang [28] performed to techno-economic evaluations of the capture plant model integrated with flue gas