Energy xxx (2016) 1–10

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Application of organic Rankine cycle in integration of thermal power plant with post-combustion CO_2 capture and compression

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A R T I C L E   I N F O

Article history:
Received 6 June 2016
Received in revised form
17 October 2016
Accepted 27 October 2016
Available online xxx

Keywords:
CO_2 capture and compression
Thermal power plant
Organic Rankine cycle
Efficiency penalty
Waste heat recovery

A B S T R A C T

Post-combustion CO_2 capture process is the most mature technology to mitigate CO_2 emissions from the large-scales emission points. However, integrating the power plant with this process leads to significant thermal efficiency penalty due to steam extraction for solvent regeneration, power consumption by CO_2 compression unit and other auxiliary equipment. In the current work, the detailed models of the 350 MW_e thermal power plant, MEA-based CO_2 capture and compression process were developed in Aspen HYSYS v8.3. Different configurations of integration process were investigated to achieve lower energy penalty. The power plant net thermal efficiency is 40.55% based on lower heating value and is reduced to 31.26% due to integration with CO_2 capture and compression process. The net efficiency of the best studied configuration is 33.4%. CO_2 compression intercoolers, steam cooler before reboiler and flue gas cooler are three low-temperature heat sources located in the integrated system were identified for utilizing by organic Rankine cycle (ORC). Three ORCs were used to recover these waste heats and can generate 17.38 MW_e extra power that increase net thermal efficiency to 35.45%. The results show that efficiency drop is reduced significantly by utilizing ORCs in integration of thermal power plant with CO_2 capture and compression.

1. Introduction

The global warming is an obvious consequence of human activities on climate system. Increasing anthropogenic greenhouse gases (GHG) emissions have led to cumulative emissions of CO_2 which contributes about 78% to the total GHG emission [1]. IEA reported 67.4% of the world electricity generation in 2013 is provided by fossil fuels [2] that released huge amount of CO_2 to atmosphere. Fossil fuel power plants are known as large CO_2 emission point and need actions to mitigate their pollution.

Carbon dioxide capture and storage (CCS) is currently the only available technology can protect the climate, however CCS application in large-scale has own challenges so proper selection of CO_2 capture technology is essential [3]. The decision about the best CO_2 capture technology for all processes seem to be difficult and depends on various factor such as costs, type of fuel and required CO_2 purity at the end of the process [4,5]. Among CO_2 capture processes, post-combustion CO_2 capture (PCC) with chemical absorption become the most mature technology for CO_2 separation of the combustion flue gas. The most commonly used solvent is Monoethanolamine (MEA) because it has a faster rate of reaction with CO_2, low cost and suitable for treating low CO_2 partial pressure [6,7]. The main disadvantage of MEA-based chemical absorption technology is the large amount of thermal energy requirement for solvent regeneration. When this technology couples with power plant it cause considerable efficiency penalty of power plant due to steam extraction for providing reboiler energy demand and power consumption by other auxiliary equipment. This efficiency penalty for coal-fired power plants was estimated about 10% [8].

Previous researchers [9,10] focused to improve the technical and economical performance of CO_2 chemical absorption cycle with simulation and parametric study and optimizing effective parameter that can reduce the reboiler energy requirement and cost of system. Several studies have been investigated different MEA-based process configurations for post combustion CO_2 capture to reduce high energy consumption of conventional CO_2 chemical absorption system. Karimi et al. [11] studied different configurations via simulation and cost calculation. Amrollahi et al. [12] discussed the selection of important parameters through process simulation of various configuration to gain required capture

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http://dx.doi.org/10.1016/j.energy.2016.10.124
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efficiency and minimum energy consumption. Ahn et al. [13] simulated different configurations and proposed a new concept of amine process to achieve lower heat duty of reboiler.

Various substances have been investigated for attaining solvents that have better properties such as lower energy penalty, lower capital cost, high absorption rate and high solvent loading capacity than MEA [14–16].

As mentioned, integration of CO_2 chemical absorption cycle and power plant lead to energy penalty and additional costs so many researches have been done to overcome these drawbacks and present well-integrated system. Auxiliary equipment for providing reboiler energy and designing modification for a supercritical steam cycle power plant have been utilized to achieve low energy penalty and capture costs [17,18].

Cifre et al. [19] modeled power plant with an integrated amine based CO_2 capture system and compression step and studied the influence of the scrubbing process parameters such as column size, solvent mass flow rate and stripper operating pressure on system efficiency. Sanpasertparnich et al. [20] investigated the effect of steam extracted from different locations from a series of steam turbine as the crossover pipe between IP/LP and different LP ports with the objective to achieve the lowest possible energy penalty. Duan et al. [21] analyzed effective parameters on the MEA regeneration energy and proposed an integration case that used heat pump technology for recovering waste heats and could decrease efficiency penalty by 2%. Xu et al. [22] designed a new integrated system for using the low-temperature energy released from CO_2 capture process to heat the condensed water in the power generation unit and circulating water in the radiant floor heating system. Liu et al. [23] performed an integrated study through process simulation and could decrease energy penalty by utilizing waste heat from CO_2 capture and compression process, taking part of low pressure cylinders out of service and adding an auxiliary turbine to decompress the extracted steam.

Some other studies have been done on the retrofit of natural gas combined cycles (NGCCs) with an amine-based post combustion carbon capture system. Ystad et al. [24] applied low-temperature CO_2 Rankine cycle in NGCC integrated with PCC to use heat sources located in the CO_2 capture and compression process and could increase net plant efficiency about 2%. Carapellucci et al. [25] studied different options to reduce plant derating by integrating an external auxiliary unit that provides heat and/or electricity to the PCC system. Luo et al. [26] simulated different case studies for NGCC power plant integrated with PCC process and compression train and stated the role of EGR and supersonic shock wave compression stage. Pan et al. [27] proposed optimal retrofitting strategies included: modifying HRSG and EGR employing and modeled them in various case studies to minimize the efficiency penalty.

Various thermodynamic cycles such as the organic Rankine cycle (ORC), supercritical Rankine cycle, Kalina cycle and Goswami cycle have been developed to convert low-temperature heat source into electricity [28]. Among these cycles ORC has attracted many attentions because of its simple structure, high reliability and easy maintenance. ORC has similar component as steam Rankine cycle but its working fluids is organic substances such as hydrocarbons and refrigerants with low boiling points. Working fluid selection for ORC is complex and very important because strictly affects the efficiency and economy of system [29]. ORC manufacturers have been present on the market since the beginning of the 1980s [30]. Khatita et al. [31] performed a case study through simulation and studied different working fluids for power generation by ORC with using waste hear recovery in gas treatment plant.

In this paper, integration options of a thermal power plant with CO_2 capture and compression process are investigated with the presented models in order to reduce the thermal efficiency drop of the power plant. Detailed steady state models of a 350 MW_e thermal power plant, CO_2 capture and compression process are developed and different integration case studies are carried out in Aspen HYSYS v8.3. Novelties of present study can be claimed as:

- A rigorous rate-based approach is employed instead of traditional equilibrium model in simulating the CO_2 capture process and an accurate model of CO_2 compression process is presented to predict their realistic performance.
- ORC is used for waste heat recovery in integration of thermal power plant with CO_2 capture and compression process in order to reduce the efficiency penalty, for the first time. Three low-temperature waste heat sources located in integrated system: intercoolers of CO_2 compression unit, pretreatment of extracted steam from IP/LP crossover and flue gas cooler have been identified and utilized to generate power by three ORCs.

2. Model development

2.1. Thermal power plant

A 350MWe thermal power plant was selected to integrate with a CO_2 capture and compression process (Fig. 1). In the boiler 92500 m^3/h natural gas (NG) burns with 15% excess air to produce 308.7 kg/s of steam at 166 bar and 529 °C which enters in HP turbine. Steam is reheated in boiler before entering IP turbine, then passes through IP and LP turbines successively for electric power generation. Eight steam flows are extracted from turbines different stages to utilize in eight feed water heaters including four low pressure, three high pressure and a deaerator. The outlet steam from LP turbine condenses to water and pumped to deaerator after passing along four low pressure heaters. Afterwards water pumped to boiler and heated again by three high pressure heaters before entering the boiler.

The NBS Steam property package was used for simulating steam cycle. Turbines and pumps were modeled by Expander and Pump blocks respectively. Feed water heaters and boiler were modeled by Heat exchanger blocks. Three heat exchangers were deployed as: economizer, re-heater and super-heater for generating steam. Hot stream of these heat exchangers is flue gas which is produced in furnace by reaction of fuel and air. Furnace is modeled by Gibbs reactor. The overall performance is shown in Table 1.

2.2. MEA-based CO_2 capture process

2.2.1. Process description

A typical MEA-based CO_2 capture process is illustrated in Fig. 2. Flue gas exhausted from power plant is directed to capture system. At the first stage hot flue gas is cooled to obtain suitable temperature for absorption process. Since the flue gas includes water vapor and its phase change during the cooling process a separator must be used after this action. The blower is used to overcome pressure drop in absorber column. The gas then enters at the bottom of the absorber and counter-currently contacts with solvent for CO_2 absorption. The treated gas exits from the top of the absorber and is washed in water-wash section to prevent solvent releasing to environment. Rich solvent from the bottom of the absorber is pumped through rich-lean heat exchanger to enter stripper for solvent regeneration. The solvent is regenerated thermally by reboiler and is returned to absorber via passing through the cooling processes. Due to MEA degradation and keeping constant solvent concentration an amount of MEA and water is added as make up. The vapor stream from top of the stripper is condensed in overhead