Applied Energy 230 (2018) 267–276

Contents lists available at ScienceDirect

Applied Energy

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

Efficiency evaluation of a coal-fired power plant integrated with chilled ammonia process using an absorption refrigerator

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HIGHLIGHTS

- An integration of chilled ammonia process using absorption refrigerator into coal-fired power plant was proposed.
- A 300 MWe subcritical coal-fired plant was selected as the baseline.
- Efficiency penalties of the overall process for different steam extraction were obtained.
- The absorption refrigerator was compared with the vapor compression refrigerator.

ARTICLE INFO

Keywords:
Post-combustion CO_2 capture
Coal-fired power plant
Chilled ammonia process
Absorption refrigerator
Vapor compression refrigerator
Coefficient of performance

ABSTRACT

Chilled ammonia process (CAP) is an alternative process for inhibiting ammonia escape during the CO_2 capture process. In this paper, the integration of a coal-fired power plant with CAP, using an absorption refrigerator (AR) to provide the chilling load, is proposed. The thermal energy consumption of the CAP and the AR, derived from a crossover pipe between the intermediate pressure and low pressure (IP-LP) steam turbine sections and from an appropriate port of a low pressure (LP) turbine, are the basic scenarios considered for this study. A systematic evaluation of a 300-MWe coal-fired power plant is conducted and its overall process is compared with the power plant integrated with CAP using the conventional vapor compression refrigerator (VCR). An analysis of the basic scenarios reveals that the efficiency penalties reduced from 13.23% to 9.82% when the steam extractions were from the IP-LP crossover pipe and LP turbine, of which a 4.26% and 2.96% loss, respectively, was contributed by the AR. Decreasing the chilling temperature, while increasing the regenerating temperature can reduce the efficiency penalty. A comparative investigation of the lower efficiency penalties of various COP_a and COP_c are recommended. Better performance can be achieved by VCR integration if the COP_c is higher than 2.0 and 3.5. The results from and an understanding of the two types of refrigerators can be used as the basis for system design and optimization.

1. Introduction

Significant CO_2 emissions due to public power and heat production are a major reason for global warming. Coal-fired power plants are responsible for a large share of these CO_2 emissions [1]. Therefore, low-carbon fuel utilization or CO_2 capture and storage (CCS) is an important strategy in climate mitigation [2,3]. CCS has been identified as the most likely technology to achieve large-scale CO_2 reduction in the short and medium terms. Post-combustion, pre-combustion and oxy-combustion are currently the major technologies being researched and applied. Among the various CO_2 capture technologies, chemical absorption approaches based on solid and liquid sorbents, such as amines, CaO, NH_3 and potassium carbonate (K_2CO_3) are widely accepted as the common or alternative method [4,5]. Several pilot CO_2 capture plants are in the planning, construction or operation stage [6,7].

Aqueous ammonia-based CO_2 capture has been reported to be more effective than conventional amine-based CO_2 capture, having reached the pilot plant stage in a relatively short period since its first use [8].

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https://doi.org/10.1016/j.apenergy.2018.08.097
Received 4 January 2018; Received in revised form 1 August 2018; Accepted 17 August 2018
0306-2619/

Nomenclature

I	internal irreversibility factor
K	heat-transfer coefficient
Q	thermal energy
T	temperature

Abbreviations

AR	absorption refrigerator
CAP	chilled ammonia process
CCS	carbon capture and storage
CFPP	coal-fired power plant
COP	coefficient of performance
DCC	direct contact cooler
ESP	electrostatic precipitator
FGD	flue gas desulfurization
HP	high pressure
IP	intermediate pressure
LP	low pressure
MEA	monoethanolamine
PCC	post-combustion CO_2 capture
VCR	vapor compression refrigerator
HPFWH	high pressure feedwater heater
LPFWH	low pressure feedwater heater

Several pilot plants have been evaluated for NH_3-based post-combustion CO_2 capture (PCC) plants, such as the aqueous ammonia process at the Munmorah pilot plant [9] and the chilled ammonia process (CAP) at Pleasant Prairie and the Mountaineer coal-fired power plant (CFPP) [10]. Goto et al. [11] suggested that the efficiency penalty can be reduced to 8.0–8.5% for the aqueous ammonia process, compared with an efficiency loss of 9.5–12.5% for the MEA-based process in the coal-fired power plant.

However, a critical technical and economic challenge for the commercial application of ammonia-based CO_2 capture is the intrinsically high volatility of NH_3·NH_3 vapor leaves the aqueous solution to enter the gas phase during the CO_2 capture process. The escaped NH_3 concentration in the vent gas is usually over 10,000 ppmv if no further measurements are taken [12–14], which will affect the CO_2 capture process, causing serious environmental problems. To suppress the ammonia slip or recover the escaped ammonia, an additional water (acid) washing device needs to be installed. Unfortunately, these measures would lead to increased capital and operating costs [15].

CAP is an alternative for reducing the ammonia slip. In CAP, the absorber is operated at low temperatures in the range of 0–20 °C [16]. This process was developed by Alstom and its technical feasibility was confirmed in a pilot plant [17]. There is an ammonia loss of up to 9% of the solvent in the conventional aqueous ammonia process, while the ammonia loss in CAP can be limited to less than 6% of the solvent [18]. However, an additional cooling load will be required in the CAP to maintain a low temperature during the absorption process. When CAP is integrated into the power plant, it will reduce the performance of the power plant. Mathias et al. [19] showed that CAP could not compete with the MEA-based process due to the large refrigeration load requirement. CAP is determined to be equivalent to the MEA-based process with regard to low pressure (LP) steam consumption. Versteeg and Rubin [20] performed a basic analysis of a coal-fired power plant integrated with CAP. They concluded that the net efficiency penalty amounted to 11.2%, while the contribution of the refrigerator was approximately 3.9%. Hanak et al. [21] suggested that the efficiency penalty of the power plant integrated with CAP varied between 10.4% and 10.9%, depending on the stripper pressure. However, they also showed that the efficiency penalty can be reduced to 8.7–8.8% through the integration of a single-stage or two-stage auxiliary steam turbine, respectively, along with a back-pressure turbine. Meanwhile, Linnenberg et al. [22] modeled the CAP in Aspen Plus and the supercritical coal-fired power plant in EBSILON Professional. Their results indicated that the efficiency penalty for the base scenario ranged between 10.4% and 11.6%, depending on the cooling water temperature. Valenti et al. [23] obtained a similar efficiency penalty of 8.6%. However, the flash drums were connected in series in their integration.

In summary, the performance of the power plant integrated with CAP is determined by both steam extraction location from the turbine and the refrigeration system. It has been determined that the optimal steam extraction option is between the intermediate and low-pressure turbines, with the pressure corresponding to the saturation temperature depending on the reboiler pinch point [24]. It should be noted that conventional steam turbines do not have an extraction point in the required range. In those turbines, the integration of a noncondensing turbine for steam extraction from an intermediate pressure (IP)/low pressure (LP) turbine crossover pipe is the most efficient. Hence, it is

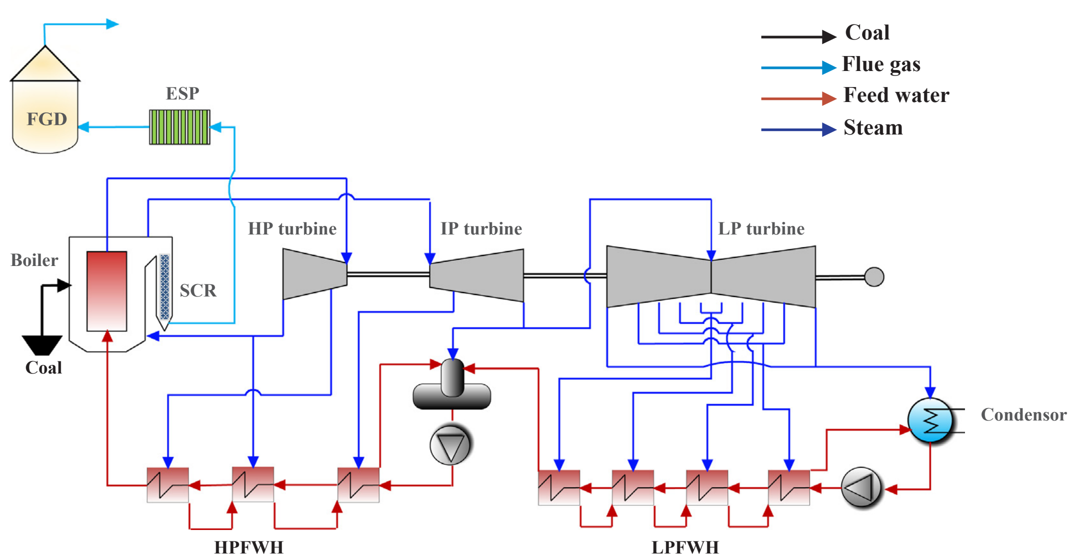

Fig. 1. Schematic diagram of the reference subcritical coal-fired power plant.