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Optimal integration of compression heat with regenerative steam Rankine cycles in oxy-combustion coal based power plants

Chao Fu [a, *], Rahul Anantharaman [b], Truls Gundersen [a]

[a] Department of Energy and Process Engineering, Norwegian University of Science and Technology, Trondheim, Norway
[b] SINTEF Energy Research, Trondheim, Norway

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ABSTRACT

The integration of process heat with regenerative steam Rankine cycles by preheating the boiler feedwater increases power generation from the steam turbines. In oxy-combustion coal based power plants, considerable compression heat from the air separation unit is available for such heat integration, however, there are at least two challenges: (1) how to integrate a heat stream with the steam cycle, and (2) how to optimize the compression scheme, accounting for the trade-off between compression work requirement and the turbine power output. This paper investigates the optimal integration of the air compression train in a cryogenic air separation unit with the regenerative steam cycle in an oxy-combustion coal based power plant using MINLP (mixed Integer non-linear programming) Two special cases (adiabatic compression and "isothermal" compression) are also investigated to compare with the optimization results. The study shows that such heat integration increases the thermal efficiency of the reference power plant by a maximum of 0.5–0.6% points. The heat integration is less attractive when the temperature difference of the heat transfer between the compressed gas and the boiler feedwater is larger than 40 °C.

1. Introduction

In regenerative steam Rankine cycles, steam is extracted from the turbines at various pressure levels to preheat the BFW (boiler feedwater). This preheating process elevates the temperature at which the BFW receives heat in the boiler, thus increases the thermal efficiency of the power plant (defined as the ratio between the net work output from the cycle and the heat input to the cycle) [1]. In practice, a finite number of closed or open FWHs (feedwater heaters) are used for regenerative preheating. The temperature differences for the heat transfer between the extracted steam and the BFW should be minimized in order to reduce the irreversibilities. However, the capital cost increases. In modern pulverized coal based power plants, 6–9 FWHs are normally used in the steam cycle [2].

Alternatively, the BFW can be preheated by external heat sources. Steam extractions from turbines can thus be reduced or eliminated, resulting in increased power generation from the turbines. Such external heat sources could be solar [3], geothermal [4] or process heat [5]. One example of process heat is the waste heat from compression processes (compression heat) in oxy-combustion coal based power plants [6–8]. Compressors for CO_2 with a single-stage pressure ratio up to 10 have been developed by Ramgen Power Systems in order to upgrade the compression heat and integrate it with steam cycles [9]. In oxy-combustion processes, relatively purified O_2 is produced in an ASU (air separation unit) and then used for combustion, resulting in highly concentrated CO_2 in the flue gas after condensing the H_2O. Current air separation technologies for high volume O_2 supply are based on cryogenic air distillation [10]. When a traditional double-column air separation scheme is applied for O_2 supply, the ASU causes a large thermal efficiency penalty of around 6% points based on the HHV (higher heating value) [7]. According to the thermodynamic studies on the entire ASU [7,11], around 40% of the exergy losses in the ASU is caused by the compression of air from 1 bar to 5–6 bar, where around 54% of the compression losses are caused by compressor inefficiency and the remaining part is due to the (inter-stage and after-stage) cooling. A promising energy saving option is to utilize the corresponding compression heat for preheating BFW in the steam cycle.

When the compression heat is to be integrated with the steam cycle, the following two challenges should be addressed: (1) how to integrate a heat stream with the steam cycle, and (2) how to design

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* Corresponding author. Tel.: +47 73592799; fax: +47 73593580.
E-mail address: chao.fu@ntnu.no (C. Fu).

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the compression scheme tailored for this heat integration. The first challenge is normally solved by using Pinch Analysis [12]. A new heat balance in the feedwater heaters after heat integration is determined by drawing the Grand Composite Curve [5–7]. The second challenge is of particular interest since "isothermal" compression (multi-stage compression with interstage cooling to lower work consumption) may no longer be favorable. Complete or partial adiabatic compression can elevate the temperature of the available compression heat, and thus potentially reduce the extractions of higher pressure steam in the regenerative feedwater preheating process. Thus, there is a trade-off between the work consumption in the compression of air and additional power generation from the steam cycle due to the integration of compression heat. An optimization of the compression scheme is required. The available heat streams from the compression processes are unknown, increasing the complexity of solving the problem at hand. This paper presents a mathematical optimization study for the heat integration problem. The objective is to investigate the maximum improvement potential in thermal efficiency by integrating the compression heat from the ASU with the steam cycle. The influence of the temperature differences for heat transfer between the compressed gas and the BFW on the heat integration results is also investigated. The paper is an extension of the work by Fu et al. [13].

2. The reference steam cycle

A 571 MW (net) supercritical pulverized coal based oxy-combustion power plant [7] is illustrated in Fig. 1. The entire power plant is modeled with the simulator Aspen Plus V7.3. The NBS/NRC (U.S. National Bureau of Standards/National Research Council of Canada) steam tables are used for the steam cycle and the PR (Peng-Robinson) property method is used for the remaining processes. The thermal input from the coal is 1879 MW and thus the thermal efficiency is 30.4%. Around 95 mol% O_2 is produced from the cryogenic ASU (air separation unit) where the air feed is compressed to 5.6 bar. A major portion of the O_2 is used as oxidant in the combustor after being mixed with the RFG (recycled flue gas) that is used to control the combustor temperature. The heat of combustion is transferred to the steam cycle for power generation. A preheater is installed to further cool the flue gas against the mixture of the O_2 and the RFG. The NOx, the particulate matter and the SOx are removed in the DeNOx, ESP (electrostatic precipitator) and FGD (flue gas desulfurization) units respectively. After desulfurization, a major portion (72%) of the flue gas is recycled while the remaining portion enters the CPU (compression and purification unit) where the CO_2 is purified to around 96 mol% and compressed to 150 bar.

A reference supercritical steam cycle [14] is shown in Fig. 2 and the stream data is presented in Table A.1 (in Appendix). The HP (high pressure) steam is heated to 242 bar/600 °C with single reheat of the IP (intermediate pressure) steam to 45 bar/620 °C. The condenser pressure is 0.069 bar. The BFW is preheated in 4 closed FWHs (FWH1-4) in the LP (lower pressure) section, 1 open FWH (FWH5, i.e. the deaerator) and 3 FWHs (FWH6-8) in the higher pressure (HP) section. The mass flows and heat balances are obtained by process simulation. The heat contribution of the extracted steam in each FWH is determined by decomposing the heat loads as shown in Fig. 3 [7]. In each FWH, the cold stream (represented by the bottom line) is the BFW. The hot streams (represented by the lines above the bottom line) are decomposed heat loads of the extracted steam at different pressure levels. They are actually mixed in each FWH. External drain coolers (flash type) are used [15]. The condensate from each FWH is flashed to a lower pressure FWH (the deaerator is a special FWH) and condensed again at the lower saturation temperature. Thus the temperature of each extracted flow of steam does not decrease continuously. The extracted steam bypasses the subsequent turbine stages from its extraction point, thus reduces the power output from the turbines. The corresponding power reduction is determined on the basis of the following procedure:

(1) In the LP section of the BFW preheating (steam N24-27), the power reduction is equal to the additional power generated when the extracted steam passes through all the subsequent turbine stages from its extraction point.
(2) In the HP section below the reheating point (steam N18) and for the deaerator (steam N19), when the steam extraction is reduced, more steam passes through the subsequent turbine

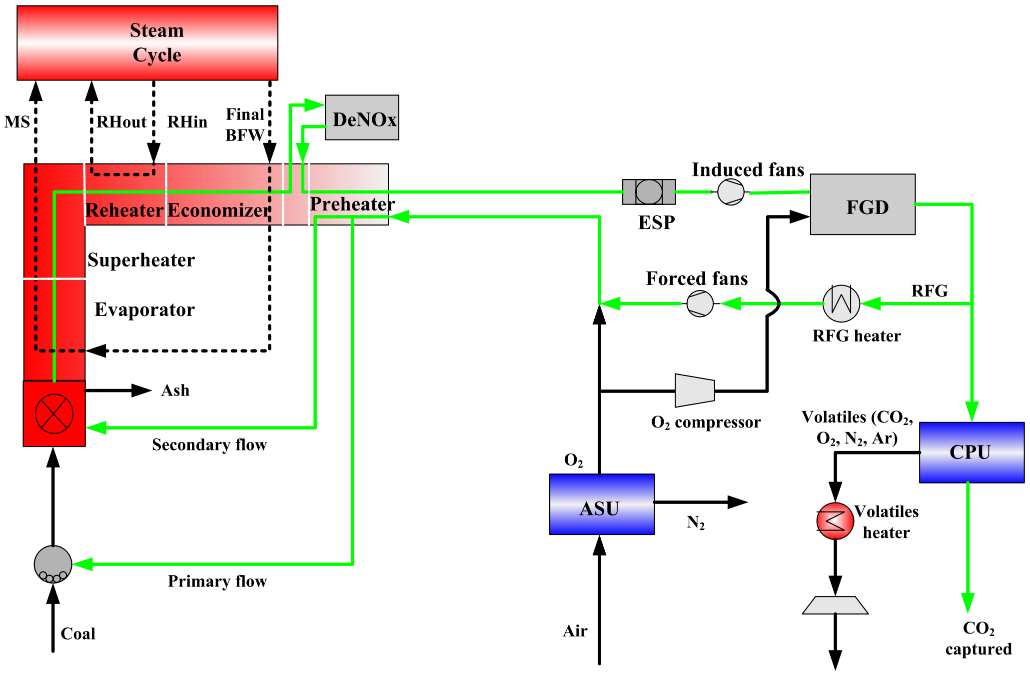

Fig. 1. The coal based oxy-combustion power plant with CO_2 capture.