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N_2 Brayton Cycle in Oxy-combustion Power Plants

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The appropriate placement of compressors and expanders was recently shown to be at the pinch temperature, meaning that the inlet temperature to these units should be at the pinch. However, the application of the rule is not obvious when multiple values of minimum approach temperature for heat transfer exist, such as in oxy-combustion power plants where both subambient (cryogenic air separation) and above ambient (the steam cycle) processes are involved. For cryogenic low purity O_2 production processes, high pressure N_2 is available from the distillation column and the pressure based exergy is normally recovered in the cold box. When the O_2 is supplied to an oxy-combustion power plant to concentrate the CO_2, considerable low temperature heat in the flue gas is lost after heat recovery in the preheater. A N_2 Brayton cycle is proposed in this paper. The high pressure N_2 is preheated to the pinch temperature of the preheater in the boiler area before expansion. The entire plant thermal efficiency increases by 0.69-0.85 % points.

1. Introduction

Oxy-combustion enables the capture of CO_2 from industrial processes such as thermal power plants and cement factories. Nitrogen is removed in an air separation unit (ASU) to avoid it being introduced to the combustion chamber. As a result, the flue gas has a high CO_2 concentration. A considerable challenge to implement oxy-combustion technology is the large energy penalty related to O_2 production (Fu and Gundersen, 2012). Cryogenic air separation technology is normally selected for high volume O_2 supply. The optimal O_2 purity is typically around 95-97 mole % for oxy-combustion processes (Wilkinson et al., 2001). In traditional cryogenic air separation processes, at least two distillation columns are used: one is operated at atmospheric pressure (lower pressure, LP) and another is operated at a pressure of 5-6 bar (higher pressure, HP). The two columns are thermally coupled in such a way that the N_2 vapor from the top of the HP column is condensed by the boiling O_2 at the bottom of the LP column. The condensed N_2 serves as liquid reflux for the two columns.

When O_2 with a purity of 95-97 mole % is the only desired product (oxy-combustion is one such case), excess N_2 is available from the HP column after the requirement of reflux for the two columns has been satisfied (Kerry, 2007). In addition, in order to feed the air to the HP column, the air feed has to be compressed to 5 - 6 bar. The work input is actually more than required (including the separation work and the refrigeration energy) when the O_2 delivery pressure is atmospheric. Two options are thus available for reducing the energy consumption of ASUs: one is to minimize the work input for the compression of the air feed (Fu and Gundersen, 2013) and another is to maximize work recovery (by expansion). This paper investigates the second option.

In coal based oxy-combustion power plants, as illustrated in Figure 1, the exhaust temperature of flue gas from the preheater is around 150-180 ^oC, resulting in considerable low temperature heat loss. Further recovery of this heat in the boiler area is a challenge due to larger heat capacity of the flue gas compared to that of the gas to be preheated (i.e. there is a pinch bottleneck in the hot end of the preheater). Assuming that the potential corrosion caused by acids can be avoided, this low temperature heat may alternatively be recovered by preheating the boiler feedwater in the steam cycle (Spliethoff, 2010) or driving an Organic Rankine Cycle, however, both options are expensive.

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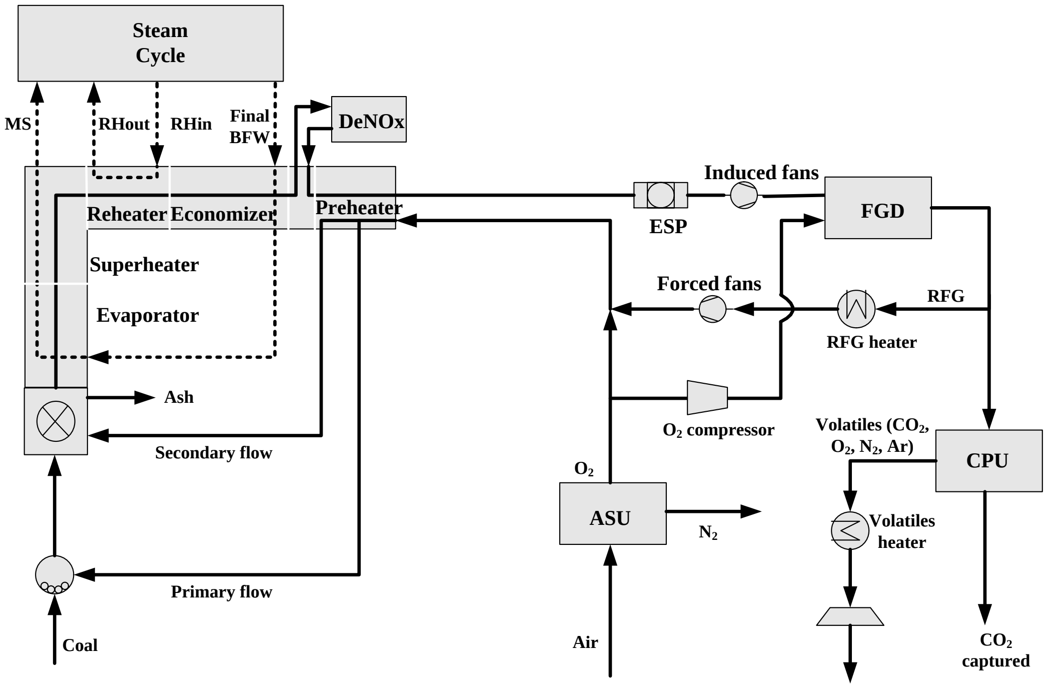

Figure 1: Illustration of coal based oxy-combustion power plants

A new approach for the recovery of work and heat in oxy-combustion processes has been developed in this paper. The pressurized N_2 is extracted from the ASU and preheated in the boiler area before expansion, thus more work can be recovered. Such integration between the ASU and the boiler actually builds a Brayton cycle using N_2 as the working fluid.

2. Cryogenic air separation

Chapter 2 Linde's double-column air distillation scheme is the basis for most existing cryogenic air separation plants around the world. Figure 2 shows an ASU derived from the double-column distillation scheme. For simplification the heat exchangers are not presented except for the coupled condenser/reboiler heat exchanger. The HP column is used for producing N_2 liquid reflux for the two columns. The main feature of this cycle is that a portion of N_2 is extracted from the top of the HP column and vented after its cold energy and pressure-based exergy are recovered. This cycle is thus termed "N_2-expansion cycle" in this paper. The amount of N_2 available from the HP column is around 18 % of the air feed (mass basis) after the reflux requirements have been satisfied (Fu, 2012).

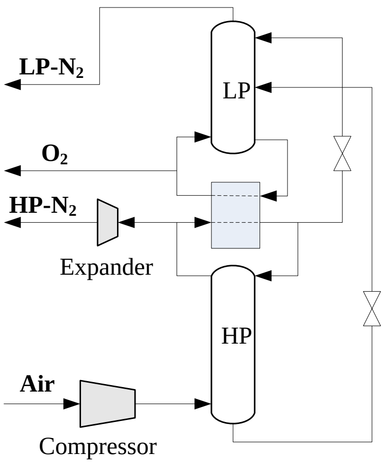

Figure 2: A N_2-expansion air separation unit

3. Low temperature heat recovery in the boiler area

In oxy-combustion coal based power plants, a portion of the flue gas (recycled flue gas, RFG) is recycled to the combustion chamber for temperature control (Wall et al., 2009). As shown in Figure 1, the RFG together with the purified O_2 is preheated against the flue gas in the preheater. The pinch temperature is located in the hot end of the air preheater since the flue gas has a larger heat capacity (mainly due to larger mass flow), as illustrated by Figure 3.

3.1 N_2 Brayton cycle

A N_2 Brayton cycle is proposed to improve the plant thermal efficiency, as shown in Figure 4. The pressurized N_2 is extracted from the top of the HP column in the ASU and heated to ambient temperature against the air feed. The N_2 (5.3 bar) is further heated against the flue gas in the preheater. The hot N_2 is then expanded to ambient pressure by a one-stage or two-stage turbine. When a two-stage turbine is used, the N_2 is reheated in the preheater after the first expansion stage, resulting in more work being recovered. After expansion, the N_2 temperature is still high enough to be used for the regeneration of molecular sieves in the pre-purification unit of the ASU (for the removal of H_2O, CO_2 and other impurities), thus the heat (steam) consumption in this unit can be reduced. This option is not included in the paper.

3.2 The placement of compressors and expanders

Aspelund et al. (2007) developed an Extended Pinch Analysis and Design (ExPAnD) procedure for utilizing pressure based exergy. Two of the heuristics are: (i) compression requires power and will add heat to the system, thus compression should preferably be done above the pinch point, and (ii) expansion provides cooling and should thus preferably be done below the pinch. In other words, both compression and expansion should preferably start at the pinch temperature. However, several pinch points may exist

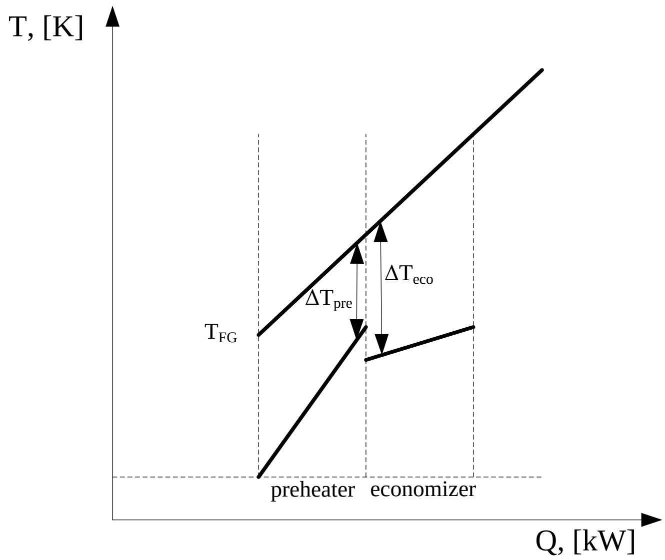

Figure 3: Flue gas cooling curve

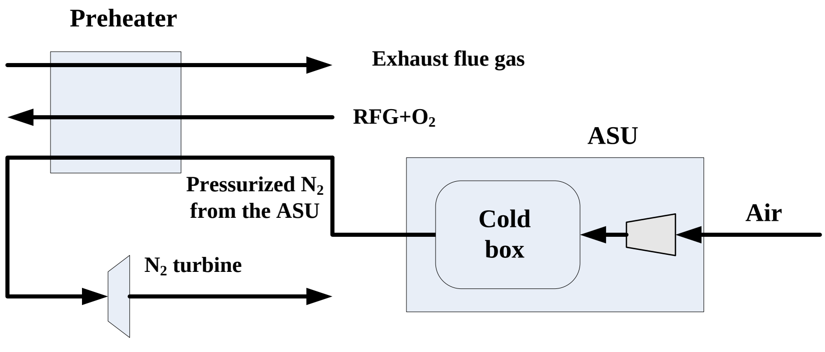

Figure 4: The N_2 Brayton cycle

in the oxy-combustion process due to multiple values of minimum approach temperature for heat transfer. A high starting temperature for expansion is favourable in order to recover more work. The Pinch temperature of the preheater is chosen as the N_2 expansion temperature in this paper. If the N_2 is further heated in the economizer or to an even higher temperature in the boiler area, more fuel must be supplied unless modifying the steam cycle. The exhaust temperature of N_2 after expansion will be high and thus further recovery of the heat is required.

3.3 The reference power plant

When oxy-combustion is applied, in order to obtain a similar heat transfer in the combustor as when air is used, the O_2 mole fraction at the combustor inlet must be 25-30 % and at the outlet 3-5 % (Wall et al., 2009). The O_2 fraction is mainly dependent on the supply of O_2 from the ASU. The adiabatic flame temperature, adjusted by changing the flue gas recycling ratio (the amount of RFG divided by the total flow of the flue gas at the recycling point), is normally slightly (100-150 K) lower than that in the air-fired case since CO_2 has a larger specific heat capacity than N_2. A coal based power plant without CO_2 capture has been chosen as the reference plant (Franco et al., 2011). The steam cycle is assumed to be fixed. The flue gas temperature at the preheater inlet is 650 K. The minimum temperature difference of the preheater is specified as 50 K. Figure 5 shows that the typical range of the flue gas recycling ratio is 0.68-0.72 (determined by the O_2 mole fraction range being 25-30 %) when oxy-combustion is applied (the O_2 supply is 95 mole %). The O_2 fraction at the combustor outlet is presented in two cases in Figure 5: 3 % and 5 %.

4. Results and discussion

An oxy-combustion power plant shown in Figure 1 has been studied as the basis. Figure 6 presents the improvement in the entire plant thermal efficiency by applying the Brayton cycle. The O_2 mole fraction at the combustor outlet has been investigated in two cases: 3 % and 5 %. From Figure 6 it can be observed that: (i) the flue gas recycling ratio has negligible influences on the performance improvement; (ii) the thermal efficiency increases by 0.69-0.81 % points when the N_2 Brayton cycle with one-stage expansion is used; (iii) a further improvement of 0.02-0.04 % points in thermal efficiency is achieved if two-stage expansion (with equal pressure ratio) is used.

The exhaust flue gas temperature is shown in Figure 7. The base case is the oxy-combustion case without application of the N_2 Brayton cycle. The exhaust flue gas temperature is 435-440 K. When N_2 is heated in the preheater, the exhaust flue gas temperature is 377-389 K for one-stage expansion and 353-371 K for two-stage expansion. Thus, the low temperature heat loss has been significantly reduced. However, the reduction of exhaust flue gas temperature has the challenge that acid gases may condense and thus corrosion takes place. Special types of heat exchangers (such as plastic) can be applied. The investment cost of course increases when the Brayton cycle is applied. However, compared to other options for low temperature heat recovery such as boiler feedwater preheating or Organic Rankine cycles, the N_2 Brayton cycle seems more attractive.

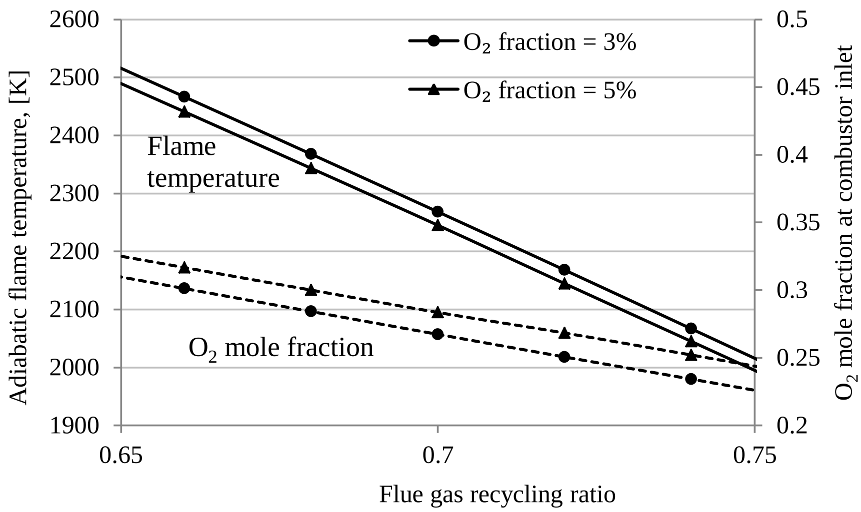

Figure 5: The influence of flue gas recycling ratio in oxy-combustion plants

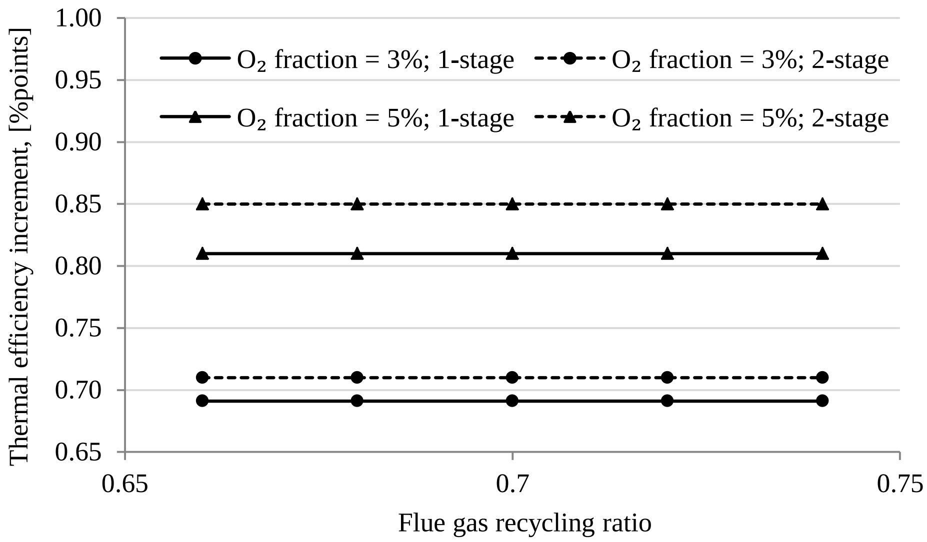

Figure 6: Thermal efficiency improvement by the Brayton cycle

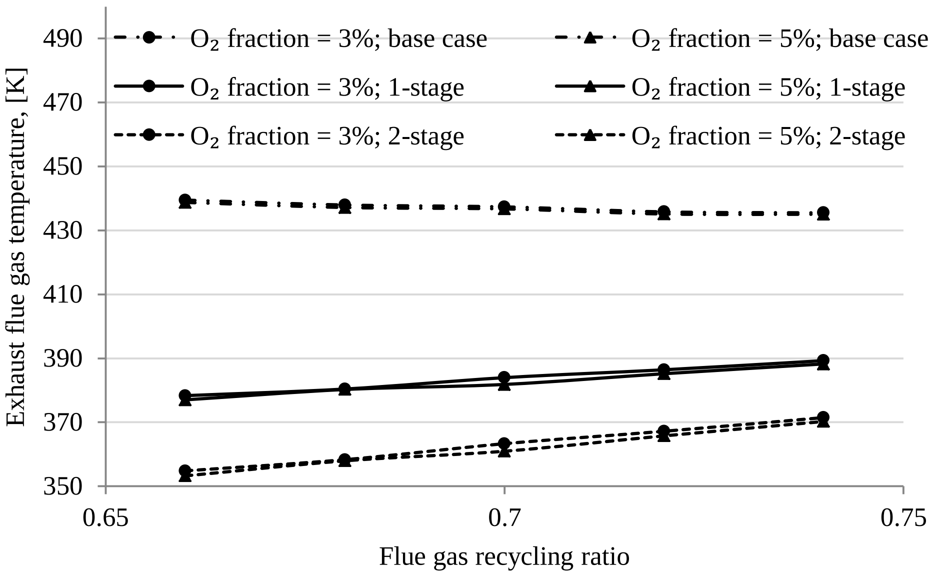

Figure 7: Exhaust flue gas temperature

5. Conclusions

Oxy-combustion enables a higher concentration of CO_2 in thermal power plants that makes CO_2 capture easier. A major challenge to implement the oxy-combustion technology is the considerable thermal efficiency penalty. Following the rule of appropriate placement of compressors and expanders, a N_2 Brayton cycle is developed by integrating the cryogenic air separation unit and the boiler area. The thermal efficiency increases by 0.69-0.81 % points over the operating range of oxy-combustion when a one-stage N_2 expansion process is used. The thermal efficiency further increases by 0.02-0.04 % points when the N_2 expands through two stages with reheating.

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