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Reducing the Power Penalty Related to CO_2 Conditioning in Oxy-coal Combustion Plants by Pinch Analysis

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Oxy-combustion is a competitive technology to enable the capture of CO_2 from coal based power plants. The CO_2 conditioning process is an important contributor to the power penalty related to CO_2 capture in such power plants. The double-stage flash process is commonly applied in literature. The efficiency penalty is around 3.6% points in this case. This paper presents a study on the CO_2 conditioning process in three cases: one-stage flash, double-stage flash and three-stage flash. The composite curves are applied to investigate the integration potential. A detailed exergy analysis has been performed to compare the plant performance in the three cases.

1. Introduction

Oxy-combustion is a promising route to capturing CO_2 especially for coal-fired power plants, since the reduction in efficiency and the increment of investment cost according to the IEA (2007) and Kanniche et al. (2010) are less than for natural gas based power plants. Moreover, the possibility of co-capture of SOx and NOx in coal based power plants is attractive when oxy-combustion is applied to capture CO_2 (IEAGHG, 2007). The core concept of oxy-combustion is to use high purity oxygen instead of air for the combustion process so that the flue gas is composed mainly of CO_2 and H_2O. The CO_2 can be separated by condensing the H_2O and then purified by chilling. After compressed to a dense phase, the CO_2 can be transported and injected into geological formations.

The power efficiency reduction related to CO_2 capture in coal-based power plants is mainly caused by two units: the air separation unit (ASU) and the CO_2 conditioning (purification & compression) process. Commercially available air separation technologies for high volume oxygen production are based on cryogenic distillation. A trade-off regarding the O_2 purity exists between the ASU and the CO_2 conditioning process considering the power efficiency penalty related to CO_2 capture. Thus the CO_2 conditioning process is an important factor for the plant performance. The double-stage flash process is commonly used to condition the CO_2 (Pipitone and Bolland, 2009). According to Fu and Gundersen (2010), the efficiency penalty is around 3.6% points in this case.

Pinch Analysis has been used to study CO_2 capture processes recently. Harkin et al. (2009) use Pinch Analysis to integrate the steam cycle and the steam extraction process for flue gas purification and solvent regeneration in a coal based power plant with post-combustion CO_2 capture. Romeo et al. (2008) present an integration study of the CO_2 compression process, the amine regeneration and the steam cycle. The study is also based on post-combustion. There are very few references available on Pinch Analysis for the sub-ambient temperature level in oxy-combustion processes. Fu and Gundersen

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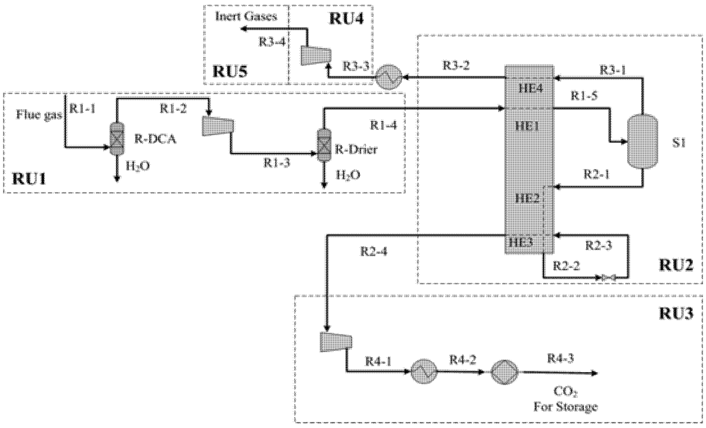
(2010) study the distribution of exergy losses in oxy-combustion processes for coal-fired power plants and investigate integration opportunities by Pinch Analysis. The purpose of this work is to study ways to improve the CO_2 conditioning process based on the results from an exergy analysis.

This paper studies the CO_2 conditioning process by using Pinch Analysis. The composite curves are applied to study the sub-ambient heat exchangers. The CO_2 conditioning process has been studied for three cases: one-stage flash, double-stage flash and three-stage flash. An exergy analysis has been performed to compare the three options. The simulator Aspen Plus has been used in this work, while the software tool PRO_PI1 is used to perform Pinch Analysis.

2. The CO_2 conditioning process

2.1 The one-stage flash process

Figure 1 shows the flowsheet of a one-stage flash CO_2 conditioning process. The molar composition of the flue gas from an oxy-coal combustion plant is: CO_2-70.7%, H_2O-15.3%, N_2-8.5%, O_2-2.5%, Ar-3.0%. The flowrate of the processed flue gas is 19 066 kmol/h. The flue gas (R1-1) first enters a direct contact aftercooler (R-DCA) to condense the water vapor before it is compressed to 24 bar by a three-stage compressor with water intercooling. It is then dried in a molecular sieve twin bed drier (R-Drier) to avoid ice formation in the sub-ambient heat exchangers. The dried flue gas (R1-4) is cooled to -54°C and separated in a flash drum (S1). The inert gases (R3-1) are heated to ambient temperature and further heated against the hot flue gas in the boiler area and expanded in a gas turbine to recover the power, before being vented to the atmosphere. The liquid CO_2 (R2-1) provides necessary refrigeration by expanding and exchanging heat with other streams. Note that the liquid CO_2 is slightly heated before expansion in order to avoid ice formation. Stream R2-4 is compressed to 78 bar by a two-stage compressor with water intercooling. The compressed CO_2 is further cooled to 25°C by



RU1: The first stage of CO_2 compression process; RU2: The CO_2 purification process; RU3: The second stage of CO_2 compression process; RU4: The tail gas turbine; RU5: The vented inerts; (RU is short for Recovery Unit)

Figure 1: Flowsheet of the one-stage flash process

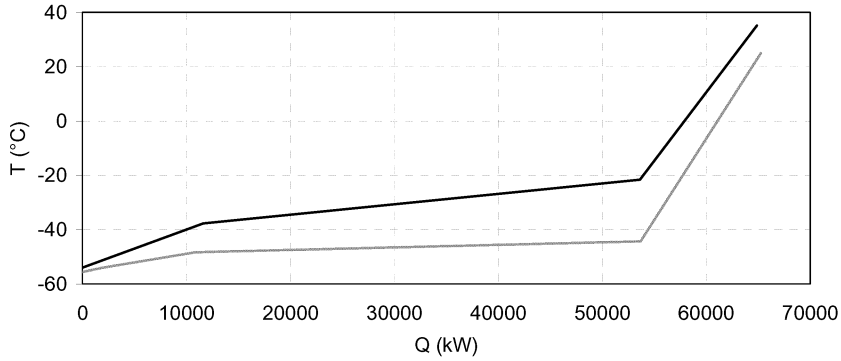


Figure 2: Composite curves of the main streams in the one-stage flash process

seawater. At this temperature and pressure, the CO_2 is in dense phase and pumped to 150 bar for transportation and saline formation storage.

Figure 2 shows the corresponding composite curves for the main streams. The minimum temperature difference is 1.5°C and it occurs in the cold end (-54/-55.5°C). The temperature difference between the hot and cold streams is larger than 10°C within the temperature range from -40°C to -20°C (for hot streams). This is a bit high for sub-ambient processes, thus causing large exergy losses in the sub-ambient heat exchangers. In order to reduce the irrversibilities, the CO_2 can be purified by double-stage flash.

2.2 The double-stage flash process

The double-stage flash process is commonly used in literature (Pipitone and Bolland, 2009), as shown in Figure 3. In this case, the CO_2 is compressed to 32 bar in the first stage of compression. After water removal, the CO_2 (R1-4) is cooled to -26°C and separated in the first flash drum (S1). The liquid CO_2 (R2-1) is expanded to 18 bar through a valve and heated to 25°C (R2-3). The vapor stream is further cooled to -54°C and separated in the second flash drum (S2). The inert gases (R5-1) are heated and

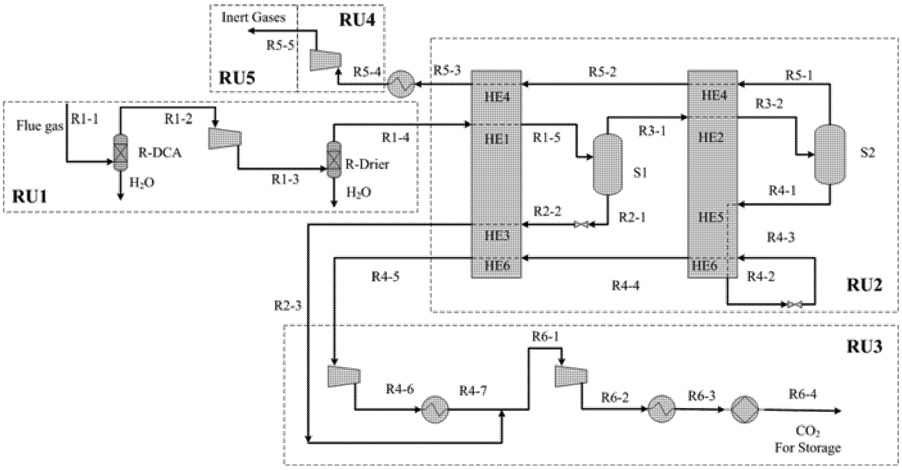


Figure 3: Flowsheet of the double-stage flash process

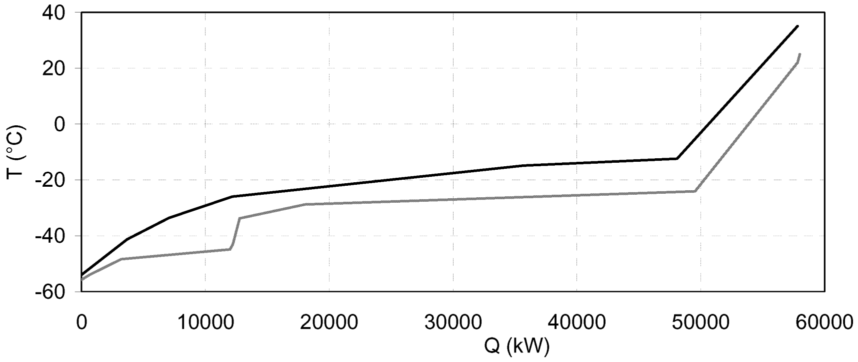


Figure 4: Composite curves of the main streams in the double-stage flash process

expanded to recover the cold energy and power. The liquid CO_2 (R4-1) is expanded and heated to provide necessary refrigeration. Stream R4-5 is compressed to the same pressure as stream R2-3 and cooled by cooling water. The two CO_2 streams are mixed (R6-1) and compressed to the desired state. The corresponding composite curves are shown in Figure 4. Compared with Figure 2, the temperature difference between the hot and cold streams becomes smaller, thus the irreversibilities are reduced. The exergy losses can be further reduced by a three-stage flash.

2.3 The three-stage flash process

A proposed three-stage flash process is shown in Figure 5. In this case, the CO_2 is compressed to 35.5 bar in the first stage of compression. The operating temperatures of the three flash drums (S1, S2, S3) are -16, -26 and -54 °C, and the liquid CO_2 from the bottoms of the flash drums is expanded to 26, 20 and 9 bar respectively. Figure 6 shows the composite curves in this case. Compared to the curves shown in Figure 4, the distance between the hot curve and the cold curve is reduced. Thus the exergy losses in the sub-ambient heat exchangers are further reduced, resulting in less work consumed in the CO_2 compressors.

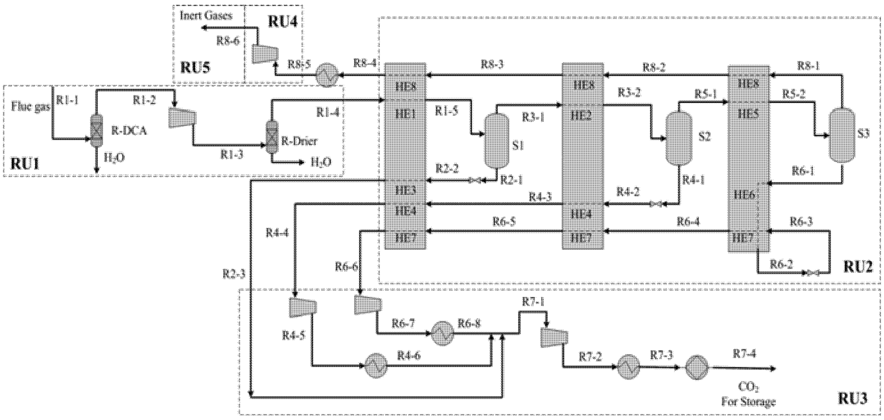


Figure 5: Flowsheet of the three-stage flash process

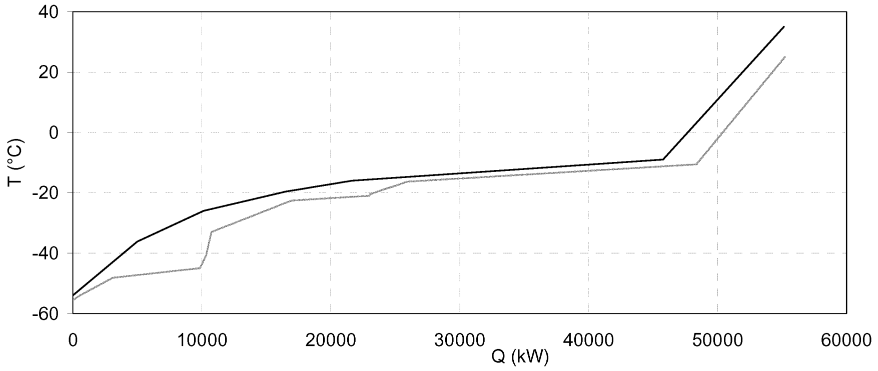


Figure 6: Composite curves of the main streams in the three-stage flash process

3. Plant performance

An exergy analysis (Hinderink *et al.*, 1996, Kotas, 1995) has been performed to investigate the exergy losses in the three processes, shown in Figure 7. The exergy losses are mainly caused by the first stage of CO_2 compression in the three cases. The irreversibilities in both the CO_2 purification process and the second stage of CO_2 compression are reduced in the three-stage flash process. The reason is that a portion of the CO_2 is expanded to a higher pressure level and, as a result, the temperature driving forces in the sub-ambient heat exchangers and the compression ratio of this portion in

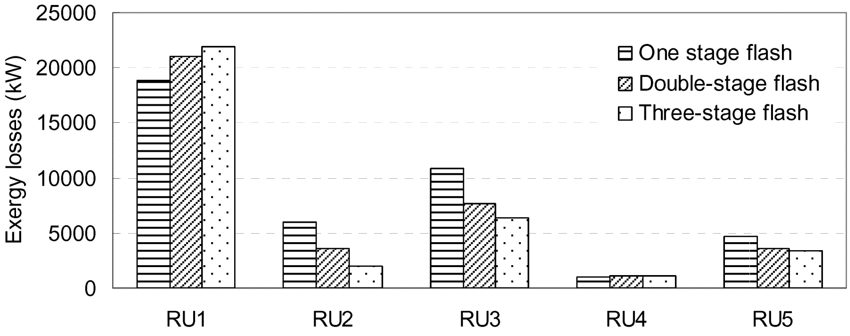


Figure 7: Exergy losses in the three studied processes

Table 1: Plant performance

Flash process	One-stage	Two-stage	Three-stage
CO_2 purity, mole %	96.3	96.3	96.3
CO_2 recovery rate, %	92.9	94.6	95.0
Power consumption, kW	71 585	69 265	67 638
Specific power consumption, kWh/kgCO_2	0.130	0.124	0.120

the second stage of CO_2 compression are reduced. The exergy losses in the CO_2 purification process are small, even though the sub-ambient heat exchangers are included. Thus the improvement by adding stages of flash may not be very attractive when also the investment cost is considered. The plant performance is listed in Table 1. Compared with the one-stage flash process, the specific power consumption has been reduced by 7.7% in the three-stage flash process. The main additional investment is two flash drums, two sub-ambient heat exchangers and two compressors.

4. Conclusion

The double-stage flash process is commonly used for conditioning CO_2 in oxy-coal combustion plants. The corresponding power efficiency penalty is around 3.6% points. The composite curves have been used to investigate the potential for improvements. The performance can be improved by adding one flash stage. The exergy losses in the sub-ambient heat exchangers and the second stage of CO_2 compression are reduced. Considering the one-stage flash process as the base case, the specific power consumption is reduced by 4.6% in the double-stage flash process and 7.7 % in the three-stage flash process. However, the investment cost will increase.

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