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Optimization of cryogenic CO_2 purification for oxy-coal combustion

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Abstract

Oxyfuel combustion is a leading potential CO_2 capture technology for power plants. As the flue gas (FG) consists of mainly H_2O and CO_2, a simpler and more energy-efficient CO_2 purification method can be used instead of the standard amine-based chemical absorption approach. For the system of oxyfuel combustion with cryogenic CO_2 purification, decreasing the oxygen purity reduces the energy consumption of the Air Separation Unit (ASU) but increases the energy consumption for the downstream cryogenic purification. Thus there exists a trade-off between the energy consumption of the ASU and that for cryogenic purification. This paper investigates the potential efficiency improvement by optimizing this trade-off. The simulated results show that there exists an optimum flue gas condensing pressure for the cryogenic purification, which is affected by the flue gas composition. In addition, decreasing the oxygen purity reduces the combined energy consumption of the ASU and the cryogenic purification, and therefore can improve the electrical efficiency. In summary, prior oxyfuel combustion analyses have assumed a high oxygen purity level of 95 mol% or 99 mol% for the combustion air, which achieves a high CO_2 concentration in the flue gases. In this Paper, we demonstrate that a lower level of oxygen purity, such as 80 mol%, in conjunction with a more extensive cryogenic purification of the flue gases can lower the total energy consumption, thereby yielding a significant benefit. However, for oxygen purity levels lower than 75 mol%, it may not be possible to still use the two-stage flash system shown here to achieve a CO_2 purity of 95 mol% and a CO_2 recovery rate of 90% simultaneously.

Keywords: CO_2 capture and storage (CCS), cryogenicpurification, oxy-coal combustion, CO_2 recovery rate, CO_2 purity, Oxygen purity, energy consumption

1. Introduction

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Oxyfuel combustion is a leading potential CO_2 capture technology. As the flue gas (FG) consists of mainly H_2O and CO_2, a simplified flue gas separation process, which is essential to achieve a high efficiency and a low cost for CO_2 capture, can be used instead of amine-based chemical absorption. Normally, high oxygen purity, such as 99 mol%, is applied in order to obtain high CO_2 purity (>95 mol%), which can reduce the amount of flue gas and further the power consumption of CO_2 compression and satisfy the requirements of CO_2 transportation and storage [1,2]. For such a technology, the major efficiency penalty caused by CO_2 capture comes from the air separation unit (ASU) and CO_2 compression and separation.

It is also possible to use low oxygen purity that can reduce the energy consumption of the ASU. However, a CO_2 purification process is then required to achieve the targeted level of 95 mol% CO_2 purity. Cryogenic separation is a common method for CO_2 purification [3-7], which has the advantages of a simple process and low energy consumption. For the system of oxyfuel combustion with cryogenic CO_2 purification, there exists a trade-off between the energy consumptions of ASU and the cryogenic purification. This paper investigates the potential efficiency improvement by optimizing the oxygen purity and the cryogenic purification.

Nomenclature

ASU	Air separation unit
CCS	CO_2 capture and storage
Comp	Compression
Cond	Condensation
FG	Flue gas
p_{cryo}	Power consumption of the cryogenic purification
T	Temperature

2. The Energy consumption of the ASU

The performance of the ASU has been simulated in Aspen Plus. The calculated results of the specific energy consumption have been shown in Fig 1 at different oxygen purities. The specific energy consumption rises linearly with the increase of oxygen purity linearly until the purity reaches 97 mol%. Then the variation of energy consumption is approximately exponential. Fig 1 also shows our results agree well with the literature data from [8-10].

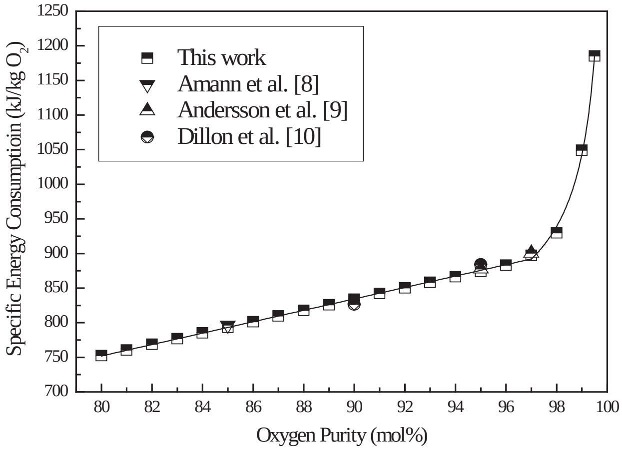


Figure 1 Energy consumption of ASU under different oxygen purities

3. Cryogenic purification

3.1. Flue gas CO_2 contents at different oxygen purities

Based on the simulation results of oxy-coal combustion, Fig 2 displays the CO_2 contents of flue gas (after water condensation) at different oxygen purities. It is obvious that the CO_2 content decreases when the oxygen purity drops. When the oxygen purity is higher or lower than 95 mol%, argon and nitrogen are the major impurities in the dry flue gas respectively. Meanwhile, the oxygen purity has to be higher than 98.5 mol% in order to achieve CO_2 purity larger than 95 mol% if only water condensation is included.

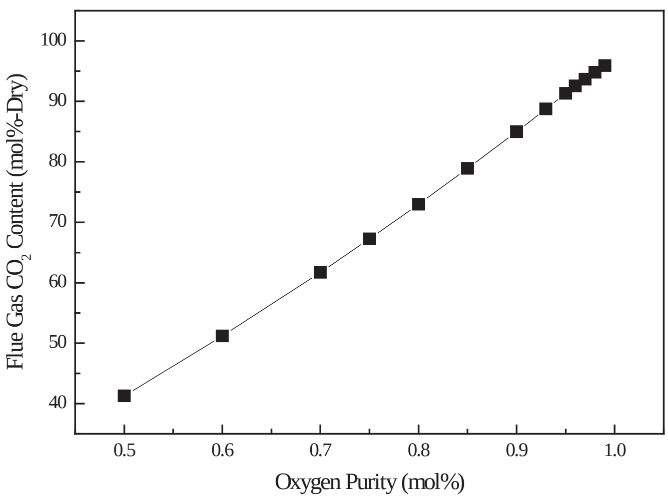


Figure 2 Flue gas CO_2 contents at different oxygen purities

3.2. Simulation of cryogenic purification

The system sketch of a two-stage flash cryogenic purification is shown in Fig 3. It mainly includes a FG compressor, two flash columns, two multi-flow heat exchangers and two CO_2 compressors. The cooling required by the FG condensation is provided by flashing down liquid CO_2 from a high pressure to low pressures in the two Flash Columns. In order to recover some compression work from the ventilated (mostly inert) gas stream, an expander is also included. A model was set up in Aspen Plus following the configuration of IEA [3,4] to simulate such a system. Simulations have been conducted under the same input used by IEA [3]. As indicated in Table 1, the results of our model agree broadly with the results from the references [3,4] and this represents a validation of our model.

Table 1 verification of the cryogenic purification model

	IEA [3]	Zanganeh et al.[4]	this work
CO_2 purity (v%)	95.8	95.7	96.6
Captured CO_2 ton/hr	441.9	443.2	447
recovery ratio %	90.4	91.03	91.82
Net power consumption MWe	64.7	60.48	60.27
Power consumption deviation from IEA result		6.5%	6.8%

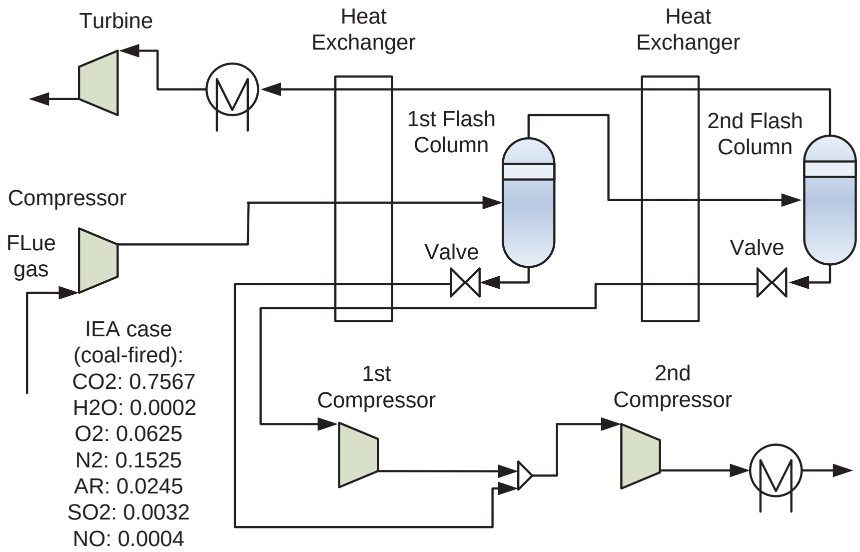


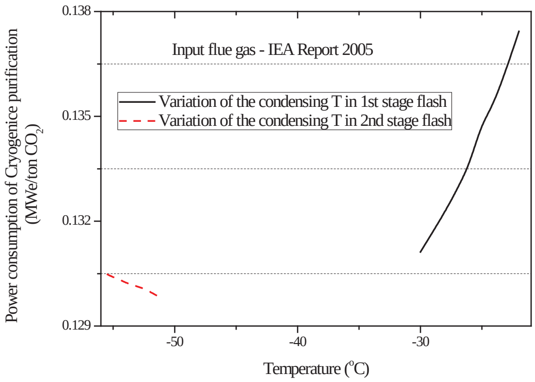
Figure 3 System sketch of the cryogenic purification

3.3. System optimization

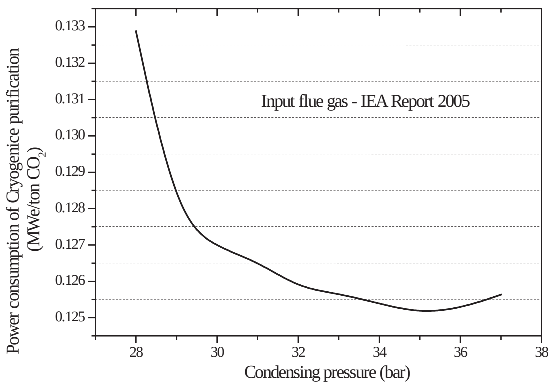
In this paper, the optimization work was conducted under the prerequisites that the CO_2 recovery rate and the CO_2 purity are equal to or larger than 90% and 95 mol% respectively.

There are three important parameters which can affect the performance of cryogenic purification: the condensing temperatures in the 1st and 2nd stage flash ($T_{1\text{-}cond}$ and $T_{2\text{-}cond}$) and the condensing pressure. The variation in the power consumption for the cryogenic purification (p_{cryo}) with certain changes in the condensing temperatures and pressure are presented in Fig 4.

Fig 4(a) shows that p_{cryo} declines with the drop of $T_{1\text{-}cond}$ while the rise of $T_{2\text{-}cond}$. $T_{1\text{-}cond}$ determines the mass flow passing the 1st stage compressor (Comp1). At a lower $T_{1\text{-}cond}$, less power is consumed by the first compressor as less FG goes into Comp1. $T_{2\text{-}cond}$ determines the total mass flow of the recovered CO_2. At a higher $T_{2\text{-}cond}$, less CO_2 is recovered which implies a lower power consumption of CO_2 compression. Fig 4(b) shows the impact of the condensing pressure. There exists an optimum value for cryogenic purification. Increasing the condensing pressure will allow the CO_2 to condense at higher temperatures. In addition, increasing the liquid CO_2 expansion pressure can increase the temperature of coolant in the heat exchangers. As the minimum temperature difference of heat transfer has been assumed as a constant, it implies at a higher condensing pressure corresponds to a higher liquid CO_2 expansion pressure. Therefore, less work is required by the CO_2 compressors. However, increasing the condensing pressure can increase the compression work consumed by the FG compressor and lower the captured CO_2 purity and increase the mass flow, which will increase the overall CO_2 compression work. Moreover, the optimum condensing pressure varies with the FG composition.



(a)



(b)

Figure 4 the power consumption at different condensing temperatures and pressures

Figure 5 shows that the energy consumption for cryogenic purification for capturing 1 ton CO_2 from the flue gas of oxy-coal combustion. This energy consumption increases with the decrease of the oxygen purity. At lower oxygen purities, colder condensing temperatures and higher condensing pressures are required to achieve the required 95 mol% purity of CO_2. Therefore higher energy consumption levels are implied. Figure 5 also shows the total energy consumption, being the sum of that for the ASU and that for the cryogenic purification. In contrast to the energy needed for the cryogenic purification, the total energy consumption decreases with lower levels of oxygen purity. For example, if the oxygen purity is decreased from 90 mol% to 80 mol%, the system electrical efficiency can be improved by about 1% of coal lower heating value. It demonstrates that the ASU has a larger effect than the cryogenic purification in the system of oxy-coal combustion system. In part this is because the energy consumption for the ASU is high (about 200-250 kWh/ton O_2), while that for the cryogenic purification step is lower (about 120-140 kWh/ton CO_2). An intuitive explanation of this result is that the cryogenic separation of air to obtain oxygen requires very cold temperatures indeed (well below -150 ^oC), while the cryogenic separation of CO_2 requires temperatures that are much less cold (in the range of -30 ~ -55 ^oC for the two Flash Columns). In accepting a lower oxygen purity from the ASU, we are shifting from a process that requires temperatures of well below -150 ^oC to one that requires a blended average of just -40 ^oC. Although the CO_2 cryogenic purification stage does require higher pressures, the important thing to recognise that within the context of the overall system (which requires high purity CO_2 at 110 bar for pipeline transport), this does not impose much of an incremental cost. We consider this to be a constructive and practical insight, which should allow for more energy efficient capture of CO_2 from power plants.

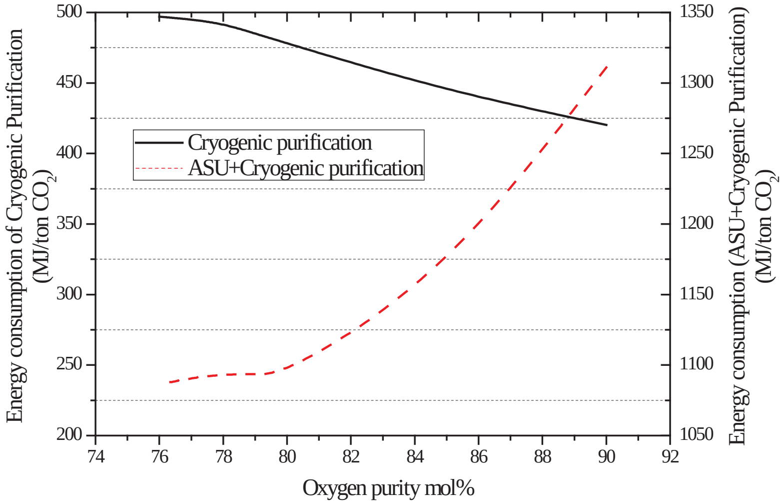


Figure 5 the energy consumption of ASU and cryogenic purification for capturing 1 ton CO_2

4. Discussions

Fig 5 shows the potential energy reduction from reducing the oxygen purity in an oxy-coal combustion system with cryogenic purification. However, it was also found that at oxygen purity levels below 75 mol%, the CO_2 concentration in the flue gases may decline to below 66 mol% (after water condensation). At this CO_2 concentration it appears to be no longer possible to use the two-stage flash system shown in Fig 3 to achieve a CO_2 purity of 95 mol% and a CO_2 recovery rate of 90% simultaneously. If more stages of flash would be applied, the energy consumption may change differently, which should be further investigated.

5. Conclusions

For the system of oxyfuel combustion with cryogenic CO_2 purification, decreasing the oxygen purity reduces the energy consumption of the ASU but increases the energy consumption for the cryogenic purification, thereby creating a trade-off between the energy consumptions of ASU and the cryogenic purification. Based on the simulated results, it can be concluded that (i) for the cryogenic purification applied in oxy-fuel combustion, there exists an optimum flue gas condensing pressure, which is affected by the flue gas composition that further depends on the oxygen purity produced by ASU; (ii) decreasing the oxygen purity reduces the total energy consumption of ASU and the cryogenic purification and therefore, can reduce the efficiency penalty caused by CO_2 capture. For example, decreasing the oxygen purity from 90 mol% to 80 mol% can improve the system electrical efficiency by about 1% of the coal lower heating value with CO_2 recovery rate of 90% and a CO_2 purity of 95 mol%.

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