Compression power requirements for Oxy-fuel CO$_2$ streams in CCS

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Abstract. CO$_2$ compression systems are commonly designed assuming negligible amount of impurities in CO$_2$ fluid, it is of practical interest to evaluate the impact of impurities in oxy-fuel streams on the compression power requirements. Compared to more traditional post-combustion and pre-combustion capture methods, oxy-fuel technology produces a CO$_2$ stream with relatively high concentration of impurities that may require partial or a high level of removal and whose presence can be expected to increase the costs of CO$_2$ compression. Four types of compression technologies employed include four-stage compressor with 4 intercoolers, single-stage supersonic shockwave compressor, three-stage compressor combined with subcritical liquefaction and pumping and three-stage compressor combined with supercritical liquefaction and pumping. The study depicts that decrement of the impurities content from 15 to 0.7%/v in the CO$_2$ streams reduced the total compression power in the compression system. The study also concludes that three-stage compressor combined with subcritical liquefaction and pumping can potentially offer higher efficiency than four-stage compressor with 4 intercoolers for almost pure CO$_2$ streams. In the case of raw oxy-fuel mixture, that carries relatively large amount of impurities, subcritical liquefaction proved to be less feasible, while supercritical liquefaction efficiency is only marginally lower than that in the four-stage compressor with 4 intercoolers.

1. Introduction

In future Carbon Capture and Sequestration (CCS) projects, CO$_2$ captured from large industrial emission sources will be purified and compressed for long-term sequestration in geological formations. Pipelines offer the most economically viable option for moderate and long distance transportation of large quantities of CO$_2$. In order to ensure single-phase transportation of CO$_2$ via pipelines, the pipeline pressures need to be maintained in the range from 85 to 150 bar [1], i.e. above the critical pressure of the fluid, which in case of pure CO$_2$ is 73 bar. At such pressures the fluid can be either in dense-phase state, at temperatures below the pseudo-critical temperatures (the temperature at which the heat capacity reaches its maximum) or in supercritical phase at temperatures above the pseudo-critical temperatures. With the increase in the fluid pressure and decrease in the temperature, the fluid compressibility and specific volume decrease, making the CO$_2$ pipeline transportation more...
economically efficient for dense-phase liquid CO$_2$. In order to compress CO$_2$ gas to the dense-phase state, several options have been previously analysed for pure CO$_2$ [2]. In particular, multistage compression combined with liquefaction and subsequent pumping of liquid phase CO$_2$ was found to be more efficient than conventional gas phase compression. This becomes practically possible in case of pure CO$_2$ due to its relatively high boiling point (ca. 20 $^\circ$C at 60 bar pressure), which allows using utility streams for liquefaction; also, pumping of a liquid is less energy demanding than gas-phase compression [3]. In case of industrial grade CO$_2$ stream, the boiling point of the liquid can either be increased or decreased depending on the nature and amount of impurities present in the CO$_2$ fluid. However, the impact of stream impurities on the CO$_2$ compression is not clear.

This paper evaluates the impact of impurities from oxy-fuel capture technology on power consumptions for compression options previously recommended by [3] for pure CO$_2$.

In the present study, the content and amount of impurities in CO$_2$ streams captured using oxy-fuel technology have been identified by Porter et al. [4]. Impure components present in CO$_2$ stream determine the thermodynamic and phase equilibrium properties of the fluid, and hence may significantly affect the power requirements for compression and pipeline transportation. In particular, density and compressibility are two properties which determine the compression work and both depend on the amount and concentration of impurities in CO$_2$ fluid [5]. Also, the power requirements for liquefaction of CO$_2$ stream largely depend on the vapour-liquid equilibrium of CO$_2$ mixtures.

Our preliminary analysis showed that impurities listed in Porter et al. [4] which amount does not exceed 0.1% v/v have no significant impact on the thermo-physical properties relevant for compression/transportation of CO$_2$ fluid. Therefore, for the purpose of the present study, the average of concentration of each component is calculated from Porter et al. [4] within the given range. To investigate the highest possibility of the effect of impure components, the composition of impure CO$_2$ from raw/dehumidified, double flashing and distillation purification processes from oxy-fuel are adopted in this study as shown in table 1.

**Table 1.** Composition of CO$_2$ streams captured from oxy-fuel combustion technology [4].

| Component (%) v/v | CO$_2$ | O$_2$ | N$_2$ | Ar | NO$_2$ | SO$_2$ | SO$_3$ | H$_2$O | CO |
|-------------------|--------|--------|--------|----|--------|--------|--------|-------|-----|
| Raw/dehumidified  | 85     | 4.70   | 5.80   | 4.47 | 0.0100 | 0.0050 | 0.002  | 0.010 | 0.0050 |
| Double flashing   | 96.70  | 1.20   | 1.60   | 0.40 | 0.0150 | 0.0036 | -      | -     | -   |
| Distillation      | 99.30  | 0.40   | 0.20   | 0.10 | 0.0033 | 0.0037 | -      | -     | -   |

In this study, in order to predict physical properties of CO$_2$ mixtures involved in equations (2) and (4), the Peng-Robinson Equation of State (PR EoS) with standard mixing rules in REFPROP package is applied as one of the simplest and accurate equations developed for CO$_2$ mixtures [6]. As discussed earlier, the presence of impure components in CO$_2$ stream can change the thermodynamic properties, affecting the compression work and cooling power requirements for impure CO$_2$.

2. Methodology

The thermodynamic analysis of the N-stage compression with intercooling involves calculating the total power consumed by compression:

$$W_{\text{Comp}} = \sum_{i=1}^{N} \frac{G}{\eta_{\text{comp},i}} \int \left( \frac{dp}{p \rho} \right)$$

(1)

$$W_{\text{Comp}} = G \sum_{i=1}^{N} \frac{1}{\eta_{\text{comp},i}} (h_i^{\text{out}} - h_i^{\text{in}})$$

(2)

where $W_{\text{Comp}}$, $G$, $\eta_{\text{comp}}$, $h_i^{\text{in}}$ and $h_i^{\text{out}}$ are the compression work, mass flow rate, isentropic compression efficiency, enthalpy at compressors’ inlet and discharge, respectively.

And the total power required for removing heat from the flow at the intercooling stages:
where $Q_{\text{cool}}$ is the total cooling duty associated with removing heat from the compressor and $W_{\text{cool}}$ is the power demand for cooling/liquefaction while $\eta_{\text{cool}}$, $T_{\text{cond}}$ and $T_{\text{ev}}$ are respectively the heat transfer efficiency of the isobaric cooling process, condensation and evaporation temperatures.

Using equations (2) and (3) implies knowledge of the fluid thermodynamic properties, namely density and enthalpy of CO$_2$ mixtures. These properties are calculated using REFPROP package [7].

The integral in equation (1) defines the compression work done on the fluid which is valid irrespective of the fluid phase state, and hence can be applied to evaluate compression work for the gas and pumping for the liquid.

3. Results and discussion

Results of calculations of the power consumed in the multistage compression of pure and impure CO$_2$ streams are presented in this section. The study is performed for impure CO$_2$ streams with the compositions described in table 1 and available compression technology options. To enable cross-comparison of compression power for the various compression technologies and various CO$_2$ mixtures, the stream conditions at the inlet and discharge of compressor are kept identical in all the cases studied. In particular, at the inlet of compressor, the pressure and temperature are set to 15 bar and 38 $^\circ$C, while the compressor discharge pressure is set to 151 bar with the discharge temperature is depending on the compression option applied. The 15 bar inlet pressure is chosen as typical value corresponding to pressure of CO$_2$ stream coming from oxy-fuel capture unit [8]. Following the study by Witkowski et al. [9], the compressors and inter-stage coolers’ efficiencies are set to $\eta_{c,i} = \eta_{h,i} = 0.75 - 0.85$ with the streams’ mass flow rate of 156.4 kg/s.

3.1. Adaptation of industrial compressor options of impure CO$_2$

Figures 1-4 show the compression pathways plotted in pressure-enthalpy phase diagrams of pure CO$_2$ and impure CO$_2$ mixtures, for the four-stage compressor with 4 intercoolers (option A), single-stage supersonic shockwave compressor (option B), three-stage compressor combined with subcritical liquefaction/refrigeration and pumping (option B) and three-stage compressor combined with supercritical liquefaction and pumping (option D), respectively.
Figure 1. Pressure-enthalpy diagrams for compression of pure CO$_2$ (a), raw/dehumidified (b), double flashing (c) and distillation (d) from oxy-fuel captures using compression option A (dashed lines).

Figure 1 presents the application of the conventional multistage compression to the pure CO$_2$ and oxy-fuel mixtures. In this case, the compression ratio for each stage is set to 1.78 with the CO$_2$ streams entering the compressor at 15 bar that corresponds to typical pressure level at the exit of oxy-fuel capture unit [8].

Figure 2. Pressure-enthalpy diagrams for compression of pure CO$_2$ (a), raw/dehumidified (b), double flashing (c) and distillation (d) from oxy-fuel captures using compression option B (dashed lines).

Figure 2 shows the compression pathways in pressure-enthalpy diagrams the option B achieved using the supersonic shockwave compressor with the compression ratio of 10 per stage. In this case, only single-stage compression is applied to compress the pressure from 15 bar to 151 bar discharge pressure. The constant pressure intercooling is used to reduce the temperature after the compression from ca. 267-295 °C back to the inlet temperature of 38 °C, respectively.
Figure 3. Pressure-enthalpy diagrams for compression of pure CO$_2$ (a), raw/dehumidified (b), double flashing (c) and distillation (d) from oxy-fuel captures using compression option C (dashed lines).

In figure 3, the compression pathways are shown for the compression option C, which integrates the three-stage compressor with pumping following liquefaction of CO$_2$ stream at subcritical temperature. In this study, the liquefaction pressure is set to 62 bar for CO$_2$ streams, while the liquefaction temperature is determined by the bubble point temperature of the fluid at this pressure:

Pure CO$_2$: $T_{liq} = 20 ^\circ C$

Oxy-fuel mixture:
Raw/dehumidified with 85 % v/v: $T_{liq} = -45 ^\circ C$
Double flashing with 96.7 % v/v: $T_{liq} = 14 ^\circ C$
Distillation with 99.9 % v/v: $T_{liq} = 19 ^\circ C$

In case of raw/dehumidified stream with 85 % v/v of CO$_2$ purity, liquefaction would require using cryogenic coolants, increasing significantly the cost of the whole process.
Figure 4. Pressure-enthalpy diagrams for compression of pure CO$_2$ (a), raw/dehumidified (b), double flashing (c) and distillation (d) from oxy-fuel captures using compression option D (dashed lines).

Figure 4 shows the compression pathways in case of compression option D, where the three-stage compressor is combined with supercritical liquefaction and pumping. In this option, the liquefaction cooling is applied at 85 bar, 15 °C for pure CO$_2$ and impure from double flashing and distillation oxy-fuel captures and 110 bar, 5 °C for raw/dehumidified CO$_2$ stream.

### 3.2. CO$_2$ compression power requirements

Table 2 shows the results of total power consumption in terms of compression and intercooling power as required for the multistage compression options A, B, C and D.

| CO$_2$ (% v/v) | Compression technology options | A     | B     | C     | D     |
|---------------|--------------------------------|-------|-------|-------|-------|
|               | Pure CO$_2$                     | 100   | 29674 | 35273 | 20508 | 24340 |
| Oxy-fuel:     | Raw/dehumidified               | 85    | 34512 | 37867 | 23128 | 29012 |
|               | Double flashing                 | 96.7  | 31092 | 35825 | 21661 | 24829 |
|               | Distillation                    | 99.3  | 30029 | 35383 | 20860 | 24438 |
|               | Intercooling work (kW)          | Pure CO$_2$ | 100   | 10750 | 51649 | 12869 | 16208 |
| Oxy-fuel:     | Raw/dehumidified               | 85    | 11163 | 54883 | 43646 | 21395 |
|               | Double flashing                 | 96.7  | 11055 | 54753 | 13357 | 16574 |
|               | Distillation                    | 99.3  | 10825 | 54232 | 13120 | 16504 |
|               | Total power = compression + intercooling work (kW) | Pure CO$_2$ | 100   | 40424 | 86922 | 33377 | 40548 |
| Oxy-fuel:     | Raw/dehumidified               | 85    | 45675 | 92750 | 66774 | 50407 |
|               | Double flashing                 | 96.7  | 42147 | 90578 | 35018 | 41403 |
|               | Distillation                    | 99.3  | 40854 | 89615 | 33980 | 40942 |

As shown in table 2 for pure CO$_2$, compression work is largest in case of single-stage supersonic shock wave compression (option B). This can be explained by higher compression ratios (10:1) applied compared to the other options. Data from table 2 also show that the cooling duty is also largest in case of option B, which is due to the significant increase in the temperature at the discharge of the compressor in this case of 285 °C compared to the relatively low discharge temperatures in the other compression options (90 °C). Applying liquefaction as can be expected reduces the compression work, but increases the energy spend on intercooling (compare options C and D with A).
As can be seen from Table 2, the presence of impure components in CO₂ stream affects both the compression power and cooling requirements for multistage compression. In particular, the compression work and intercooling work rise as concentration of impurities increase. The rising demand of compression work is related to the changes of bubble point curves for that CO₂ stream. For options C and D, the intercooling work increases as liquefaction temperature declines from 20 to -45 °C. This is because the coefficient of performance (COP) of refrigerator decreases and the required energy level of the heating steam increase as the liquefaction temperature drop [10]. In case of option B, increasing the impurities in the stream requires enormous amount of power to cool down the system to acceptable level due to high compression ratio applied. Importantly, the subcritical compression technology (option C) is more economically efficient than other options, resulting with lower total power consumption for the mixtures with low concentration of impure components (< 3.3 % v/v). The total power consumption required for oxy-fuel distillation with 99.3 % v/v CO₂ is about the same compared with pure CO₂ for all compression strategies applied.

4. Conclusions

The present study describes the result analysis of the impact of impurities from oxy-fuel capture technology on the compression power requirements for CO₂ pipeline transportation. The study compares various compression technologies including the four-stage compressor with 4 intercoolers, single-stage supersonic shockwave compressor and three-stage compressor combined with liquefaction and pumping. The results of this study indicate the presence of impurities show significant impacts on compression and intercooling work. In particular, the CO₂ stream from raw/dehumidified presents considerably different total power consumption, in comparison to double flashing and distillation processes. It was found that the compression power is increased by 7-19 % more than that for the compression of pure CO₂, while for intercooling power, the demand can be up to 32 % for streams with impurities less than 3.3 % v/v. In case of raw dehumidified stream with 15 % v/v of impurities, the intercooling power was found nearly 2 times higher than intercooling power of pure CO₂. From this study, the integration of multistage compression with liquefaction and pumping can greatly decrease the compression power as compared to all compression options. However, further declines of liquefaction temperature will reflect the intercooling work with increase the energy consumption. In case of single-stage supersonic shockwave compressor, the highest total power consumption is observed due to high compression ratio applied.

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References

[1] Lemontzoglou A, Pantoleontos G, Asimakopoulou A G, Tsongidis N I and Konstandopoulos A G 2017 Int. J. Greenh. Gas Con. 66 10-24
[2] Moore J J, Lerche A, Delgado H, Allison T and Pacheco J 2011 The 40th Turbomachinery Symposium 107–20
[3] Witkowski A and Majkut M 2012 Arch. Mech. Eng. 3 1–18
[4] Porter R T J, Fairweather M, Pourkashani an M and Woolley R M 2015 Int. J. Greenh. Gas Con. 36 161–74
[5] Chima O and Dmitriy K 2018 Appl. Energy 230 816–35
[6] Mahmoud N, Chapoy A, Burgass R and Tohidi B 2017 J. Chem. Thermodyn. 111 157-72
[7] Goos E, Riedel U, Zhao L and Blum L 2011 Energy Procedia 4 3778–85.
[8] Gusca J and Blumberga D 2011 Energy Procedia 4 2526–32
[9] Witkowski A, Rusin A, Majkut M, Rulik S and Stolecka K 2013 Energy Convers. Manag. 76 665–73
[10] Duan L, Chen X and Yang Y 2013 Int. J. Energy Res. 37 1453–64
[11] Martynov S B, Daud N K, Mahgerefteh H, Brown S and Porter R T J 2016 Int. J. Greenh. Gas Con. 54 652-61