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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/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 ºC 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].

Oxy-fuel combustion	Component (% v/v)								
	CO_2	O_2	N_2	Ar	NO_2	SO_2	SO_3	H_2O	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:

$$W_{Comp} = \sum_{i=1}^{N} \frac{G}{\eta_{comp,i}} \int_{P_i^{in}}^{P_i^{out}} \left(\frac{dp}{\rho} \right)_s \tag{1}$$

$$W_{comp} = G \sum_{i=1}^{N} \frac{1}{\eta_{comp,i}} \left(h_i^{out} - h_i^{in} \right) \tag{2}$$

where W_{comp}, G, η_{comp}, h_{in}^i and h_{out}^i 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:

$$Q_{cool} = G \sum_{i=2}^{N} \left(h_{i-1}^{out} - h_i^{in} \right) \tag{3}$$

$$W_{cool} = \frac{Q_{cool}}{\eta_{cool}} \left(\frac{T_{cond} - T_{ev}}{T_{ev}} \right) \tag{4}$$

where Q_{cool} is the total cooling duty associated with removing heat from the compressor and W_{cool} is the power demand for cooling/liquefaction while η_{cool}, T_{cond} and T_{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 °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 $\eta_{c,i}=\eta_{h,i}=075-0.85$ with the streams' mass flow rate of 156.4 kg/s.

3.1. Adaptation of industrial compressor options of impure CO_2.
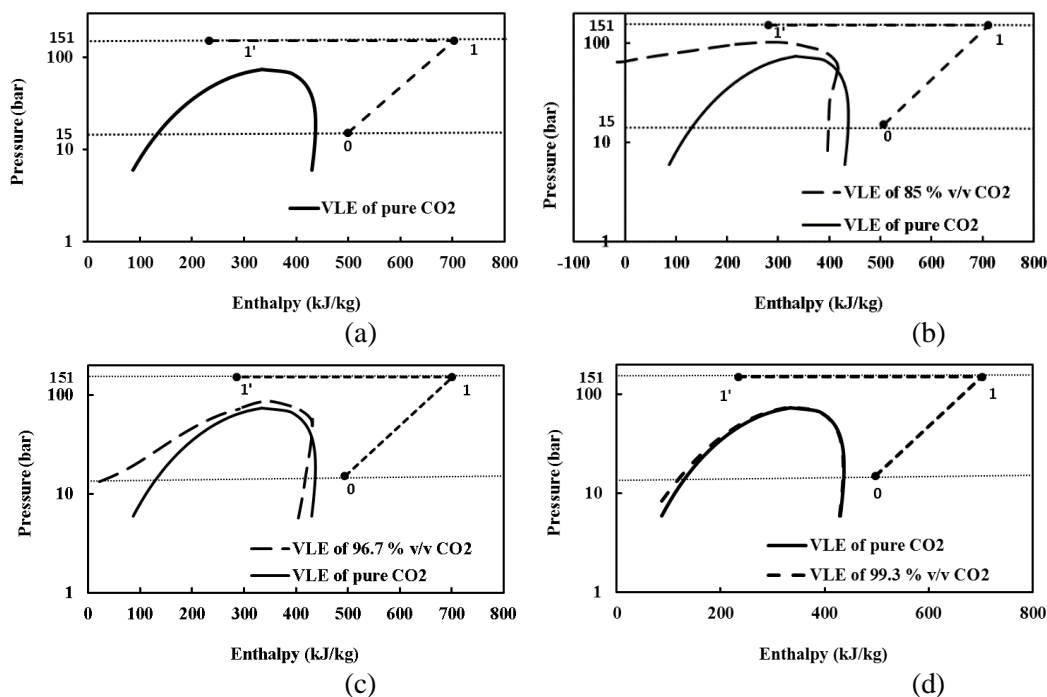
Figures 1-4 show the compression pathways plotted in pressure-enthalpy phase diagrams of pure CO_2 and impure CO_2 mixtures, for the four-stage compressor with 4 intercoolers (option A), single-stage supersonic shockwave compressor (option B), three-stage compressor combined with subcritical liquefaction/refrigeration and pumping (option B) and three-stage compressor combined with supercritical liquefaction and pumping (option D), respectively.
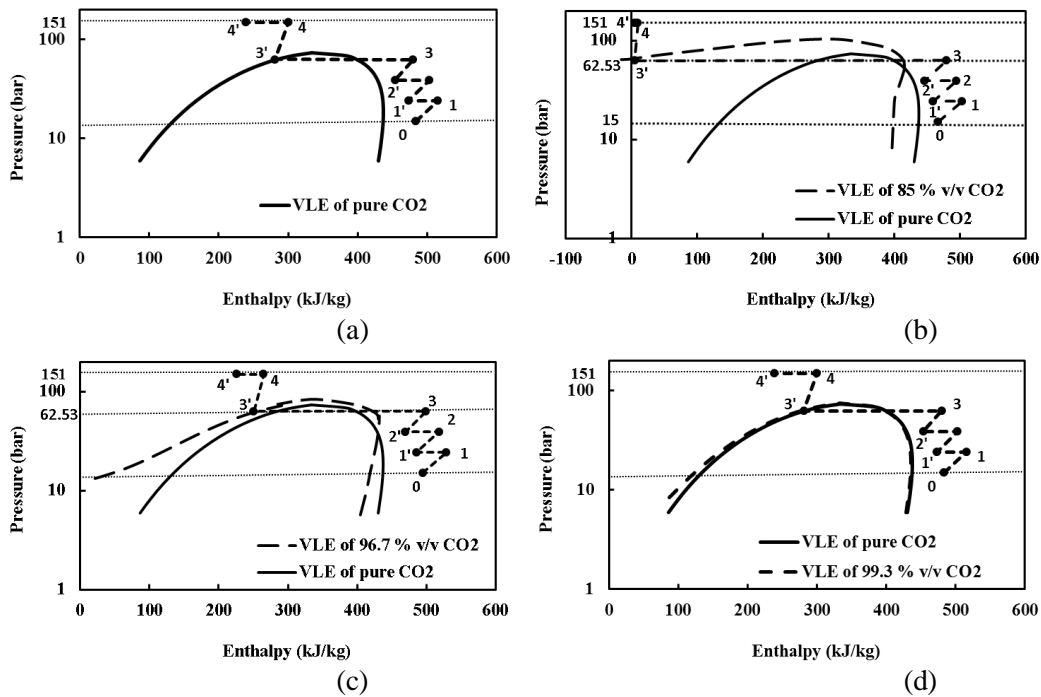

(a)   (b)

(c)   (d)
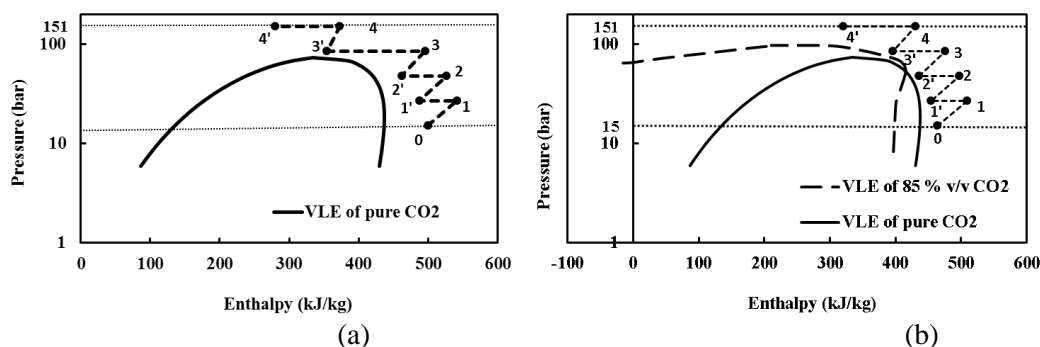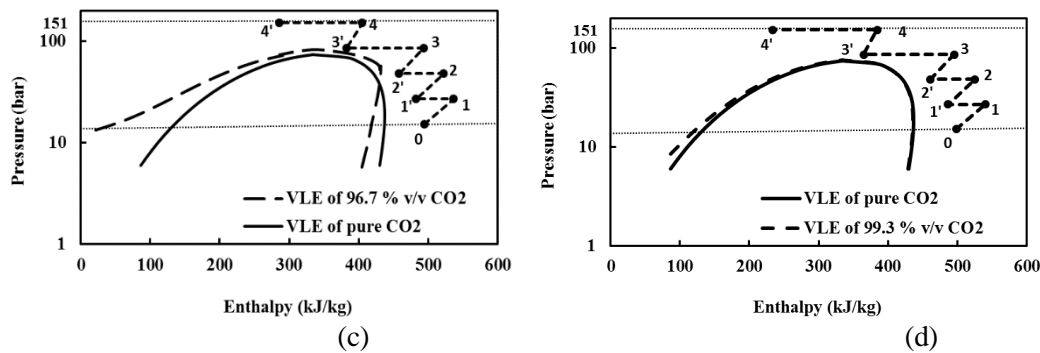
Figure 1. Pressure-enthalpy diagrams for compression of pure CO_2 (a), raw/dehumidified (b), double flashing (c) and distillation (d) from oxy-fuel captures using compression option A (dashed lines).

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 enter the compressor at 15 bar that corresponds to typical pressure level at the exit of oxy-fuel capture unit [8].

(a)   (b)

(c)   (d)

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 $^{\circ}$C back to the inlet temperature of 38 $^{\circ}$C, respectively.

(a)

(b)

(c)

(d)

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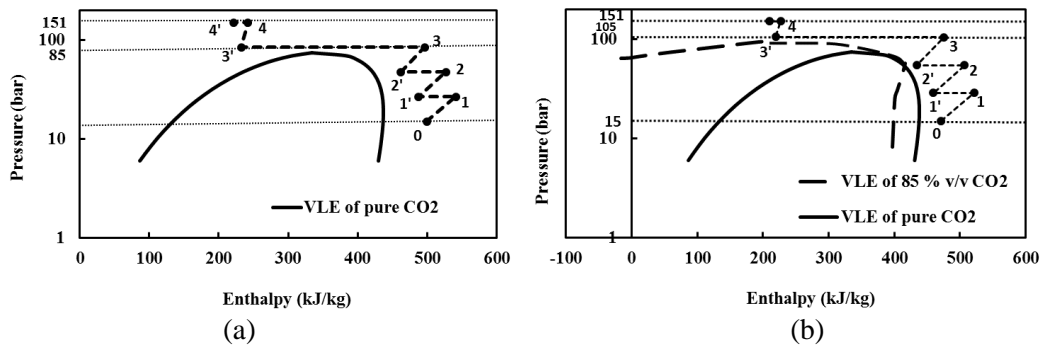Raw/dehumidified with 85 % v/v: T_{liq} = -45 °C
Double flashing with 96.7 % v/v: T_{liq} = 14 °C
Distillation with 99.9 % v/v: T_{liq} = 19 °C

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.

(a)

(b)
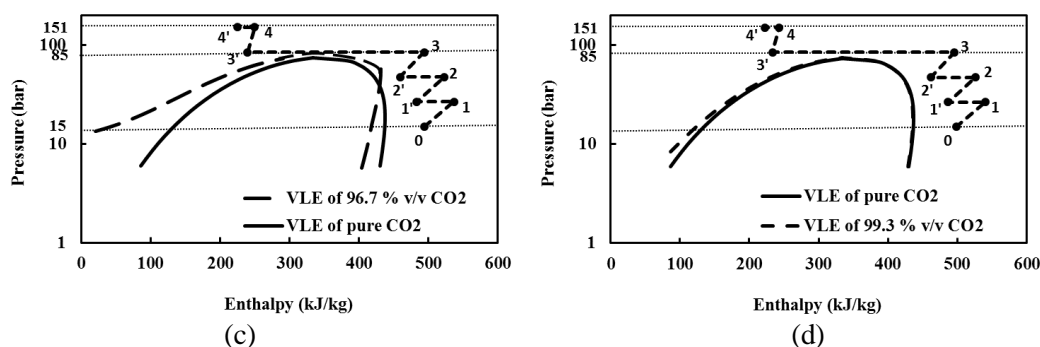
Figure 4. Pressure-enthalpy diagrams for compression of pure CO_2 (a), raw/dehumidified (b), double flashing (c) and distillation (d) from oxy-fuel captures using compression option D (dashed lines).

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.

Table 2. Power consumption for the compression technology options employed.

	CO_2 (% v/v)	Compression technology options			
		A	B	C	D
		Compression power (kW)			
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 CO_2 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 CO_2 streams. For options C and D, the intercooling work increases as liquefaction temperature declines from 20 to - 45 ^{o}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 CO_2 is about the same compared with pure CO_2 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 CO_2 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 CO_2 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 CO_2, 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 CO_2. 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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