PAPER • OPEN ACCESS

Investigations on power requirements for industrial compression strategies for Carbon Capture and Sequestration

To cite this article: N K Daud *et al* 2019 *J. Phys.: Conf. Ser.* **1349** 012010

Investigations on power requirements for industrial compression strategies for Carbon Capture and Sequestration

N K Daud[a]*, N Nasuha[b], S Martynov[c] and H Mahgerefteh[d]

[a]Faculty of Chemical Engineering & Natural Resources, Universiti Malaysia Pahang, Lebuhraya Tun Razak, 26300 Gambang, Pahang, Malaysia
[b]Faculty of Chemical Engineering, Universiti Teknologi MARA, Cawangan Pulau Pinang, Kampus Permatang Pauh, 13500 Permatang Pauh, Pulau Pinang
[c,d]Department of Chemical Engineering, University College London, London WC1E7JE

* khonisah@ump.edu.my

Abstract. The main purpose of this study is to identify the optimum multistage compression strategies for minimising the compression and intercooler power requirements for pure CO_2 stream. An analytical model based on thermodynamics principles is developed and applied to determine the power requirements for various compression strategies for pure CO_2 stream. The compression options examined include conventional multistage integrally geared centrifugal compressors (option A), supersonic shockwave compressors (option B) and multistage compression combined with subcritical (option C) and supercritical liquefaction (option D) and pumping. In the case of determining the power demand for inter-stage cooling and liquefaction, a thermodynamic model based on Carnot refrigeration cycle is applied. From the previous study by [1], the power demand for inter-stage cooling duty was assumed to have been neglected. However, based on the present study, the inter-stage cooling duty is predicted to be significantly higher and contributes approximately 30% of the total power requirement for compression options A, C and D, while reaches 58% when applied to option B. It is also found that compression option C can offer higher efficiency than other compression strategies, while supercritical liquefaction efficiency is only marginally higher than that in the compression option A.

1. Introduction

Carbon Capture and Sequestration (CCS) has been proposed as a promising technology for mitigating the impact of CO_2 emissions from manufacturing industry and power generation sources, such as coal-burning power plants, on global warming [2]. A fundamental part of the CCS chain is the transportation of CO_2 captured from emitters to locations of geological sequestration. Long-distance onshore transportation of large quantities of CO_2 can be most efficiently achieved using pipelines transmitting CO_2 in the dense-phase at pressures typically above 86 bar [3], i.e. above the fluid critical point pressure [4]. Given the relatively low pressure of captured CO_2 [5], the pipeline transportation would require additional facilities for compression of the stream.

The cost of CO_2 compression is however significant and may be up to 8-12 % of the electricity generated [3]. In addition, the available conventional CO_2 compression system is so expensive which requires stainless steel construction in the presence of water vapour and applies the aerodynamic design practice that limits the stage pressure ratio on heavier gas such as CO_2 [6]. For these reasons, the development of efficient schemes for the compression and conditioning of CO_2 prior to its transportation by pipeline, and integration of these schemes within CCS, is an important practical issue, which is attracting increasing attention [6], [7], [8], [9]. Furthermore, several studies have examined the opportunities for integration of the compression in CCS and the power generation process. [5] investigated coupling CO_2 compression with the organic Rankine cycle to re-utilise the heat of compression in power plant operation, showing that the energy requirements can be reduced by *ca.* 17 and 30 % for conventional and shockwave compression, respectively. Also, [7] has shown that utilising the heat from the intercooling process in the preheating section of steam cycle can give *ca.* 40 % savings in compression power. [10] proposed integrating CO_2 compression with the liquefaction using ammonia absorption refrigeration system powered by the exhaust heat from steam turbines in coal-fired power plant, that proved to greatly reduce the power consumed in CO_2 compression. [8] has analysed various options for conditioning of CO_2 streams, suggesting using expansion of a fraction of compressed CO_2 as a refrigerant in a condenser column for removing volatile components. These findings provide relevant data and act as a benchmark since they exemplify how various industrial compression strategies can be integrated in the CCS system for near pure CO_2 streams.

In particular, [1] and [6] have quantified the power demands for various industrial CO_2 compression systems, including conventional 8-stage integrally geared centrifugal compression, advanced supersonic shockwave compression and multistage compression combined with subcritical or supercritical liquefaction and pumping. The authors found that total compression power was not only determined by the compressor efficiency but is a strong function of thermodynamic process. While these studies quantified power requirements for industrial compression of CO_2, their practical application is, however, limited due to the underlying assumption of negligibly small amount of inter-stage cooling duty in CO_2 total compression power.

In this paper, a rigorous thermodynamic model is applied to compute and compare power consumption in terms of compression and inter-stage cooling power for different compression options of pure CO_2 stream. The analysis is performed assuming compression of 156.4 kg/s of CO_2 from 1.5 bar, 38 °C to a dense-phase state at 151 bar pressure [1], suitable for the subsequent pipeline transportation and storage. An account of the compression strategies evaluated in the study is presented along with a description of the thermodynamic analysis method employed to determine the total power consumption for CO_2 compression and operating intercooling pumps and an analysis of the results of the calculation of power requirements for multistage compression.

2. Method

In the present study, a thermodynamic analysis method is applied to determine the thermodynamic state of CO_2 stream and quantify the power consumption in compression and inter-stage cooling for each step of a multistage compression. The process is modelled accounting for isentropic efficiencies of compression/pumping stages and thermal efficiencies of heat exchange in isobaric intercoolers. In particular, the total power consumed in the *N*-stage compression/pumping is calculated as [3]:

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

where, G and ρ are the mass flow rate and density of CO_2 stream, respectively, while p_i^{in}, p_i^{out} and $\eta_{comp,i}$ are respectively the inlet and outlet pressures and isentropic efficiency of the i-th compression stage. The subscript s denotes isentropic compression.

Using the first law of thermodynamics, $dh = Tds + \frac{dp}{\rho}$ and assuming isentropic compression, Equation (1) may be written as:

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

where h_i^{in} and h_i^{out} are enthalpies of the stream at the suction (*in*) and discharge (*out*) of the *i*-th compression stage.

The total cooling duty associated with removing the heat of compression and possibly liquefying the CO_2 stream is given by [3]:

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

In this study, the CO_2 cooling/liquefaction power demand is calculated based on Carnot refrigeration cycle. This cooling power demand is associated with the work spent in an ideal compression refrigeration cycle when moving the heat from a coolant evaporation temperature, T_{ev} to condensation temperature, T_{cond} [11]:

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

where η_{cool} is the efficiency of refrigeration process. The coolant evaporation temperature T_{ev} is set to be 5 ^{o}C less than the CO_2 stream cooling temperature, while the condensation temperature, T_{cond} is assumed to be 38 ^{o}C which is based on inter-stage cooling gas temperature. This model does not involve specification of the type of refrigerant, hence enabling the comparison of the cooling and liquefaction power consumption for various multistage compression strategies.

The integral in Equation (1) defines the compression work done on the fluid which is valid irrespective of the CO_2 mixture phase state, and hence can be applied to evaluate compression work for the gas and pumping work for the liquid. This integral is evaluated numerically using a 15-point Gauss-Kronrod quadrature rule in QUADPACK library [12].

3. Results and Discussion

As the of compression much depends on the power consumption, our primary objective is to compare the power demands for compression of pure CO_2 using different compression strategies. To make such comparison we use the thermodynamic analysis method as described in Section 2.0 where the power demand for compression is calculated using rigorous equations accounting for real fluid behaviour of CO_2. Multistage compression is designed in such a way that we have certain fluid phases (gas or liquid) at certain stages of compression. The operating conditions of the pure CO_2 stream and thermodynamic paths for the compression options are set to match the fluid phase requirements for the processes of compression, liquefaction and pumping. The operating parameters are set depending on the real application in the process industry. This is followed by application of the Equations (2) and (4) to calculate the power requirements for compression of pure CO_2 stream.

In the present study in order to determine the power requirements in various compression strategies, basic parameters of compression processes are set the same for all the compression options based on recommendations from the previous study performed by [6] for pure CO_2. In particular, the study assumes compression of the CO_2 stream from 1.5 bar, 38 ^{o}C to a supercritical or dense-phase fluid at

151 bar pressure, as required for pipeline transportation and geological storage. Furthermore, the CO_2 mass flow rate and the least heat transfer temperature difference are respectively set to G = 156.4 kg/s and ΔT_i = 5 °C, while the compressors' and inter-stage coolers' as well as cooling water pumps' efficiencies are set to $\eta_{c,i} = \eta_{h,i} = 0.75 - 0.85$ depending on compression technology applied and $\eta_{p,i} = 0.61$ [1, 13, 14]. Following [6], the intermediate cooling temperature is set to 38 °C. The rest of this section describes adaptation of the various compression options to the pure CO_2 stream. To illustrate these changes to the compression schemes, pressure-enthalpy diagrams in Figures 1(a)-(d) are plotted showing the comparison of compression paths for options A-D for pure CO_2 stream, respectively.

3.1 Multistage compression of pure CO_2 stream

Figure 1(a) illustrates the application of the compression option A to the pure CO_2 stream. The pathway 0 to 8' shows the repeated compression and cooling down of the pure CO_2 stream performed at 1.5 bar, 38 °C initial conditions to 151 bar, 38 °C suitable for pipeline transportation (Figure 1 (a)). With the compression in every stage being nearly adiabatic, this results in an increment of outlet temperature in CO_2 compression. Implementation of the inter-cooling between compression stages can make the process approach isothermal, which can decrease the power consumption of the compressor. The inlet and outlet pressure conditions as well as pressure ratio are the most influential parameters in determining the number of compressor stages. In order to compress the pure CO_2 stream, the pressure ratio is applied at 1.78 which results in eight stages of compressor being used for this compression option.

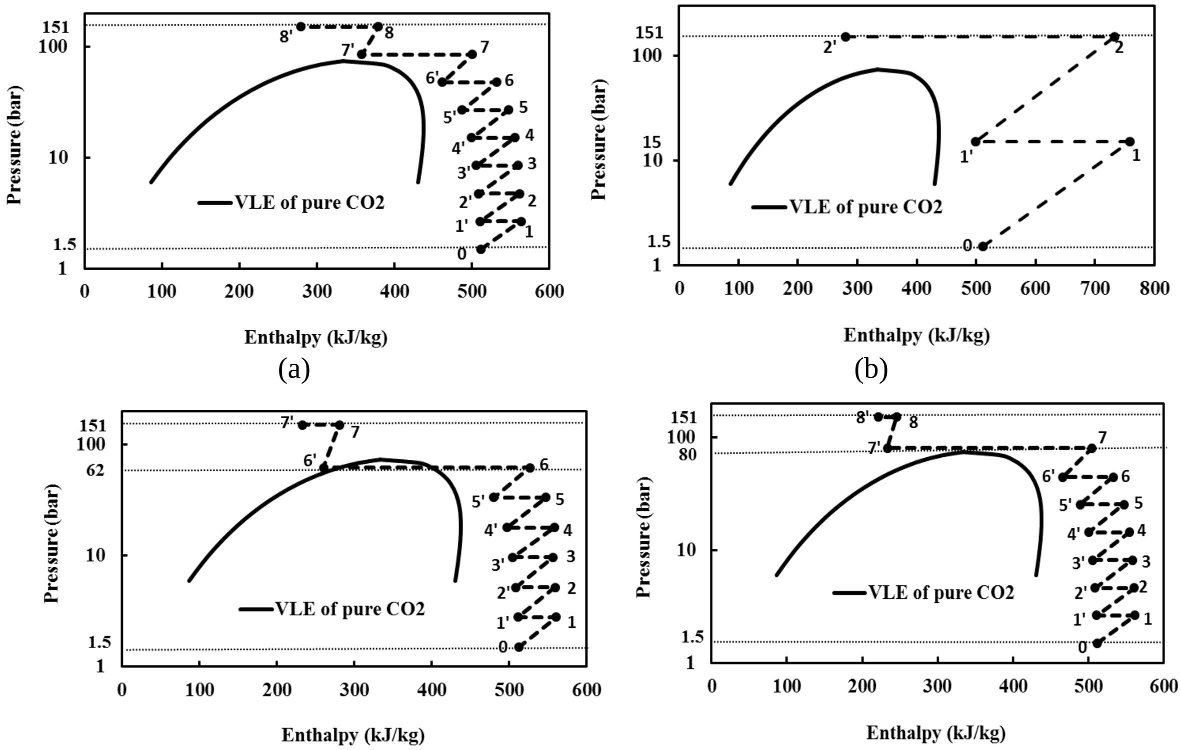

Figure 1. Phase envelope boundaries and thermodynamic paths for compression of pure CO_2 using conventional multistage integrally geared centrifugal compressors (option A) (a), advanced supersonic shockwave compressors (option B) (b), multistage compression combined with subcritical liquefaction and pumping (option C) (c) and multistage compression combined with supercritical liquefaction and pumping (option D) (d).

Processes 0-1, 1'-2, 2'-3, 3'-4, 4'-5, 5'-6, 6'-7 and 7'-8 are the adiabatic compression in compressors, and processes 1-1', 2-2', 3-3', 4-4', 5-5', 6-6', 7-7' and 8-8'are the inter-cooling system used to reduce the outlet temperature approximately between 90-95 ^oC from each compressor stage to 38 ^oC. At the first stage of compressor, CO_2 gas from inlet 0 is compressed to state 1 before it flows through the cooler at point 1-1'. Then it flows through stage two at state 1' to increase the pressure. The process is repeated until the phase of CO_2 is changed to supercritical conditions at high pressure, above the critical pressure of approximately 151 bar.

Figure 1(b) illustrates the thermodynamic compression paths for option B, achieved using the advanced supersonic shockwave compression with pressure ratio of 10 per stage. In this case, two stages of compressor which involves low pressure (LP) and high pressure (HP) stages are used to increase the pressure from 1.5 to 151 bar at discharge. Applying only two stages of compression option B to compress the stream is practically feasible in CCS applications which significantly reduces the total capital costs of the overall process. The intercooling system is applied to reduce the temperature after the compression from *ca.* 279 ^oC back down to 38 ^oC.

In Figure 1(c), the thermodynamic compression paths are shown for compression option C, which combines multistage compression with pumping following liquefaction of CO_2 at subcritical pressures. In this option, the 6-stage compression process is adapted for pure CO_2 to compress the fluid before liquefaction and pumping to the final pressure of 151 bar, 20 ^oC with the pressure ratio of *ca.* 1.85 applied. The advantage of option C comes from the fact that using pumps is cheaper than operating compressors. However, in order to use this advantage, the liquefaction should be achieved at intermediate pressures below the discharge pressure of the compressor (151 bar) without significant rise in the process cost. Thus, [6] and [13] have recommended liquefaction at pressure around 62 bar, which corresponds to the bubble point temperature of 20 ^oC for the pure CO_2.

Figure 1(d) shows the thermodynamic paths in case of compression option D, where 7-stages of compression are combined with supercritical liquefaction and pumping to compress the CO_2 streams. The supercritical liquefaction pressure of 80 bar is chosen to be just above the maximum saturation pressure of the stream with the corresponding 'liquefaction' temperature of *ca.* 15 ^oC. As can be seen in Figure 1(d), the pressure of pure CO_2 is increased slightly above than critical pressure (73.77 bar) using seven stages of compression with pressure ratio of *ca.* 1.76 applied before liquefaction using water as a cooling medium followed pumping to 151 bar for pipeline transportation. The underlying premise of the liquefaction approach is that liquid pumps require significantly less power to raise pressure and are considerably less expensive than gas compressors [6].

3.2 Multistage compression power demands

Table 1 summarises the results of calculation of the total power and its constituents (compression power and intercooling pump power) evaluated using equations in Section 2.0 for the multistage compression options A, B, C and D. To enable comparison for streams, the analysis is performed starting from 1.5 bar and 38 ^oC with the mass flow rate of the stream at 156.4 kg/s.

Table 1. Power Consumption in Multistage Compression / Intercooling of Pure CO_2 Stream, Evaluated for Different Compression Options.

	Compression Option			
	A	B	C	D
Compression Power (MW)	79	107	60	76
Inter-cooling power (MW)	24	150	31	33
Total power of compression and intercooling (MW)	103	257	91	109

The results in Table 1 show that the amount of power required by each compression option varies significantly according to the thermodynamic paths. Option B, advanced supersonic shockwave compression, indicates a requirement of *ca.* 35 % additional compression power compared to option A. The compression work is largest in case of compression option B due to the higher compression ratios compared to the compression option A. Also, the results for option C show that the compression power can be saved by *ca.* 24 % as compared to the compression option A. In addition, applying compression with subcritical liquefaction using utility streams (option C) is feasible for pure CO_2 with minimum compression work (60 MW), subcritical liquefaction at 62 bar pressure can be practically achieved at 20 ^oC, which would be less expensive to operate than other compression options. Applying liquefaction, as can be expected, reduces the compression power demand in this system (compare options C and D with option A). All these trends are in agreement with the study by [1].

The inter-cooling power for operating the inter-stage coolers is estimated to be relatively small in comparison with the compression power when using the compression options A, C and D. However, when using compression option B, the cooling system operation can take up about 40 % of the compression power and becomes nearly 5.25 times higher than the intercooling power demand of compression option A. This is due to the increment in the temperature at the discharge of the compressor (279 ^oC), compared to relatively low discharge temperatures in the other compression options. The relatively large cooling duties in comparison with the compression power can be primarily attributed to a fact that at high pressure system, the enthalpy of gas phase depends not only on temperature but becomes a strong function of pressure. As a result, the enthalpy increase in isentropic compression becomes less than the enthalpy decrease in the subsequent cooling to the original temperature. Possible strategies for removing such large amounts of heat from the CO_2 compression, may include optimising the heat integration between the CO_2 compression and other processes in the CCS plant.

4. Conclusions

The present study describes the results of thermodynamic analysis of the power requirements for compression of pure CO_2 stream captured in capture units at 1.5 to 151 bar pressure required for subsequent pipeline transportation. This work lays the foundation for practical optimisation of CO_2 compression, which should be performed not in isolation from other processes involved in the CCS chain, such as the CO_2 capture and transport. On the other hand, the discharge pressure of the compressor should be selected based on the pressure requirements for pipeline transportation. It was necessary to set the same initial and discharge pressures for all the compression options in order to compare the power requirements for various compression strategies adapted for pure CO_2 stream. Furthermore, the costs of CO_2 compression can potentially be reduced by integrating the CO_2 compression with the operation of the CO_2 emission plant, e.g. when utilizing the CO_2 compression heat and using utility streams for CO_2 liquefaction. The potential available heat from advanced supersonic shockwave compression system for example could be used to regenerate amine solutions in the regenerator for post-combustion capture or pre-heat the feed-water in the plant boiler system.

Acknowledgment

First author (N K Daud) acknowledges the funding received from the Research University Grant under agreement number RDU1803177 from Universiti Malaysia Pahang (UMP).

References

[1] Witkowski A Rusin A Majkut M Rulik S and Stolecka K 2013 Comprehensive analysis of pipeline transportation systems for CO_2 sequestration. Thermodynamics and safety problems *Energy Convers. Manag.* **76,** p. 665–673.

[2] Leung D Y C Caramanna G and Maroto-Valer M M 2014 An overview of current status of carbon dioxide capture and storage technologies *J. Renew. Sustain. Energy* **39,** p. 426–443.

[3] Martynov S B Daud N K Mahgerefteh H Brown S and Porter R T J 2016 Impact of stream impurities on compressor power requirements for CO_2 pipeline transportation *Int. J. Greenh. Gas Con.* **54,** p. 652–661.

[4] Yoo B Y Choi D K Kim H J Moon Y S Na H S and Lee S G 2013 Development of CO_2 terminal and CO_2 carrier for future commercialized CCS market *Int. J. Greenh. Gas Con.* **12,** p. 323–332.

[5] Pei P Barsea K Andres J G and Nasaha J 2014 Waste heat recovery in CO_2 compression *Int. J. Greenh. Gas Con.* **30,** p. 86–96.

[6] Witkowski A and Majkut M 2012 The impact of CO_2 compression systems on the compressor power required for a pulverized coal-fired power plant in post-combustion carbon dioxide sequestration *Arch. Mech. Eng.* ***3,*** p. 1–18.

[7] Romeo L M Bolea I Lara Y and Escosa J M 2009 Optimization of intercooling compression in CO_2 capture systems *Appl. Therm. Eng.* **29,** p. 1744–1751.

[8] Aspelund A and Jordal K 2007 Gas conditioning-The interface between CO_2 capture and transport. *Int. J. Greenh. Gas Con.* 1**,** p. 343–354.

[9] Moore J J Lerche A Delgado H Allison T and Pacheco J 2011 Development of Advanced centrifugal compressors and pumps for carbon capture and sequestration applications *The 40th Turbomachinery Symposium* p. 107–120.

[10] Duan L Chen X and Yang Y 2013 Study on a novel process for CO_2 compression and liquefaction integrated with the refrigeration process *Int. J. Energy Res.* **37,** p. 1453–1464.

[11] Jobson M 2014 Distillation: Fundamentals and Principles. Energy Considerations in Distillation. Academic Press, Elsevier.

[12] Piessens R De Doncker-Kapenga E Überhuber C W and Kahaner D K 1983 Quadpack, A Subroutine Package for Automatic Integration *Springer Ser. Comp. Mathem, Springer,* University of Leeds.

[13] Aspelund A 2010 CO_2 compression, transport and injection processes and technology *In: Developments and Innovation in CO_2 Capture and Storage Technology: CO_2 Capture, Transport And Industrial Applications* Elsevier Woodhead Publishing Series.

[14] Sulzer P 2010 Behavior of Centrifugal Pumps in Operation *Centrifugal Pump Handbook (3rd Edition).* Elsevier.