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A comparison of the Process Integration of Shockwave CO_2 compression with conventional turbo machinery into PCC power station design.

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Abstract

This paper discusses the energy penalty of solvent based post combustion capture for three different power stations and includes a comparison of shockwave CO_2 compression versus conventional turbo machinery on the energy penalty associated with carbon capture and storage. This study uses pinch analysis to determine targets for the energy penalty of three different power stations that include a brown coal power plant with no reheat stage, a more efficient brown coal power station and a black coal power station. Heat integration can be used to reduce the energy penalty of all power stations combined with CCS. It is also found that when heat integration is considered, the heat that can be recovered in shockwave compressor inter/after-coolers reduces the amount of steam that needs to be extracted from the steam turbine. Hence, the net power output from the power station will be higher when shockwave compressors are used for CO_2 compression compared to conventional turbo-machinery.

Keywords: CCS, Post Combustion, Heat Integration, Compression

1. Introduction

Post Combustion Capture (PCC) of CO_2 from existing pulverised coal fired power stations will be an important tool in a carbon constrained environment in order to avoid stranding existing assets. A significant proportion of the estimated cost of carbon capture and storage (CCS) for PCC from coal-fired power stations is due to the additional energy expended to capture the CO_2 and to compress it for transport and storage. The two largest requirements for energy for a solvent based PCC plant are the heat to regenerate the solvent and the energy to compress the CO_2.

CO_2 compression using conventional turbo-machinery will typically require eight stages of compression and represent approximately one third of the capital and operating costs of a post combustion, amine based CCS system.

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Conventional compression is typically limited by ensuring the Mach number of the inlet flow is less than 0.9 to avoid shockwaves in the blade passages, however this limits the stage speed and/or diameter and results in pressure ratios per stage of less than 2:1 for CO_2. As a consequence a typical CO_2 compression system for CCS requires between 8-10 stages to produce an overall ratio of 100:1. CO_2 compression can be simplified with shockwave compression. The design of these compressors is based on principles used in supersonic aircrafts and uses Mach numbers of greater than one and can obtain compression ratios of greater than ten per stage, thereby reducing the number of compression stages to just two for CCS [1].

With two stages of compression, shockwave compressors utilise fewer stages of inter-cooling and the compressor discharge temperatures are significantly greater than conventional turbo-machinery. This higher temperature heat can be utilised in the power station and carbon capture plant design to reduce the energy penalty impact associated with CCS. While not a feature of this paper the reduced number of stages and smaller physical footprint of the shockwave compression technology is also expected to reduce capital costs for compression [1].

The impact of a PCC plant will not only be dependent on the type of capture plant and compression employed, but will also depend on the original power plant to which it is applied. Power plants with lower efficiencies will require larger CCS units, but will generally have more low-grade waste heat which could be utilised to offset the impact of the addition of CCS. Brown coal power plants may be able to be retrofitted with pre-drying technology to improve the efficiencies, however this will reduce the amount of useful low-grade heat that is available and the overall energy penalty may or may not be improved by the addition of drying. Therefore, it is important to compare not only different capture and compression technologies, but to also compare them on a range of power station types.

This paper reviews the impact of adding a solvent based carbon capture plant with compression to three power stations and compares the net electrical power produced from the power station with varying levels of heat integration and with both conventional and shockwave compressors. This work expands on work that has been published previously [2, 3] and more details on the simulation basis and the methodology to perform the heat integration can be found in these papers. In this paper the additional heat and power required by the CCS plant is provided by the power station. Where there is a deficit of heat, steam is extracted from the turbine to provide the heat, which reduces the amount of power produced by the steam turbine. However the use of pinch analysis can reduce the amount of extraction steam required by using the available waste heat in other sources such as the compressor intercoolers, the solvent regenerator condenser and the flue gas.

2. Background to Case Studies

Two brown coal and one black coal power station will be used as examples with a generic amine based solvent capture plant. The first brown coal power station (Plant A) has a simple steam cycle with no reheat which is less efficient than the second brown coal power station (Plant B) which has a single reheat steam cycle, the same cycle that is used in the black coal power station (Plant C). The power stations are represented in Figure 1. For each power station there will be up to four cases studied, each with both conventional and shockwave compression.

1. Base Case: The existing plant with no CCS.
2. CCS: This case includes CCS, but with no heat integration. The regenerator is supplied steam from the best turbine extraction point. No heat is recovered in the CCS plant.
3. Integrated CCS: This case includes CCS and allows maximum heat integration between the power station and the carbon capture plant and compressor intercoolers using pinch analysis and a ΔT_{min} of 3 °C.
5. CCS & Drying: Includes CCS and coal pre-drying from 60 wt% water to 45 wt% water. Air preheat is removed to minimise the increase in combustion temperature to around 100 °C.

Note that as the focus of this paper is on the comparison of conventional and shockwave compression there are fewer cases reported than covered in the previous work[2], however the case numbering of the previous work is applied in this paper. It should also be noted that the values in this paper cannot be compared directly to the previous work [2] as the CO_2 compressor models used in this paper have been updated and are more detailed. The conventional compressors modelled in this paper are based on in-line single shaft compressor technology using the Dresser-Rand DATUM compressor estimating tool [4], the detail of the shockwave compressors were supplied by Ramgen Power Systems (Baldwin, P. 2010 pers. comm., 27 July).

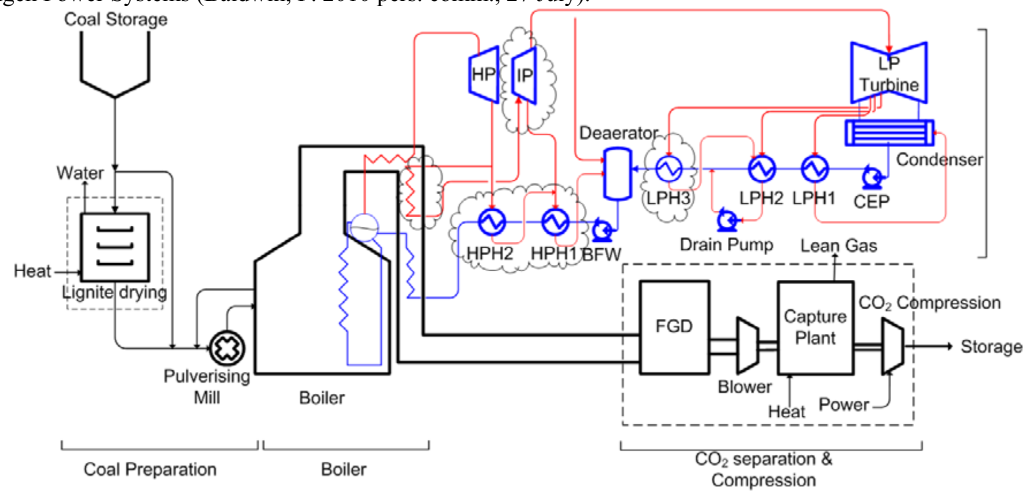

Figure 1 Power Station model. Dotted lines represent new equipment that may be added for CCS. Equipment in Plant B & C that is not in Plant A has been clouded.

3. Results

The results are presented in 6 parts; 3.1-3.3 contains the results of the individual power stations, 3.4 at the impact of the CO_2 pressure, 3.5 at the impact of ΔT_{min} and 3.6 compares the use of shockwave to conventional compression.

3.1. Plant A - Brown Coal Power Station

Table 1: Plant A – Brown Coal Power Station Results

		1	2	3	5
Conventional Turbo Machinery					
Steam Extraction Rates:					
HP Exhaust / LP 1 / LP 2	kg/s	10.9 / 11.4 / 8.7	111.6 / 11.4 / 8.7	52.8 / 0.2 / 0	41.05 / 7.1 / 0
Gross Electricity	MW	220	172	205	208
Auxiliary Power	MW	14	24	24	24
CO_2 compression Power	MW	-	27	27	27
Net Electrical Power	MW	206	122	155	158
Efficiency (HHV)	%	23.0	13.6	17.3	17.7
Energy Penalty	%	-	40.9	24.9	23.3
Shockwave Compression					
Steam Extraction Rates					
HP Exhaust / LP 1 / LP 2	kg/s	10.9 / 11.4 / 8.7	111.6 / 11.4 / 8.7	47.3 / 0.5 /0	35.6 / 8.5 / 0
Gross Electricity	MW	220	172	208	211
Auxiliary Power	MW	14	24	24	24
CO_2 compression Power	MW	-	26	26	26
Net Electrical Power	MW	206	122	158	161
Efficiency (HHV)	%	23.0	13.6	17.6	17.9
Energy Penalty	%	-	40.7	23.2	22.0

This power station has a relatively low base efficiency of 23 % (HHV) without CCS, due to the very high moisture brown coal and the simple steam cycle. Therefore, with the addition of CCS the energy penalty is relatively high at 41 % due to the large amount of energy that is required for CO_2 capture compared with the amount of energy that the power station produces. However as this power station has low base plant efficiency there is a significant amount of waste heat available. The flue gas leaves the air-heater at 260 °C and therefore heat integration can enable significantly reduced energy penalties of 25 and 23 %. When heat integration is taken into account, coal pre-drying provides a small improvement in the energy penalty which is reduced by 1-2 % depending on the type of compressor installed.

For this power station the net electrical power production for the power station without heat integration does not favour either conventional compressors or the shockwave compressors as the net output is comparable. However, when heat integration is taken into consideration, the net electrical power production of the power station is greater with shockwave compression; the heat recovered from the compressor inter/after-coolers enables a reduction in the amount of extraction steam required.

The pinch point for the power station and the CCS plant is invariably located at the CCS solvent regenerator reboiler temperature, and therefore heat that is available above this temperature will be useful to reduce the energy penalty. Therefore it is clear that conventional compressors with exhaust temperatures around 130 °C cannot provide significant amounts of useful heat, whereas shockwave compressor intercoolers with temperatures greater than 220 °C will provide more useful heat (see section 3.6 for more detail).

3.2. Plant B – Higher Efficiency Brown Coal Power Station

Table 2: Plant B – Brown Coal Power Station with Reheat Results

		1	2	3	5
Conventional Turbo Machinery					
Steam Extraction Rates					
HP Exhaust / IP 1 / IP 2	kg/s	45.8 / 20.1 / 15.4	45.8 / 20.1 / 15.4	2.0 / 21.1 / 8.8	2.0 / 4.4 / 1.3
LP Bleed 1 / LP 2 / LP3	kg/s	13.9 / 25.8 / 15.1	13.9 / 206.7 / 15.1	5.2 / 189.7 / 0	0.5 / 208.1 / 0
Gross Electricity	MW	520	441	510	525
Auxiliary Power	MW	30	46	46	46
CO_2 compression Power	MW	-	50	50	50
Net Electrical Power	MW	490	346	414	429
Efficiency (HHV)	%	28.0	19.8	23.7	24.5
Energy Penalty	%	-	29.5	15.6	12.5
Shockwave Compression					
Steam Extraction Rates					
HP Exhaust / IP 1 / IP 2	kg/s	45.8 / 20.1 / 15.4	45.8 / 20.1 / 15.4	2.0 / 14.6 / 5.0	2.0 / 0 / 0
LP Bleed 1 / LP 2 / LP3	kg/s	13.9 / 25.8 / 15.1	13.9 / 206.7 / 15.1	6.4 / 190.7 / 0	0 / 207.7 / 0
Gross Electricity	MW	520	441	517	530
Auxiliary Power	MW	30	46	46	46
CO_2 compression Power	MW	-	48	48	48
Net Electrical Power	MW	490	347	423	436
Efficiency (HHV)	%	28.0	19.9	24.2	24.9
Energy Penalty	%	-	29.2	13.7	11.1

The second brown coal power station, Plant B, is more efficient than Plant A due to the higher complexity of the steam cycle which has high pressure feedwater heaters and steam reheat where Plant A does not. The energy penalty associated with the addition of CCS to the power station is therefore lower for the Plant B compared to Plant A when no heat integration is taken into account. The amount of CO_2 required to be captured and compressed per MW of power produced will be less for Plant B compared to Plant A, and therefore the capture plant will have lower heat and power requirements and therefore lower energy penalty.

Heat integration can halve the energy penalty for this power station, reducing it from 29 % down to 14 %. There would be significant changes required to the power station to enable these energy savings to be made; the HP steam exhaust which is currently used for the high pressure feedwater heaters is reduced from 45.8 kg/s to 2 kg/s. Not only will another source of heat be required for the HP heaters, but the steam flowrate through the steam re-heater and IP turbine will increase by 44 kg/s so there is potential that both of these will need to be modified. Changes are also likely to be needed to the source of heat for the air-preheat or reductions in the temperature driving forces in the heat exchanger. Under all cases it appears as though the LP turbine would require modifications as the steam flow from the bleed point is increased by over 100 kg/s in each case. As with Plant A the addition of drying has a minor improvement in the energy penalty of the power station reducing it to 11 %.

The comparison of shockwave compression to conventional compression is the same for Plant B as it is for Plant A. When no heat integration is considered the net power from the power station is comparable for conventional and shockwave compression. When heat integration is included, the net electrical output of the power station with shockwave compression is higher for all cases, for Case 3 it is close to 10 MWe better than for conventional compression.

3.3. Plant C – Black Coal Power Station

Table 3: Plant C – Black Coal Power Station Results (Note that Case 5 is not applied to Plant C as no drying is required for black coal)

		1	2	3
Conventional Turbo Machinery				
Steam Extraction Rates				
HP Exhaust / IP 1 / IP 2	kg/s	25.0 / 16.0 / 18.5	25.0 / 16.0 /18.5	5.4 / 20.0 / 14.4
LP Bleed 1 / LP 2 / LP 3	kg/s	6.8 / 11.0 / 14.5	100.8 / 11.0 / 14.5	106.5 / 0.1 / 0
Gross Electricity	MW	358	306	335
Auxiliary Power	MW	24	31	31
CO_2 compression Power	MW	-	27	27
Net Electrical Power	MW	334	249	277
Efficiency (HHV)	%	36.0	26.9	29.9
Energy Penalty	%	-	25.4	16.9
Shockwave Compression				
Steam Extraction Rates				
HP Exhaust / IP 1 / IP 2	kg/s	25.0 / 16.0 / 18.5	25.0 / 16.0 / 18.5	5.8 / 17.0 / 11.8
LP Bleed 1 / LP 2 / LP 3	kg/s	6.8 / 11.0 / 14.5	100.8 / 11.0 / 14.5	107.7 / 0.2 / 0
Gross Electricity	MW	358	306	339
Auxiliary Power	MW	24	31	31
CO_2 compression Power	MW	-	26	26
Net Electrical Power	MW	334	250	282
Efficiency (HHV)	%	36.0	27.0	30.4
Energy Penalty	%	-	25.1	15.5

The energy penalty associated with the black coal power station Plant C is less than both Plant A and B for the case with no heat integration, due to the higher base efficiency, which means less heat and power is required for the CCS plant per MW of electricity produced. However, when heat integration is included, the energy penalty of Plant B is lower than Plant C. This is due to Plant B having more waste heat available in the flue gas compared to Plant C, the flue gas temperatures of Plant B is 190 °C compared to 140 °C for Plant C.

When heat integration is not taken into account the power station sent out power for shockwave compressors and the conventional compression are comparable; with the power station with shockwave compression producing about 1 MWe more of sent out power than the conventional compression. When the heat available in the compressor inter/after-coolers is returned to the power station cycle and carbon capture plant, the net power generated by the power station is 5 MWe greater for shockwave compression compared to the conventional compression, which is an efficiency improvement of 0.5 % points.

3.4. Impact of CO_2 pressure

A CO_2 pressure of 100 bar will generally be close to the minimum discharge pressure required to meet transport and storage requirements. The suction pressure for many solvent plants could also be lower than 1.8 bar. If the compression ratio is increased, the compression power and the inter/after-cooler duties will also be increased. Using Plant C as an example, the impact of increasing the compression ratio to 150 has been reviewed in Table 4, including heat integration. With the compression ratio increase to 150 the configurations of the conventional compressor will change;

- 8 stage in-line compressors increase to 10 stages.
- A decrease in the in-line compression aero efficiency of the last two stages to ~62 and 56 % (polytropic).
- In-line compression prices will increase.
- Shockwave compressors will remain with 2 stages - shockwave compression can handle a compression ratio of 150, and therefore price increase will be marginal at most.

Increasing the compression ratio from 55.5 to 150 reduced the net electrical power output by 3.6 MWe for the shockwave compression and 7.3 MWe for conventional compression, therefore the performance of the shockwave compression relative to the conventional compression is improving as the compression ratio increases.

Table 4: Impact of increasing the CO_2 pressure to 150 bar on the black coal power station

		Conventional Compression	Shockwave Compression
Gross Electricity	MW	336	343
Auxiliary Power	MW	31	31
CO_2 compression Power	MW	35	34
Net Electrical Power	MW	270	279
Efficiency (HHV)	%	29.1	30.1
Energy Penalty	%	19.1	16.6

3.5. Impact of ΔT_{min}

The ΔT_{min} used throughout this work is an optimistic 3 °C, which is based on the ΔT_{min} that can often be found in the feedwater heaters of power stations. However, a ΔT_{min} of 3 °C is unlikely to be a realistic minimum for a gas-gas exchanger like the air-preheater. Therefore the impact of varying the ΔT_{min} on the net electrical power is shown in Table 5 for Plant B. A ΔT_{min} of 3, 10 and 20 °C was used as well as a variable ΔT_{min}. The variable ΔT_{min} allows the different streams to have different ΔT_{min}, the overall ΔT_{min} for a heat exchanger will be the combination of half the two streams ΔT_{min}. The variable ΔT_{min}, uses 5 °C for liquid streams, the regenerator reboiler and the extraction steam, 10 °C for steam generation, the CO_2 compressor intercoolers and the regenerator condenser, and 20 °C for the flue gas and air preheater.

The ΔT_{min} has a large impact on the energy penalty with the energy penalty increasing from 14 % to 26 % when increasing from 3 °C to 20 °C. However, when a variable ΔT_{min} is used that is likely to reflect more closely the economic ΔT_{min}, the energy penalty is not far from when a ΔT_{min} of 3 °C is used. This is due to only small regions actually having driving forces that are near the minimum. The impact of changing the ΔT_{min} is similar for both the conventional turbo machinery and the shockwave compression. In all cases the shockwave compression has a lower energy penalty when comparing the same $\Delta T_{min.}$.

Table 5: Impact of ΔT_{min} on the Net Electrical Power Production for Plant B

		Conventional Turbo Machinery				Shockwave Compression			
ΔT_{min}		3	10	20	Variable	3	10	20	Variable
Steam Extraction Rates									
HP Exhaust	kg/s	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
IP Bleed 1	kg/s	21.1	16.2	71.6	27.5	14.6	9.1	58.6	61.7
IP Bleed 2	kg/s	8.8	10.4	0	9.6	5.0	7.2	0	5.2
LP Bleed 1	kg/s	5.2	196.6	152.9	5.4	6.4	197.5	156.6	6.0
LP Bleed 2	kg/s	189.7	1.4	47.3	189.8	190.7	4.5	50.9	190.6
LP Bleed 3	kg/s	0	0	0	0	0	0	0	0
Net Electrical Power	MW	414	391	353	407	423	400	362	416
Energy Penalty	%	15.6	20.1	28.0	16.9	13.7	18.4	26.1	15.1

3.6. Shockwave Versus Conventional Compression

As seen in the cases above, the net work of the conventional in-line compressors and the shockwave compressors are similar with the shockwave compressors expected to be slightly lower. The in-line compressors are characterised by many stages of compression and therefore inter-cooling which lowers the average temperature of the gas to keep the net work as low as possible, but due to the unique CO_2 properties at higher pressures and the reduced component sizes, the efficiency of in-line compression in the later stages drops off considerably and this increases the net work. Whereas shockwave compressors are advantaged by maintaining high stage efficiencies but the net shaft work is increased by the relatively high average gas temperature. However, as shown in this study, the higher temperatures in the shockwave compressors exhausts may be utilised in the power station and/or carbon capture plant.

The temperature of exhaust gas from the Shockwave compressors is 220/230 °C whilst the conventional compressor is between 129-167 °C. For Plant B, the heat removed to cool the CO_2 in the shockwave compression is 28/49 MW for the first and second stage respectively, whereas the conventional compression has 13/14/16/36 MW for the four stages of cooling. Therefore, the total amount of cooling is comparable for the two cases; 77 MW compared to 79 MW, however the temperature at which the heat is available is very different.

The pinch point temperature divides the process into a process requiring heat (above the pinch) and a process releasing heat (below the pinch). This temperature is invariably located at the solvent plant reboiler temperature; approximately 118 °C for this solvent plant. Therefore, below 118 °C there is a surplus of heat in the process, in the example shown in Figure 2(A), close to 600 MW of cooling is required below the pinch point. Therefore, heat that is available above the pinch point is useful heat, and heat that is available below the pinch is not necessarily useful, as there is surplus of heat available from other sources at these temperature levels. Hence, a significant proportion of heat from the Ramgen intercoolers is useful heat, whilst almost all of the heat available in the conventional compressors will need to be removed using cooling utilities. This can be seen in Figure 2(B), which shows the available energy in the CO_2 in the Shockwave compressor inter/after-coolers and the conventional compressors inter inter/after-coolers. There is around 37 MW of heat available in the shockwave compressor inter/after-coolers above 118 °C compared to less than 12 MW for conventional compression. When actually incorporating the heat from the compressor inter/after-coolers it is more likely that the heat from shockwave compressors would be recovered as there is three times the amount of heat compared to the conventional compressors.

The heat available in the shockwave compression can be used in a number of locations; to offset close to 10 % of the heat required by the solvent regeneration, to provide heat to a portion of the boiler feed water or the air preheat and is able to provide close to 50 % of the heat for drying the coal (in this case where the coal is dried from 60-45 wt%). The best use of the heat in the shockwave compression inter/after-coolers is that which will utilise the high temperature of the exhaust CO_2, and therefore thermodynamically the most favoured use of the energy is in boiler feed water heating or air pre-heat. It is possible in Plant B to heat up to 93 kg/s of boiler feed water to greater than 200 °C, this reduces the feedwater heating demand by close to 25 %.

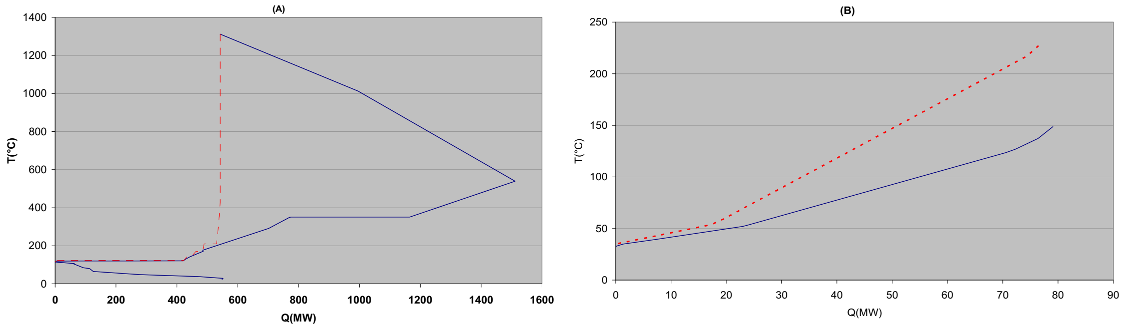

Figure 2 (A) Grand Composite Curve of Plant B (solid line) shown with the extraction steam curve required to satisfy the deficit of heat. (B) Amount of heat available in the conventional compressor inter/after-coolers (Solid line) compared to the shockwave compressor (dotted line).

As there is a surplus of heat in the process below 118 °C the fact that the shockwave compressors have less than 40 MW of heat below these temperatures compared to close to 70 MW for the conventional compressors, the cooling utility will be lower for the plant with properly integrated shockwave compressors. Additional cooling utilities lead to increases in auxiliary power requirements. Therefore, having lower cooling utilities benefits the shockwave compression system compared to conventional compressors.

4. Conclusion

The importance of heat integration is highlighted by the large reductions in energy penalty from the unintegrated cases (Case 2) to the integrated case (Case 3). The improvement in the energy penalty due to heat integration is between 36 and 52 % for the three cases. The actual improvement will be a trade-off between the capital cost of the heat exchanger network and the operability of the power station with the energy savings generated by the heat exchanger network.

For all cases in this paper the net electrical power from a power station with CCS using shockwave compression is greater than the power station using conventional inline turbo-machinery, especially when the heat in the inter/after-coolers is utilised in the power station or carbon capture process. There is also likely to be a reduction in cooling requirements using shockwave compression. Shockwave compression for CO_2 is a promising technology as it is expected to have a lower capital costs and smaller footprint than conventional turbo-machinery and from the results in this paper appears to fare more favourably from an energy perspective.

5. Acknowledgement

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