

# Assessment of Thermodynamic Efficiency of Carbon Dioxide Separation in Capture Plants by Using Gas–Liquid Absorption

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**Abstract** Typical carbon capture plants include CO<sub>2</sub> separation and compression steps. CO<sub>2</sub> separation from diluted flue gases may be achieved by using gas-liquid absorption. This process requires work input for e.g. separating CO<sub>2</sub> from flue gases and regenerating the CO<sub>2</sub> loaded solvent. Hence, CO<sub>2</sub> capture plants involving gas-liquid absorption consume a remarkable part of power and thermal energy generated by power plants. By increasing the thermodynamic efficiency of capture plants one can increase the produced power and save fossil fuels. Therefore, this study provides a quantitative assessment of the thermodynamic efficiency of CO<sub>2</sub> separation in capture plants. To this aim the minimum work required for CO<sub>2</sub> separation and actual work input in realistic carbon capture plants are estimated. The results reveal that for the state-of-the-art MEA solvent the thermodynamic efficiency of the capture plant is about 16%, for state-of-the-art advanced solvent based capture process (ASBCP) is about 25%, while given the progress in developing ASBCPs in near future it may reach about 30%. Additional measures to reduce the energy requirement of the capture plant such as heat pumps are also discussed. This all means that CO<sub>2</sub> separation by gas-liquid absorption is still a relatively inefficient process and remarkable potential for further improvements with step change innovations in gas-liquid absorption exist and may be beneficially used for optimising CO<sub>2</sub> capture plants.

## Nomenclature

|       |                                        |
|-------|----------------------------------------|
| ASBCP | Advanced solvent based capture process |
| $E$   | Energy, J                              |
| $G$   | Gibbs free energy, J                   |
| MEA   | Monoethanolamine                       |
| $n$   | Molar flow rate, kmol/s                |

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|                  |                                                    |
|------------------|----------------------------------------------------|
| NGCC             | Natural gas combined cycle                         |
| $p_i$            | Partial pressure of the $i$ -th gas, Pa            |
| $p$              | Total pressure, Pa                                 |
| PC               | Pulverised coal                                    |
| PCC              | Postcombustion capture                             |
| $Q$              | Heat, J                                            |
| $R$              | Ideal gas constant = 8.314 J/(mol K)               |
| $T$              | Absolute temperature, K                            |
| $T_{REF}$        | Reference temperature = 293.15 K                   |
| $T_{SOURCE}$     | Source temperature = 393.15 K                      |
| $W$              | Work, J                                            |
| $W_{act}$        | Actual work, J                                     |
| $W_{min}$        | Minimum work of separation, J                      |
| $y_i^{CO_2}$     | Mole fraction of $CO_2$ in the gas mixture $i$ , – |
| $y_i^{i-CO_2}$   | Mole fraction of non- $CO_2$ remainder, –          |
| $\eta$           | Thermodynamic efficiency, –                        |
| $\eta_{turbine}$ | Turbine efficiency = 90%                           |

### Subscripts and superscripts

|       |            |
|-------|------------|
| A     | Stream A   |
| B     | Stream B   |
| C     | Stream C   |
| i     | Index      |
| sep   | Separation |
| TOTAL | Total      |

## 1 Introduction

Energy efficient decarbonisation of the energy sector and major industries is essential for achieving sustainable development. Recent research efforts in  $CO_2$  capture led to the development of many new processes that may facilitate reduction of  $CO_2$  emissions. However, technological readiness levels (TRLs) of these processes are different and they use different necessary energetic inputs (e.g. waste heat, extracted stream, compressor work). It is thus difficult to compare the performance of such diverse processes [1]. Mature  $CO_2$  capture technologies may have slightly improved energy efficiencies compared to emerging technologies but at the same time they may offer much less potential for further improvements. Due to technology learning the future energy efficiency performance of various technological options currently at different stages of development is often unclear [2].

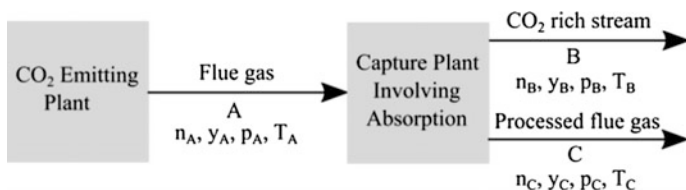
CO<sub>2</sub> capture by gas-liquid absorption undergoes rapid development and several new processes aimed at reducing its energy requirements have recently been proposed. Examples include solvent blends and advanced solvent based capture processes applying facilitated CO<sub>2</sub> capture by employing phase changing solvents, catalysed absorption or microencapsulated solvents [3, 4]. These new techniques should be explored in order to assess their potential for getting closer to the thermodynamic limits of CO<sub>2</sub> capture.

Two laws of thermodynamics are essential tools for assessing the energy efficiency of CO<sub>2</sub> capture plants. The first law reflects the principle of energy conservation and the second law accounts for process irreversibility. The second law efficiency shows how far a given capture process is from its thermodynamic limit. The methodology employed in this study uses the minimum work required for CO<sub>2</sub> separation under idealised operating conditions which is calculated from the combined first and second law of thermodynamics. Further, actual work of CO<sub>2</sub> separation is estimated through literature surveys and confirmed by calculations.

The provided assessment of thermodynamic efficiencies offer some qualitative insights into the energy efficiency of CO<sub>2</sub> capture by gas-liquid absorption and may quantify potentials for future improvements. The study begins with calculation of the minimum work of CO<sub>2</sub> separation (Sect. 2) which is followed by the determination of actual work requirements from actual capture plant evidence and by calculation (Sect. 3). The thermodynamic efficiency of CO<sub>2</sub> separation in capture plants involving gas-liquid absorption is calculated in Sect. 4. Section 5 discusses additional related measures capable of reducing the work requirements of CO<sub>2</sub> separation. Finally, Sect. 6 summarises conclusions drawn from the study.

## 2 Minimum Thermodynamic Work of CO<sub>2</sub> Separation

The minimum work required for CO<sub>2</sub> separation under idealised operating conditions is calculated from the combined first and second law of thermodynamics. It uses the flow rates and compositions of inlet and outlet streams and operating temperature. Figure 1 shows a CO<sub>2</sub> capture plant along with a CO<sub>2</sub> emitting plant and corresponding gas streams. Stream A represents a flue gas comprising CO<sub>2</sub> while stream B is a CO<sub>2</sub> rich stream, and stream C is the remainder of flue gases. The capture plant operates with a certain fixed capture rate and the purity level of CO<sub>2</sub> rich stream is imposed.



**Fig. 1** Schematic of the CO<sub>2</sub> capture plant involving gas-liquid absorption

The minimum work required for separating CO<sub>2</sub> from a flue gas mixture for an isothermal and isobaric process equals to the negative of the difference in Gibbs free energy of the separated final states (streams B and C in Fig. 1) from the mixed initial state (stream A in Fig. 1). This is the negative of Gibbs free energy of mixing. For an ideal gas the Gibbs free energy change between stream A to streams B and C is:

$$W_{\min} = \Delta G_{\text{sep}} = \Delta G_B + \Delta G_C - \Delta G_A \quad (1)$$

For an ideal mixture, the partial molar Gibbs free energy for each gas is [5, 6]:

$$\frac{\partial G}{\partial n_i} = G_i^0 + RT \ln \left( \frac{p_i}{p} \right) \quad (2)$$

Therefore, the total Gibbs free energy of an ideal gas mixture can be expressed as:

$$G_{\text{TOTAL}} = \sum_i n_i \frac{\partial G}{\partial n_i} \quad (3)$$

The minimum work required to shift from state A to states B and C is associated with the free energy difference between the product and reactant states, which can be calculated by inserting Eqs. (2) to (3) resulting in:

$$G_A = n_A^{\text{CO}_2} G_{\text{CO}_2}^0 + n_A^{\text{A-CO}_2} G_{\text{A-CO}_2}^0 + RT (n_A^{\text{CO}_2} \ln(y_A^{\text{CO}_2}) + n_A^{\text{A-CO}_2} \ln(y_A^{\text{A-CO}_2})) \quad (4A)$$

$$G_B = n_B^{\text{CO}_2} G_{\text{CO}_2}^0 + n_B^{\text{B-CO}_2} G_{\text{B-CO}_2}^0 + RT (n_B^{\text{CO}_2} \ln(y_B^{\text{CO}_2}) + n_B^{\text{B-CO}_2} \ln(y_B^{\text{B-CO}_2})) \quad (4B)$$

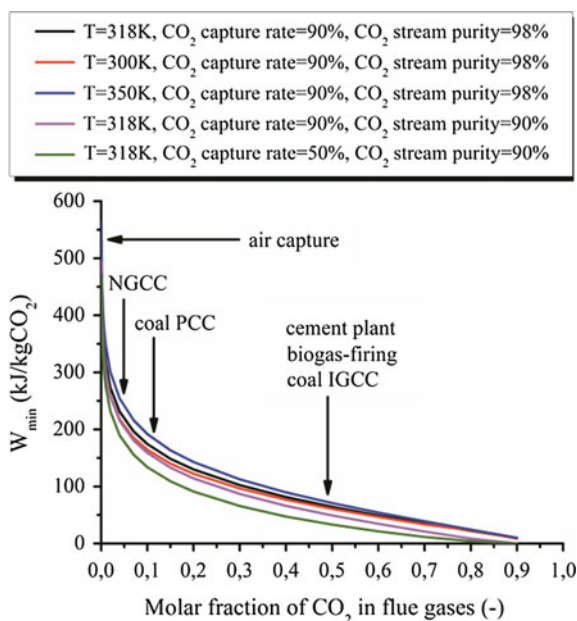
$$G_C = n_C^{\text{CO}_2} G_{\text{CO}_2}^0 + n_C^{\text{C-CO}_2} G_{\text{C-CO}_2}^0 + RT (n_C^{\text{CO}_2} \ln(y_C^{\text{CO}_2}) + n_C^{\text{C-CO}_2} \ln(y_C^{\text{C-CO}_2})) \quad (4C)$$

This ideal mixing takes place at constant temperature and pressure. By substituting Eqs. (4A–C) to Eq. (1) the minimum work of separation is obtained:

$$W_{\min} = RT \left[ \begin{aligned} & n_B (y_B^{\text{CO}_2} \ln(y_B^{\text{CO}_2}) + (1 - y_B^{\text{CO}_2}) \ln(1 - y_B^{\text{CO}_2})) \\ & + n_C (y_C^{\text{CO}_2} \ln(y_C^{\text{CO}_2}) + (1 - y_C^{\text{CO}_2}) \ln(1 - y_C^{\text{CO}_2})) \\ & - n_A (y_A^{\text{CO}_2} \ln(y_A^{\text{CO}_2}) + (1 - y_A^{\text{CO}_2}) \ln(1 - y_A^{\text{CO}_2})) \end{aligned} \right] \quad (5)$$

Equation (5) is subsequently used to calculate the minimum work of separation. Figure 2 presents the minimum work  $W_{\min}$  for CO<sub>2</sub> separation as a function of the molar concentration of CO<sub>2</sub> in the gas mixture (stream A in Fig. 1). Varied

**Fig. 2** Impact of temperature, CO<sub>2</sub> capture rate and CO<sub>2</sub> stream purity on the minimum thermodynamic work of CO<sub>2</sub> separation for gases with different CO<sub>2</sub> contents. Parameters varied: T—(300–350 K), capture rate—(50–90%), CO<sub>2</sub> stream purity—(90–98%)



parameters include T (300–350 K), capture rate (50–90%), and CO<sub>2</sub> stream purity (90–98%). As it can be observed the minimum work required for CO<sub>2</sub> separation increases with decreasing CO<sub>2</sub> concentration. In contrast,  $W_{\min}$  increases with increasing temperature, capture rate and CO<sub>2</sub> stream purity.

More specifically, the minimum work per kg of CO<sub>2</sub> captured in fixed temperature of 318 K, capture rate of 90% and CO<sub>2</sub> stream purity of 98% at inlet gas comprising 10% CO<sub>2</sub> is 174 kJ/kgCO<sub>2</sub>. When CO<sub>2</sub> is separated from air (inlet gas contains 0.04% CO<sub>2</sub>) the minimum work is 509 kJ/kgCO<sub>2</sub>, which is three times greater. When CO<sub>2</sub> is separated from biogas [7–9] combustion flue gases (inlet gas has 50% CO<sub>2</sub>)  $W_{\min}$  is 54 kJ/kgCO<sub>2</sub>, which is three times smaller. Effect of temperature is less pronounced: at 300 K  $W_{\min}$  is 164 kJ/kgCO<sub>2</sub> (6% less) and at 350 K it is 192 kJ/kgCO<sub>2</sub> (10% more). When capture rate is decreased to 50%  $W_{\min}$  is 149 kJ/kgCO<sub>2</sub> (14% less). When CO<sub>2</sub> purity is set at 90%  $W_{\min}$  is 159 kJ/kgCO<sub>2</sub> (11% less).

### 3 Actual Work Requirement of CO<sub>2</sub> Separation in Realistic Carbon Capture Plants

The minimum work of separation reflects a theoretical idealised isothermal and isobaric CO<sub>2</sub> capture process that cannot be achieved in the practice. In an actual CO<sub>2</sub> capture plant employing gas-liquid absorption significantly more work will be

required. For example, pumps are required to deliver the solvent to the scrubber and stripper which takes work. Similarly electrical blowers drive a flue gas through the scrubber. The solvent regeneration requires thermal energy to obtain the CO<sub>2</sub> rich and regenerated solvent streams. Each of these processes have associated efficiencies based upon irreversibilities, such as friction, heat transfer, gas expansion, gas mixing, etc. Therefore, actual work requirement depends on the unit operations of the capture process and their individual efficiencies.

Consequently, in addition to the minimum work which is insufficient to operate a CO<sub>2</sub> capture plant some extra work is needed. This lost work or lost exergy reflects inefficiencies of a given process realisation and cannot be avoided in the practice. The actual work of CO<sub>2</sub> separation can be estimated by using evidence from realistic carbon capture plants or by calculation of a model carbon capture plant. These two methods are employed below.

### 3.1 Evidence from Realistic Carbon Capture Plants

The actual work requirement of CO<sub>2</sub> capture plants involving gas-liquid absorption operated under realistic conditions can be found in literature. Table 1 summarises such evidence taken from literature relevant to state-of-the-art CO<sub>2</sub> capture solvents (especially MEA). It gives a breakdown of work requirement involving contributions from the flue gas blower, rich/lean solvent pumps, reboiler, and miscellaneous minor components.

As seen from Table 1 work requirement of plant components varies across various CO<sub>2</sub> capture plants reported in literature. It is associated with differences in

**Table 1** Literature overview of breakdowns of actual work requirements of realistic carbon capture plants involving state-of-the-art gas-liquid absorption

| Capture plant item                                          | Work requirement [kJ/kgCO <sub>2</sub> ] | References |
|-------------------------------------------------------------|------------------------------------------|------------|
| Flue gas blower                                             | 50                                       | [10]       |
|                                                             | 70                                       | [11]       |
| Rich/lean solvent pumps                                     | 37                                       | [12]       |
|                                                             | 2                                        | [13]       |
|                                                             | 3.2                                      | [14]       |
|                                                             | 1.2                                      | [15]       |
| Work equivalent of reboiler duty<br>(actual thermal energy) | 716–1110                                 | [10]       |
|                                                             | (2867–4443)                              | [14]       |
|                                                             | 497 (3956)                               | [11]       |
|                                                             | 491 (4063)                               | [12]       |
|                                                             | 964 (2892)                               |            |
| Miscellaneous (baseload—control valves,<br>minor units)     | 25                                       | [10]       |

**Table 2** Representative actual work requirements of CO<sub>2</sub> separation in capture plants involving state-of-the-art gas-liquid absorption

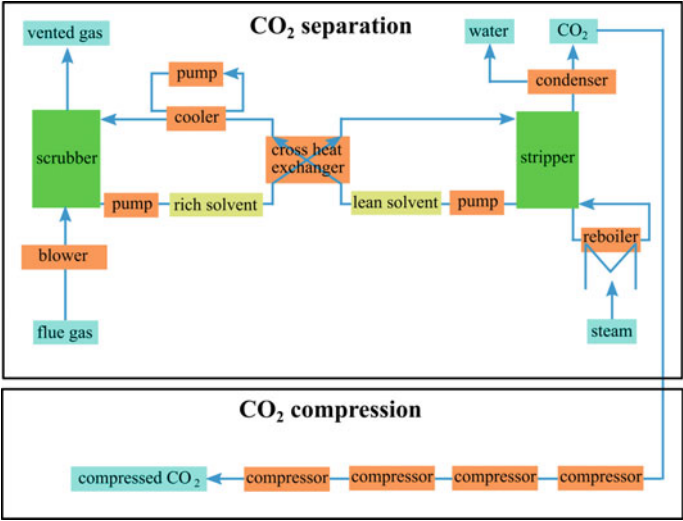
| Capture plant item                                   | Work requirement [kJ/kgCO <sub>2</sub> ] |
|------------------------------------------------------|------------------------------------------|
| Flue gas blower                                      | 70                                       |
| Rich/lean solvent pumps                              | 10                                       |
| Work equivalent of reboiler duty                     | 900                                      |
| Miscellaneous (baseload—control valves, minor units) | 25                                       |
| Total                                                | 1005                                     |

plant design, flue gas CO<sub>2</sub> content, flue gas contaminants, capture rate, plant capacity, employed solvent etc.

Table 2 summarises representative actual work requirements of CO<sub>2</sub> separation by state-of-the-art gas-liquid absorption.

3.2 Calculations for a Model Carbon Capture Plant

Figure 3 displays a schematic of a model CO<sub>2</sub> capture plant that is used to calculate work requirements and thus to improve the consistency of literature evidence provided in Sect. 3.1. It illustrates that a model CO<sub>2</sub> capture plant consists of two major components: (i) CO<sub>2</sub> separation and (ii) CO<sub>2</sub> compression. In order to



**Fig. 3** Schematic of a model CO<sub>2</sub> capture plant involving state-of-the-art gas-liquid absorption used in the calculation of actual work requirements of CO<sub>2</sub> separation

calculate work required for separating CO<sub>2</sub> only the former component needs to be accounted for.

The methodology used in current calculations includes blowing work, pumping work, reboiler equivalent work and miscellaneous contributions. It has recently been applied for evaluating power requirements of CO<sub>2</sub> separation from biogas by using gas-liquid absorption involving pressurised water scrubbing [16]. Here, heat released in the condenser is neglected and integration measures are not accounted for, except the cross heat exchanger.

### 3.2.1 Blowing Work

The work requirement for blowing flue gas is calculated from the gas flow rate ( $q_G$ ) and total pressure rise ( $\Delta p$ ). The shaft work requirement ( $W_B$ ) is obtained by using the mechanical efficiency of the blower ( $\eta_B$ ).

$$W_B = q_G \Delta p / \eta_B \quad (6)$$

The mechanical efficiency values of 0.78 and 0.75 are used for the blower and pump, respectively [17].

### 3.2.2 Pumping Work

The work requirements for pumping the rich and lean solvents as well as cooling water are calculated from the water density ( $\rho_L$ ), gravitational acceleration ( $g$ ) and liquid flow rate ( $q_L$ ). In order to obtain shaft power ( $W_P$ ), the mechanical efficiency of a pump ( $\eta_P$ ) is also accounted for.

$$W_P = \rho_L g q_L H_T / \eta_P \quad (7)$$

The total pumping work includes contributions from pumping the rich and lean solvents as well as cooling water ( $W_{P-RS}$ ,  $W_{P-LS}$ ,  $W_{P-COOL}$ ).

The total pressure head ( $H_T$ ) is needed to calculate work requirement for pumping and blowing. It is calculated as the sum of the pressure difference ( $H_{SCR} - H_{ATM}$ ), the static ( $H_S$ ) and dynamic ( $H_D$ ) heads as follows:

$$H_T = (H_{SCR} - H_{ATM}) + H_S + H_D \quad (8)$$

The pressure difference  $H_{SCR} - H_{ATM}$  is obtained by subtracting the pressure in the scrubber and the atmospheric pressure.

The static head is taken equal to the height of columns (scrubber/stripper). The dynamic head is calculated from the Darcy-Weisbach equation assuming optimum gas velocity 20 m/s and liquid velocity 2.5 m/s:

$$H_D = f \frac{L}{D} \frac{w^2}{2g} \quad (9)$$

Friction factor  $f$  is obtained explicitly from a relationship approximating the Colebrook-White equation [18].

$$f = \frac{6.4}{\left( \ln(Re) - \ln\left(1 + 0.01Re \frac{\varepsilon}{D}\right) \left(1 + 10\sqrt{\frac{\varepsilon}{D}}\right) \right)^{2.4}} \quad (10)$$

CO<sub>2</sub> scrubbing is more efficient at lower temperatures characterised by increased CO<sub>2</sub> solubility. Therefore, lean solvent is cooled in a heat exchanger using water as a coolant. Cooling is designed to reduce lean solvent temperature to 5 K above ambient temperature. The flow rate of cooling water ( $q_{COOL}$ ) required to cool the lean solvent is calculated from energy balance and subsequently inserted into Eq. (7) to calculate pumping work associated with lean solvent cooling.

$$q_{COOL} = \frac{q_C \rho_C C_{PC} (T_{Cout} - T_{Cin})}{\rho_L C_{PL} (T_{Lout} - T_{Lin})} \quad (11)$$

### 3.2.3 Reboiler Equivalent Work

$Q_{sens}$  is estimated as heat that needs to be added to heat the solvent from temperature  $T_{INLET}$  to  $T_{STRIPPER}$ :

$$Q_{sens} = m_S C_p (T_{STRIPPER} - T_{INLET}) \quad (12)$$

$$Q_{vap} = m_S H_{vap} \quad (13)$$

$$Q_{act} = Q_{sens} + Q_{vap} \quad (14)$$

Thermal energy is subsequently converted to equivalent work by using a conversion factor obtained from Carnot efficiency [19, 20]. In addition, turbine efficiency is used to convert the work into electricity.

$$W_{equivalent} = Q_{act} \eta_{turbine} \left( \frac{T_{SOURCE} - T_{REF}}{T_{SOURCE}} \right) \quad (15)$$

### 3.2.4 Miscellaneous Contributions to Total Work

Miscellaneous contributions to total work include control valves and other minor units associated with CO<sub>2</sub> separation.

**Table 3** Calculated work requirements of the model CO<sub>2</sub> capture plant involving CO<sub>2</sub> separation by state-of-the-art gas-liquid absorption

| Capture plant item                                   | Work requirement [kJ/kgCO <sub>2</sub> ] |
|------------------------------------------------------|------------------------------------------|
| Flue gas blower                                      | 40                                       |
| Rich/lean solvent pumps                              | 20                                       |
| Work equivalent of reboiler duty                     | 890                                      |
| Miscellaneous (baseload—control valves, minor units) | 25                                       |
| Total                                                | 975                                      |

### 3.2.5 Total Work Requirement of the Model CO<sub>2</sub> Capture Plant

The calculations takes into account CO<sub>2</sub> capture plant technical parameters from [21]. The results are presented in Table 3. As seen from comparison of Tables 2 and 3 total work requirement and breakdown are similar. Therefore these calculated actual work requirements will be used in the next Section.

## 4 Thermodynamic Efficiency of CO<sub>2</sub> Separation

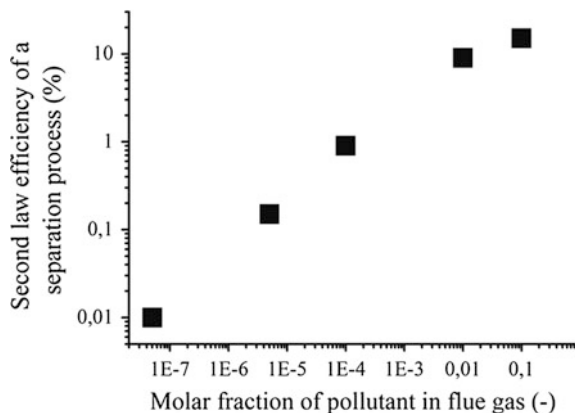
Based on the minimum work of separation and actual work requirements the thermodynamic efficiency may be calculated as the ratio of minimum and actual work.

$$\eta = \frac{W_{\min}}{W_{act}} \quad (16)$$

$W_{\min}$  is the useful effect of separating flue gases and it is equal to the Gibbs free energy of CO<sub>2</sub> separation.  $W_{act}$  is the work input required to run the realistic CO<sub>2</sub> capture plant.  $W_{act}$  includes work consumed by pumps, blowers and compressors as well as work equivalent of thermal energy consumed by the stripper. This thermodynamic efficiency uses only work or work equivalent inputs/outputs and is therefore consistent with the second law of thermodynamics.

Thermodynamic efficiencies of separation processes have been investigated for a variety of pollutant reduction techniques in a wide range of concentrations. In Fig. 4 the second law efficiency is plotted as a function of pollutants concentration (at separation rate 90%, PC power plant 500 MW<sub>el</sub>). Data are adopted from various real separation processes such as CO<sub>2</sub> capture in coal PCC plants (by amine scrubbing) and NGCC plants (by amine scrubbing), as well as for separations of NO<sub>x</sub> (by selective catalytic reduction), SO<sub>x</sub> (by wet flue gas desulfurization), and Hg (by activated carbon injection). As it can be observed the second law efficiency increases with increasing pollutant concentration [22]. In view of these results the specific nature of CO<sub>2</sub> is such that it has very high concentration compared to other

**Fig. 4** Influence of pollutant concentration in flue gases on the second law efficiency of a flue gas cleaning process, data adapted from [23]

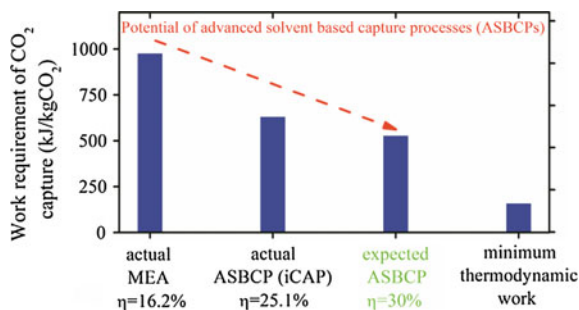


typical pollutants contained in flue gases, e.g.  $\text{SO}_x$ ,  $\text{NO}_x$  or Hg. It means that  $\text{CO}_2$  separation may require different approaches than other highly diluted pollutants. Due to higher concentrations and flow rates the thermodynamic efficiency is more pronounced for separating  $\text{CO}_2$  than other minor contaminants.

The  $\text{CO}_2$  capture plant separates relatively concentrated gases and therefore the second law efficiency of  $\text{CO}_2$  separation is higher than that of diluted pollutants, typically it is higher than 10%.

The minimum work of separation (for 90%  $\text{CO}_2$  capture rate, 98%  $\text{CO}_2$  stream purity, temperature 318 K, and 13%  $\text{CO}_2$  content in flue gases) amounts to 158 kJ/kg $\text{CO}_2$ . Taking into account the actual work requirement of MEA based  $\text{CO}_2$  capture of about 975 kJ/kg $\text{CO}_2$  the second law efficiency calculated from Eq. 16 is 16.2%. The iCAP project obtained a two immiscible liquid phases based ASBCP with the experimental energy requirement of 2400 kJ/kg $\text{CO}_2$  for solvent regeneration. It translates to total work equivalent of about 630 kJ/kg $\text{CO}_2$  and yields the second law efficiency of 25.1%. Given this progress and several other ongoing projects the second law efficiency of about 30% (527 kJ/kg $\text{CO}_2$ ) may be achieved by  $\text{CO}_2$  capture systems employing innovative ASBCPs in the future. Figure 5 compares these calculations and expectations.

**Fig. 5** Potential for the reduction of work requirement of  $\text{CO}_2$  capture by ASBCPs with technology development. Parameters:  $\text{CO}_2$  capture rate—90%,  $\text{CO}_2$  stream purity—98%, temperature—318 K,  $\text{CO}_2$  content in flue gases—13%



It is worth to mention that a typical PC power plant having a CO<sub>2</sub> emission intensity of 1000 kgCO<sub>2</sub>/MWh<sub>el</sub> (0.000278 kgCO<sub>2</sub>/kJ<sub>el</sub>) produces 3600 kJ<sub>el</sub>/kgCO<sub>2</sub> emitted. Consequently, the state-of-the art MEA CO<sub>2</sub> capture process that consumes 975 kJ/kgCO<sub>2</sub> would use 27% of electricity delivered by such a power plant.

It emphasises that the progress in reducing work requirement of CO<sub>2</sub> separation is essential.

## 5 Examples of Additional Measures Capable of Reducing Work Requirement

The actual work can be decreased by optimising one or all of the separation steps. The optimisation may rely on tuning existing CO<sub>2</sub> capture processes or applying new ones bringing a step change in technology [e.g. advanced solvent based capture processes (ASBCPs)].

As shown in breakdown given in Table 3 the most significant contribution is associated with reboiler duty. Therefore, techniques that deliver thermal energy to the reboiler may greatly improve the performance of CO<sub>2</sub> capture plants. For example, heat pumps are able deliver thermal energy taken from the environment or waste heat sources available in power plants [24]. Namely, using an absorption-driven heat pump for waste heat recovery the energy requirement of a conventional solvent based CO<sub>2</sub> separation may be potentially reduced to 1670 kJ/kgCO<sub>2</sub> [25]. If a heat pump uses renewable energy taken from the environment the CO<sub>2</sub> capture plant may overcome thermodynamic limits of closed systems. The application of heat pumps may rely on cooling the scrubber which enhances absorption and heating the stripper which enhances solvent regeneration. The scrubber is fed with flue gases having relatively high temperature which ensures that this type of heat source is stable in capture plants.

Another measure is associated with improved allocation of thermal energy within capture plants. It may also be achieved by a distributed cross heat exchanger. This device functions by delivering more of the heat to the bottom section of the stripper than to the top section. The stripper with lower temperature at the top has a lower solvent vapour fraction, which reduces useful heat lost to the condenser [19, 25].

Further, process intensification techniques for dedicated for post-combustion CO<sub>2</sub> capture [26], if could be suitably integrated with ASBCPs can add additional energy efficiency benefits to the whole capture plant.

## 6 Conclusions

This study analyses thermodynamic efficiency of CO<sub>2</sub> separation by gas-liquid absorption. The minimum work required for CO<sub>2</sub> separation under idealised operating conditions is provided. Insights in blowing work, pumping work, reboiler equivalent work and miscellaneous contributions are given based on realistic capture plants found in literature and calculations made for the model CO<sub>2</sub> capture plant. Taking into account actual work required to separate CO<sub>2</sub> the second law efficiency is calculated. For the MEA solvent it is about 16%, for the state-of-the-art ASBCP about 25%, and for future ASBCPs it may achieve about 30% or more.

The second law efficiency is limited to closed systems. However, when a CO<sub>2</sub> capture plant operates as an open system the thermodynamic limits may be overcome. This can be implemented by using renewable energy, e.g. through heat pumps utilisation. Heat pumps may also facilitate the distribution of thermal energy within the system thus leading to limited irreversibilities and exergy losses and consequently to improved thermodynamic efficiency. Heat management is particularly relevant since it is clearly the major contributor to total work requirement of CO<sub>2</sub> separation, at least when thermal regeneration of solvent is employed. Due to the scale of CO<sub>2</sub> capture plants all feasible measures need to be applied simultaneously in order to achieve the meaningful reduction of work requirement of CO<sub>2</sub> separation.

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