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Thermodynamic analysis and profitability study of a power unit with an added CO_2 capture plant

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Abstract

Concerns over greenhouse gas emissions are driving a requirement for newly built coal power units to satisfy the so-called "capture ready" conditions. This paper presents the a thermo-economic analysis supplemented by a cost evaluation of a power unit for ultra-supercritical parameters expanded by an amine-based CO_2 capture plant. The analysis was performed with the use of an integrated package containing the IPSEpro, MATLAB and Revenue Requirement Method implemented in MOExcel. The 0D model of a post combustion capture installation was developed based on complex CFD calculations of the absorber and stripper. A number of CFD simulations were conducted to create a large database, which was then utilized to develop suitable correlations describing the process

Thermodynamic and economic calculations were performed in respect of a power plant coupled with a CO_2 separation unit for a varying ratio of amine solvent to the exhaust gas stream (L/G). A local minimum for reboiler heat duty was found for L/G≈3.5 revealing the optimal post combustion capture configuration. It was observed that complementing the power unit with a post-combustion capture (PCC) installation causes a slight increase in the investment costs due to the drop in efficiency, but more important is the rise in total cost due to the investment associated with the CO_2 capture plant. It was found that about 14 years is required to compensate the investment cost of the PCC installation.

Keywords: Ultra-supercritical power plant, thermal cycle, post-combustion capture, CCS, MEA.

1. Introduction

Despite concerns about carbon dioxide emissions from the combustion of fossil fuels, long term predictions show that they will still be the dominant fuel on the planet for the next few decades [1]. To encourage reductions in CO_2 emissions in Europe, the European Commission imposed CO_2 emission limits and carbon related charges. .

One mature technology that can be implemented in the short term to existing power plants which is able to reduce CO_2 emissions is post-combustion capture (PCC) [2]. PCC utilizes a chemical solvent, usually monoethanolamine, to separate CO_2 from flue gas in the absorber column [3]. Captured CO_2 is then released from the amine solution in the desorber (stripper) with additional heat and transported to the storage location. The additional heat supply to the stripper column leads to a substantial reduction in power plant (PP) efficiency, which makes the PCC process relatively expensive.

An increase in overall PP efficiency can alleviate the high expenditure resulting from the PCC installation. A noticeable efficiency improvement can be achieved through raising PP operating conditions to ultra-supercritical levels, i.e. 700°C and 35 MPa [4].

Construction of a complex PP installation coupled with a PCC unit requires a thermodynamic and economic analysis. There is a need to identify least-cost

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generation technologies, taking into account physical, economic, and regulatory conditions.

It is important for the power industry to decide whether the expenditures for new generation plant extended with PCC plant for a given CO_2 separation technology are reasonable. It is known that the economics of a PCC strategy are still unclear, because it depends not only on estimated cost, but also on the regulatory environment. That is why priority should be given to implementing new conceptual technologies developed on the basis of complex analysis, including numerical simulations.

The present work focuses on the development of a 0D PCC model, based on complex CFD modelling of key elements of PCC, i.e., absorber and stripper [5], its implementation in the structure of power plant and a thermodynamic analysis to determine the optimal operating point of the entire installation. The analysis was performed for thermal cycles of a coal-fired 900 MW power unit, for which thermodynamic calculations were carried out in previous investigations [6–8].

This study also aims to identify the energy effectiveness of CO_2 capture, yielding the minimum energy penalty, and to demonstrate its correlation with plant efficiency and CO_2 absorbent flow rate (or the MEA stream into the exhaust gas stream L/G).

2. Object of the research

The study looks at an ultra supercritical power plant coupled with a PCC unit. A graphical illustration of it is presented in Fig. 1 whereas the model itself was developed in IPSEpro environment. As can be seen from Fig. 1, two cycles are distinguished with scatter squares, i.e., a power plant and amine based PCC unit. The main PP components are: boiler (B), high pressure (HP) intermediate pressure (IP) low pressure (LP) turbine sections, additional tuning turbine (T-T), condenser, five preheaters of low pressure regeneration system, deaerator (DEA), and three preheaters of high pressure regeneration system. The PCC cycle consists of an absorber (A), desorber (D) and a heat exchanger located between these two columns. Information about the basic operating parameters is presented in Tab. 1

A significant portion of heat needs to be taken from the thermal cycle for the purpose of CO_2 separation. The choice of the most suitable steam-extraction point for this need should fulfil the following thermodynamic requirements: firstly, the steam temperature should be high enough to heat the aqueous MEA solution in the reboiler to a temperature of $T_{reb}\approx 122^{\circ}C$ [9]. Secondly, the steam extraction point should be technically attainable and should ensure a sufficiently high steam flux with the lowest possible adverse impact on PP operating conditions. One solution to this deadlock could be a steam drain from the first bleed point of the LP turbine [10]. Research performed by Brasington [11] revealed that this solution is possible only when the steam flux delivered to the LP section is increased, which consequently would lead to a rise in investment cost due to the turbine being larger. Marion et al. [12] proposed another solution, i.e., to drain the steam from the crosspipe between IP and LP turbine sections. This solution does not require any noticeable changes in construction of turbine sections, and its implementation is more favoured in the most recent literature [13–16]. That is why this solution was applied in this study.

The steam used for the amine regeneration purpose must be returned to the thermal cycle. Hence it is important to select the optimal steam drop point. Two solutions can be be found in the literature, i.e., the steam drop to the deaerator [13, 17] or to the condenser [18]. Both were examined within the framework of the Strategic Program and the results were presented in the summary report [19]. The analysis revealed that the steam discharge into the condenser leads to a much greater drop in PP efficiency than if the steam was delivered to the deaerator. Hence the former solution is taken into account in this study.

It is worth mentioning that the present form of the 0D numerical model of PP discussed above derives from extensive work performed at the Institute of Thermal Machinery over the last few years. First, the credibility of the numerical tool, IPSEpro, was verified against data delivered from a 460 MW supercritical PP operating in Łagisza [20]. Next, the authors developed a new PP cycle operating with the adopted ultra supercritical conditions according to the concept proposed by Łukowicz et al. [21]. This cycle was then equipped with a tuning turbine, further to an idea given by Kjaer and Drihhaus [22]. A detailed analysis of the ultra-supercritical PP with and without additional TT can be found in [6].

3. 0D model of PCC process

Most of the available PCC models are in the form of 0D and 1D commercial and in-house codes [1], in which the flow hydrodynamics are usually very simplified (for example the liquid holdup is assumed to be constant,

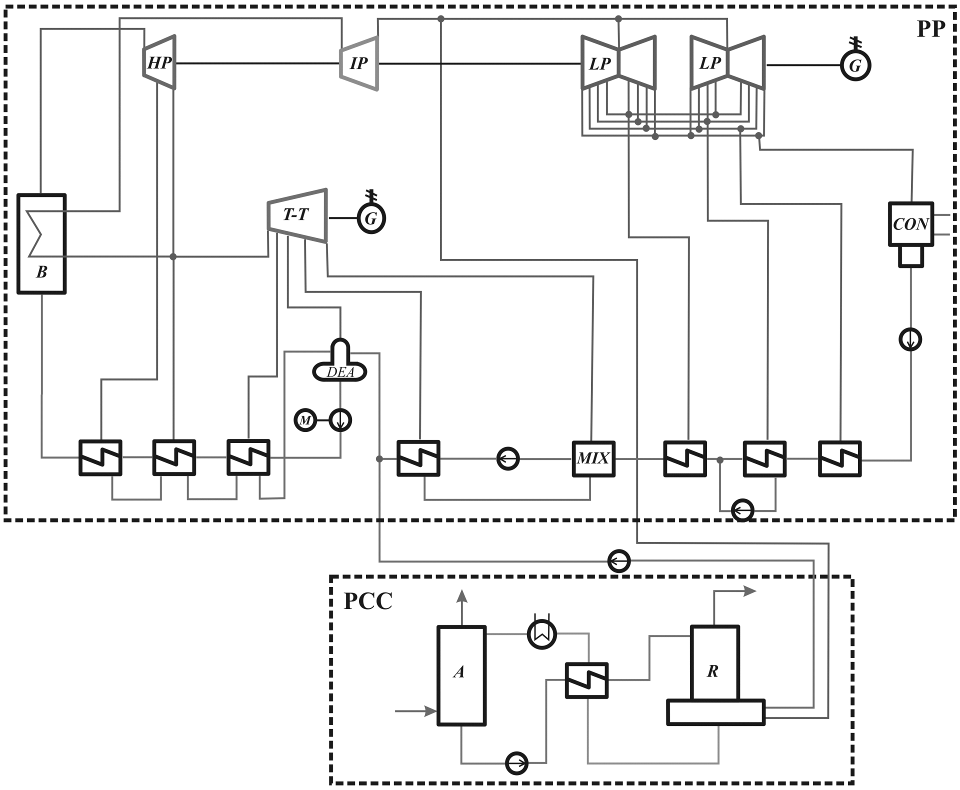

Figure 1: Object of the research – power plant coupled with a CO_2 separation unit

Table 1: Operating parameters of PP installation coupled with PCC unit.

unit	location	parameter		value	unit
PP	live steam parameters	temperature		702	°C
		pressure		357.5	bar
	reheated steam parameters	temperature		721	°C
		pressure		75	bar
		efficiency	without PCC	52.11	%
			with PCC	45.46	%
		gross electric power	without PCC	905	MW
			with PCC	806	MW
PCC	absorber inlet	temperature		40	°C
		CO_2 loading		0.27	-
		L/G		3.5	kg/kg
	absorber outlet	CO_2 loading		0.43-	-
	stripper inlet	temperature		114.7	°C
	stripper outlet	temperature		121.8	°C
	-	capture efficiency		80	%
	-	reboiler heat duty		7.5	MJ/kg CO_2

regardless of the liquid flux changes). Moreover, according to the work of Bazmi et al. [23] "the relative error for available in literature correlation is within the range between 30% and 127% for pressure drop and up to 50% for liquid holdup."

The standard IPSEpro library does not contain a CO_2 separation module, hence the PCC unit needed to be implemented into the code. For that purpose the complex computational fluid dynamics (CFD) model of the PCC process was developed. During the development of the CFD model particular attention was placed on flow hydrodynamics occurring inside the absorber and stripper columns, equipped with packed beds in order to accurately reflect phenomena such as pressure drop and liquid holdup. The proposed CFD approach utilizes the complex fluid dynamics model proposed by Billet [24] which enables actual values of liquid holdup and pressure drop to be determined for most of the random and structural packing types. More details about the numerical modelling of the absorption and stripping processes can be found in the works [25] and [26] respectively.

A number of CFD simulations were conducted to create a large database, which was utilized to develop suitable correlations describing the process. The most important parameters at the outlet of the absorber and stripper columns from the PCC process point of view are: temperature and MEA loading [27]. These parameters were correlated with the liquid to gas ratio (L/G), inlet solvent temperature ($T_{l,in}$) and inlet loading (α_{in}) for the absorber column and with inlet temperature, liquid flux (L), inlet loading and power (P) delivered for the stripper:

$$\alpha_{out,absorber} = f_\alpha\left(\frac{L}{G}, T_{l,in}, \alpha_{in}\right) \quad (1)$$

$$T_{out,absorber} = f_T\left(\frac{L}{G}, T_{l,in}, \alpha_{in}\right) \quad (2)$$

$$\alpha_{out,stripper} = f_\alpha\left(L, T_{l,in}, \alpha_{in}, P\right) \quad (3)$$

$$T_{out,stripper} = f_T\left(L, T_{l,in}, \alpha_{in}, P\right) \quad (4)$$

The 0D model presented in Fig. 1 was developed based on the above correlations. As can be seen, the structure of the installation is simplified, because it consists only of an absorber, stripper, heat exchanger, pump and cooler.

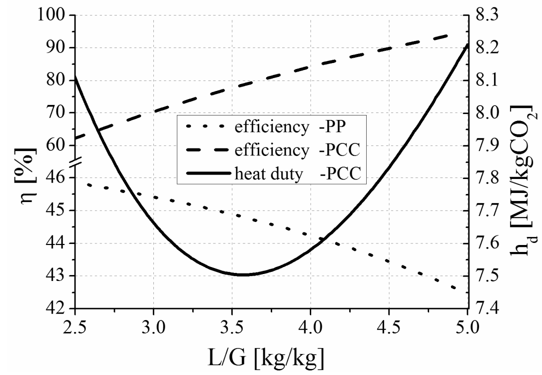

Figure 2: CO_2 capture and PP efficiencies and heat duty vs L/G.

4. Thermodynamic study of PP equiped with PCC

The aim of the next stage of the research was to estimate the optimal operating conditions of PP equipped with a PCC unit. The parametric analysis was aimed at showing the influence of L/G on three parameters: PP and CO_2 capture efficiency, and heat demand. Fig. 2 reveals the presence of the expected local minimum for heat demand curve in the close vicinity of $L/G = 3.5$ is 7.5 MJ/kgCO_2. The corresponding PP and CO_2 capture efficiencies are 44.8% and 78%, respectively. It should be noted that the optimal value of heat demand required to capture 1 kg of CO_2 noticeably exceeds these given in the literature [28], i.e., between 3.2 and 4.5 MJ/kgCO_2. A closer look at the numerical model is need in order to explain the discrepancy between the numerical calculations and literature data.

The 0D model of PCC process was developed based on correlations determined with the use of CFD models of the absorber and stripper columns. The reference for the CFD simulations was the small laboratory installation located at the Institute for Chemical Processing of Coal in Zabrze (IChPW) [29]. The absorption process analysis showed that the packing section was not high enough to achieve sufficiently high values of amine loadings at the column outlet. This was manifested by a sudden halt in the CO_2 separation process when the solvent left the packing section. This happened in most cases even before the reaction rate reached its maximum level. Common pilot installations contain a packed bed of heights within the range 3.3 m - 11.1 m [30, 31]. Moreover, the small height of the packing also has a noticeable impact on temperature estimation at the absorber outlet. CO_2 absorption is an exothermic process accompanied with a noticeable heat release [32]. The reaction rate did not achieve a local maximum and

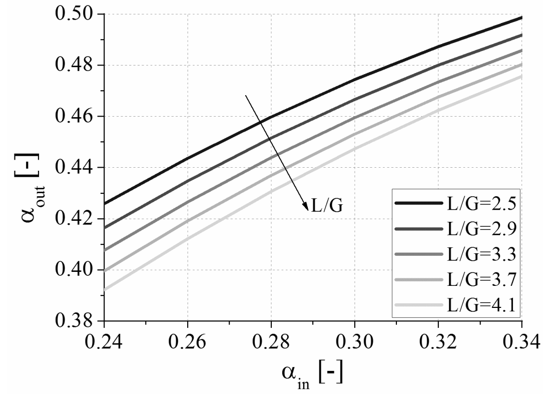

Figure 3: α_{in} vs α_{out} for selected values of L/G in the absorber column

the heat released due to the exothermic feature of the chemical absorption was significantly reduced and thus the rise in solvent temperature in the packing section was reduced as well.

According to the available literature, the reduction in heat duty to the value of 3.7 MJ/kgCO_2 for L/G=4 is possible when the MEA loading at the absorber outlet is close to the value of α_{out}=0.452 under the inlet value of $\alpha_{in} = 0.213$ [13]. This means that the difference between outlet and inlet loading should be equal to $\Delta\alpha = 0.239$ for $L/G = 4$. Fig. 3 shows the range of changes of rich loading as a function of lean loading for selected values of L/G. The results were obtained with the use of the 0D model of the PCC process. As can be seen, the outlet loading decreases with the rise in L/G. Moreover, the difference between loadings with the rise in inlet loading decreases from $\Delta\alpha = 0.15213$ for $\alpha_{in} = 0.24$ to $\Delta\alpha = 0.13562$ for $\alpha_{in} = 0.34$ for the highest considered $L/G = 4.1$. Taking into account the loading rise of $\Delta\alpha = 0.15213$ for $\alpha_{in} = 0.24$ shown in Fig. 3, this means that the difference is about 30% smaller than the one given in work [13]. That is why the heat demand of the process determined with the use of the 0D PCC model is noticeably larger.

Further investigations were performed in light of this discrepancy. During the computations the live steam flux remained unchanged for each analyzed case. Four configurations of ultra-supercritical PP were considered during the calculations:

- reference unit – without PCC,
- with PCC and for $L/G = 2.5$,
- with PCC and for $L/G = 3.0$,
- with PCC and for$L/G = 3.5$.

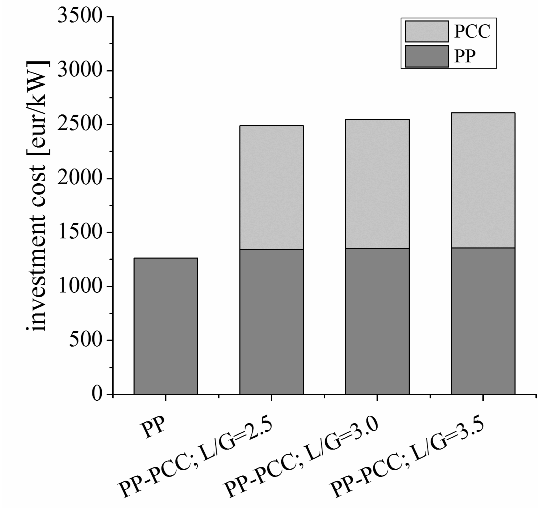

Figure 4: Investment cost of PP with and without PCC related to 1 kW power

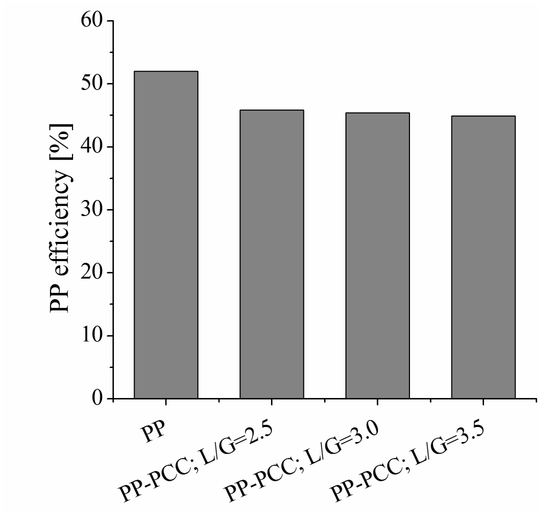

Figure 5: PP efficiency with and without PCC

Fig. 5 provides information about PP efficiency defined as a ratio of total power generated to the fuel chemical energy. A noticeable decrease in efficiency from 52.11% to 45.84% can be observed as a result of the implementation of the PCC unit. Moreover, the increase in L/G from 2.5 to 3.5 leads to a decrease in PP efficiency from 45.84% to 44.88%.

5. Economic analysis of PCC coupled with PP

Integration of the PCC installation with the thermal cycle unit leads consequently not only to a decrease in PP efficiency but also to an increase in the production

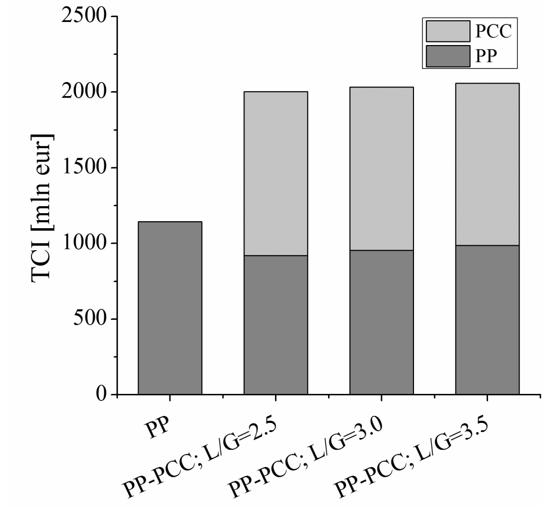

Figure 6: TCI of PP with and without PCC

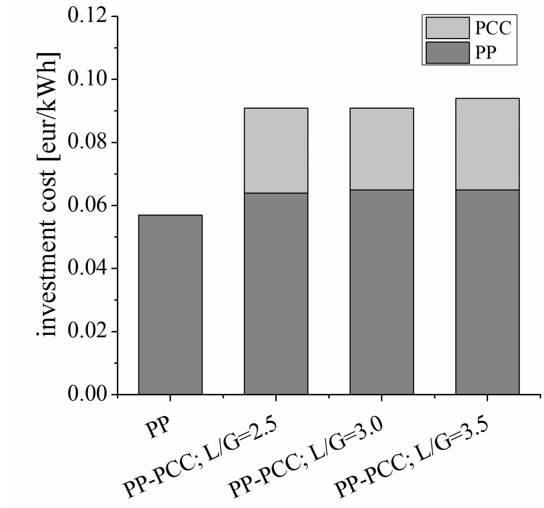

Figure 7: Investment cost of PP with and without PCC related to the 1 kW power

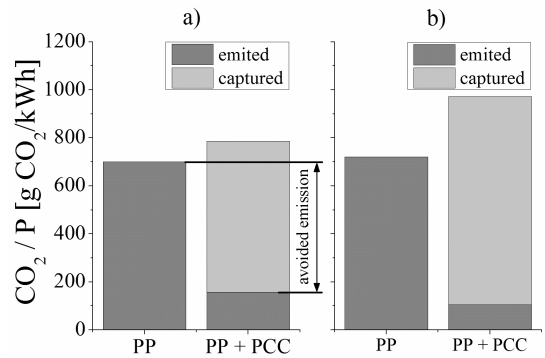

Figure 8: Comparison of amount of CO_2 produced in the installation with and without PCC, IMC results (a) and data taken from work [35] (b), both figures share the same scale

cost of electricity. An advanced thermoeconomic approach is necessary to estimate the profitability of the PCC installation. For that purpose a Revenue Requirement Method (RRM) was used for the economic analysis of the modelled installation. A detailed description of the RRM approach, together with assumptions made, can be found in the work [33].

The study also investigated the impact of the PCC installation and investment costs. Fig. 4 shows the Total Cost Investment (TCI) related to power for each considered case. Implementation of the PCC unit requires additional heat to be supplied, which consequently leads to a decrease in PP output power. Purchase Equipment Cost (PEC), i.e., costs of each device in the installation are calculated based on the actual values of PP operating conditions. This means that with the change in PP output power, local values of the main operating parameters (temperatures, pressures, enthalpies, etc.) change as well. Thus it influences the investment cost presented in Fig. 4 in the form of dark-gray bars. As can be seen, on one hand, implementation of the PCC installation causes only a minor rise in PP unit cost. However, taking into account the PCC installation total investment cost rises from 85% to 91.9% for $L/G = 2.5$ and $L/G = 3.5$ respectively.

Analyzing the TCI of PP alone (see Fig. 6) it can be seen that the value of this particular economic indicator decreases when the PCC installation is implemented. The main reason for this feature results from a steam drain from the PP for amine solvent regeneration purposes in the stripper column. This leads to a reduction in the size of some PP devices, in particular in the LP section, which consequently results in lower PEC related to their reference prices.

Fig. 7 provides information about the values of levelized plant cost (MPUC) for an assumed PP economic life of 20 years. For the PP alone the MPUC is equal to 0.057 EUR/kWh. Implementation of the PCC unit causes a increase in the value of MPUC of PP to about 0.064 EUR/kWh and up to 0.09 EUR/kWh for the entire installation (dark and light bars together). The data indicates that for the PP installation equipped with a PCC unit, the levelized cost rises from 40% to 44.6% for $L/G = 2.5$ and $L/G = 3.5$%, respectively.

The next part of this paper contains a supplementary cost analysis. It should be noted that the increase

Table 2: Comparison of PP parameters analyzed in Fig. 6 with additional data taken from the work [34]

		IMC	work [35]	work [34]	unit
output power	without PCC	905	600	582	MW
	with PCC	806	506	545	MW
plant efficiency	without PCC	52.11	45.9	41.4	%
	with PCC	45.46	34.3	30.9	%
CO_2 share in flue gas		15	15	-	%
CO_2 capture efficiency		80	90	90	%
CO_2 emission	without PCC	700.7	726	820	gCO2/kWh
	with PCC	157.4	97	111	gCO2/kWh
change in CO2 emission		12.3	32.2	-	%

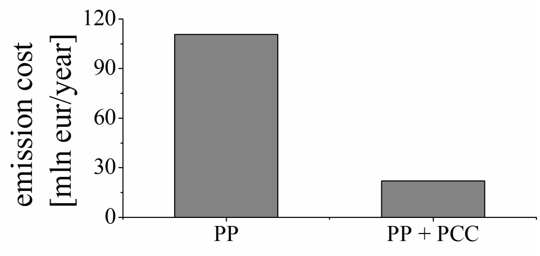

Figure 9: Comparison of CO_2 emission from PP without and with PCC in a one year period.

in PP efficiency results in lower fuel consumption and therefore causes a reduction in CO_2 emissions related to 1 kWh. On the other hand after the implementation of the PCC into the PP, additional energy is required for CO_2 separation, which leads to a decrease in PP efficiency and an increase in CO_2 production related to 1 kWh. Tab. 2 contains complete data for the discussed power plants and comparison with reference data. The first one [35] is a study performed at a selected coal fired power plant in Germany, while the second [34] is a report on carbon capture plant operating in the USA. Fig. 8 presents the changes in CO_2 emissions resulting from both implementation of the PCC unit and decrease in PP efficiency for two different installations, i.e., present (for $L/G = 3.5$) and the one analyzed in the work [35]. It should be noted that the compared installations are not identical. The most important differences are manifested in parameters such as nominal power and PP efficiency (see Tab. 2 for more details). These discrepancies have a noticeable impact on total CO_2 emissions per unit of power. As can be seen from Fig. 8. the PP analyzed in this paper is characterized by almost identical CO_2 emissions per unit of power as the one in [35].

The difference appears after implementation of the PCC unit when the CO_2 emission rises by 12.3%. This increase is just 1/3 of the increase that happens when the installation from [35] is concerned. This may result from the much greater decrease in PP efficiency for the reference case.

The object of further study was the analysis of both the cost related to CO_2 emission into the atmosphere and its reduction after the implementation of the PCC unit. For that purpose the cost of emission was taken from [36] as 21.8 Euro/MgCO_2, whereas the total operating time was assumed to be 8000 hours in a one year period. As can be seen from Fig. 9 the emission cost of a 905 MW power plant is 110.5 million euros per year. Implementation of the PCC unit leads to a reduction in that cost to 22.1 million euros per year. During the entire PP life time (20 years) this leads to a saving of about 1768 million euros. Taking into account the TCI of the PCC unit at the level of 1150 million euros, it can be estimated that about 14 years is required to compensate the investment cost. After that payback period the PCC installation becomes profitable.

6. Conclusions

The search for the optimal configuration of the post combustion capture unit is a very important issue, as its implementation to the power plant leads to a substantial decrease in thermal cycle efficiency. To carry out the necessary thermodynamic analysis a 0D model of post combustion capture installation was developed based on complex CFD calculations of the absorber and stripper.

Thermodynamic and economic calculations were performed for a power plant coupled with a CO_2 separation unit for varying ratios of amine solvents to exhaust gas (L/G). The thermodynamic study of PP coupled with the PCC unit revealed the presence of a local minimum for heat demand for L/G≈3.5, being the optimal configuration for CO_2 separation purposes.

The economic estimations of the investment cost were performed for four different ultra-supercritical PP configurations: the thermal cycle alone and equipped with a PCC unit and for that case three different L/G values were examined. It was observed that implementation of a PCC unit leads to a slight increase in the unit cost of reference PP and to a significant increase in unit cost where the entire installation is concerned. It was also observed that the TCI increased with the rise in L/G. It was estimated that about 14 years is required to compensate the investment cost of the PCC installation.

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