Modelling of CO_2 capture using Aspen Plus for EDF power plant, Krakow, Poland

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Abstract

This work describes the functioning of the EDF CHP plant, Krakow, Poland and modelling of CO_2 capture unit. Aspen Plus simulation software was used for modeling of the reference thermal-steam cycle model of the power unit in EDF CHP plant, Krakow, Poland. Coal is combusted at the mass flow rate of 32.5 ton/h with boiler thermal efficiency of 212.4 MW. After the development of power unit model, CO_2 capture unit using the post combustion capture method was modelled. Aqueous monoethanolamine (MEA) is used as the solvent for absorption of CO_2 since it is highly reactive with CO_2 and CO_2 capture of 85% was envisaged in this model. The models were developed in order to integrate the power unit and capture unit. Integration relies on the most optimal arrangement for steam utilization from the power unit so that there will be minimum efficiency reduction of the plant. The results obtained from the simulation model provide the amount of CO_2 that is not emitted in the atmosphere and how much energy is utilized for capturing. Finally energy penalty imposed by CCS unit using aqueous MEA as solvent on the EDF CHP plant was estimated. About 65.3 ton/h of CO_2 was captured with energy penalty of 8.1 MW by flue gas compressor and 209 GJ/h by stripper re-boiler. Thermal energy consumed by re-boiler is about 3.2 GJ/ton CO_2, which is bit less than published literature data of 3.65 GJ/ton CO_2.

1 Introduction

Due to global warming and climate change there has been significant increased in efforts to reduce the green house gasses in the atmosphere. One of the major green house gas in the atmosphere is CO_2. IPCC (Intergovernmental Panel on Climate Change) have said to reduce the global CO2 emissions by 50-80% by 2050 [1].

Economic growth of any country can be measured by amount of its CO_2 emission. As the country is more developed it will utilize more Energy and the energy is produced and utilized at the cost of increase green house gases emission in the atmosphere. Top 4 CO_2 emitting countries are China (28.03%), U.S (15.9%), India (5.81%) and Russia (4.79%). China emits more CO_2 compare to the total of next two countries U.S and India together [2].

Most of the energy used by a country is in the form of electric energy. Future trend of electricity demand shows that the demand for electricity is expected to rise for more than 65% from year 2014 to 2040 i.e about 2.5 times faster than overall energy demand. The growth of demand will mainly take place in non-OECD countries like China and India due to there increasing population and expanding economies. Electricity demand in India will rise by almost 185% by 2040. In 2014 almost 50% of the electricity is used in industrial sector and 50% in Residential and Commercial regions. It is estimated that industrial electricity demand will rise by 55%, while there will be rise of 70% in residential and commercial electricity demand from year 2014-2020. Demand of electricity for transportation will be doubled by 2020 [3].

It has been forecasted that by the year 2040 oil, natural gas and coal will be providing about 80% of the energy demand of the world [4]. Since global energy supply will mostly be dependent on Coal and electricity demand is going to increase in the future, new ways need to be assessed in order to reduce the CO_2 emissions from the coal fired power plants. CO_2 can be captured basically by 3 ways oxyfuel combustion, pre combustion CO_2 capture and post combustion CO_2 capture. Post combustion capture is generally utilized since it is much easier to retrofit in currently running power plant. As the name suggests post combustion capture involves separating CO_2 from the fuel gas after the combustion of fuel.

2 EDF Power Plant Overview

The coal fired power plant in EDF Krakow is a medium-size coal-fired power plant located in the eastern part of Krakow City. The construction process of power plant was started in 1963 and has been completed by 1986. The plant is divided into 4 units and each unit has its separate power cycle. Total capacity of plant is 460 MW electric and 1118 MW thermal. In the winter time EDF power plant acts as one of the major hot water distribution center of Krakow City. About 63% of the citizens in Krakow use hot water from municipal system of which 72% is delivered by EDF Krakow. In co-generation mode, total efficiency of power plant is about 85% but it only have 35% electricity generation effieciency.

2.1 Functioning Of Power Plant

A pulverized coal fired boiler is an industrial or utility boiler that generates thermal energy by burning pulverized coal (also known as powdered coal or coal dust since it is as fine as face powder in cosmetic makeup) that is blown into the firebox. The basic functionality of a firing system using pulverized fuel is to utilize the whole volume of the furnace for the combustion of the solid fuels. Coal is grounded to the size of fine grain, mixed with air and then burned in the flue gas flow. Biomass and other material can also be added to the mixture. Coal contains mineral matter which is converted to ash during combustion. The ash is removed as bottom ash and fly ash. The bottom ash is removed at the furnace bottom. This type of boiler dominates the electric power industry, providing steam to drive large turbines. Pulverized coal provides the thermal energy which produces about 50% of the world electric supply.

EDF Power plant is comprised of four units. Two of them are equipped with 120MW RAFAKO OP-380 pulverized coal boilers, connected with the condensing turbine containing steam split. Those splits are used in the winter time to heat up water for municipal heating network.

Another two units are equipped with 110MW RAFAKO OP-430 pulverized coal boilers connected with the back pressure turbine. These two units do not contain condenser. When there isn't sufficient demand of hot water, then cooling towers are used to cool down steam from these units. There are two cooling tower in the power plant. All turbines are linked to the 13.8 kV, hydrogen-cooled generators.

3 Aspen Plus Overview

Aspen Plus is a computer aided simulation and chemical process optimisation software used in petrochemical, polymer and other manufacturing industries for the design, operation, and optimization of safe, profitable manufacturing facilities.[5]

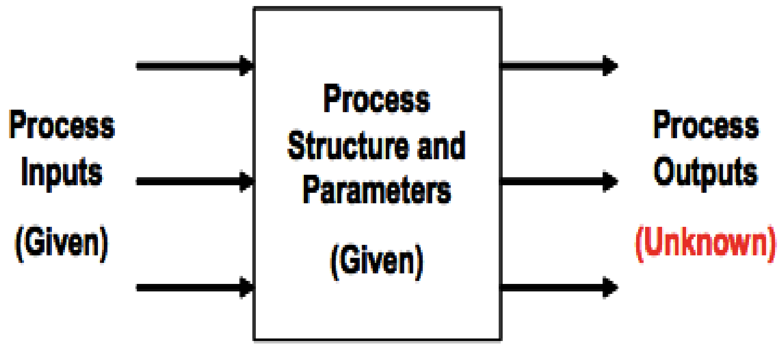

Figure 1: Process simulation model [6].
(Source:http://wp.auburn.edu/eden/wp-content/uploads/2012/03/4460-Aspen-Notes-2012.pdf)

Simulation softwares are used to predict the behaviour of the process and in order to do that a process model has to be defined. Process model is a complete layout and it consist of flowsheet, chemical components and operating conditions.

4 Setup

Chemical absorption method was used among the available post combustion carbon capture methods for this work. The basic schematic of CO_2 capture is shown in figure 2. CO_2 from the flue gas is absorbed in solvent in the absorber section, cleaned gas is released from the top and solvent rich in CO_2 pass from the bottom of absorber to the stripper section. The solvent used for absorption of CO_2 is monoethanolamine (MEA). In the stripper section the CO_2 is stripped from the rich solvent and released from the top and the lean solvent is recycled back to the absorber column [7].

Different amines like MEA, MDEA, DEA can be used for absorbing CO_2. CO_2 is absorbed in the amines in different ways and it follows different mechanisms. These amines are bases and they react with the acid, they are also soluble in water due to the presence of the alcohol group. These amines can be classified as primary, secondary or tertiary amines according to the different organic group that is attached to the Nitrogen. These different amines react differently, primary and secondary amines have higher heat of absorption and hence react faster compare to the the tertiary amine but high amount of energy is required in order to regenerate the primary and secondary amine. CO_2 reacts with MEA amine solution to undergo Carbamate formation. Carbamate formation takes place by 2 mechanisms [8]

1. Zwitterion Mechanism

It is a 2 step mechanism. Firstlly water reacts with amine and a hydrogen bond is formed between the Amine and water molecule. Then the reaction with CO_2 takes place and a bond is formed between amine and CO_2. This is an unstable intermediate which further undergo proton transfer to form the carbamate [9].

2. Termolecular Mechanism

This is a single step mechanism. In it the bond formation and proton transfer take place simultaneously. Amine is the base molecule, it forms a bond with CO_2 and proton transfer take place in single step [9].

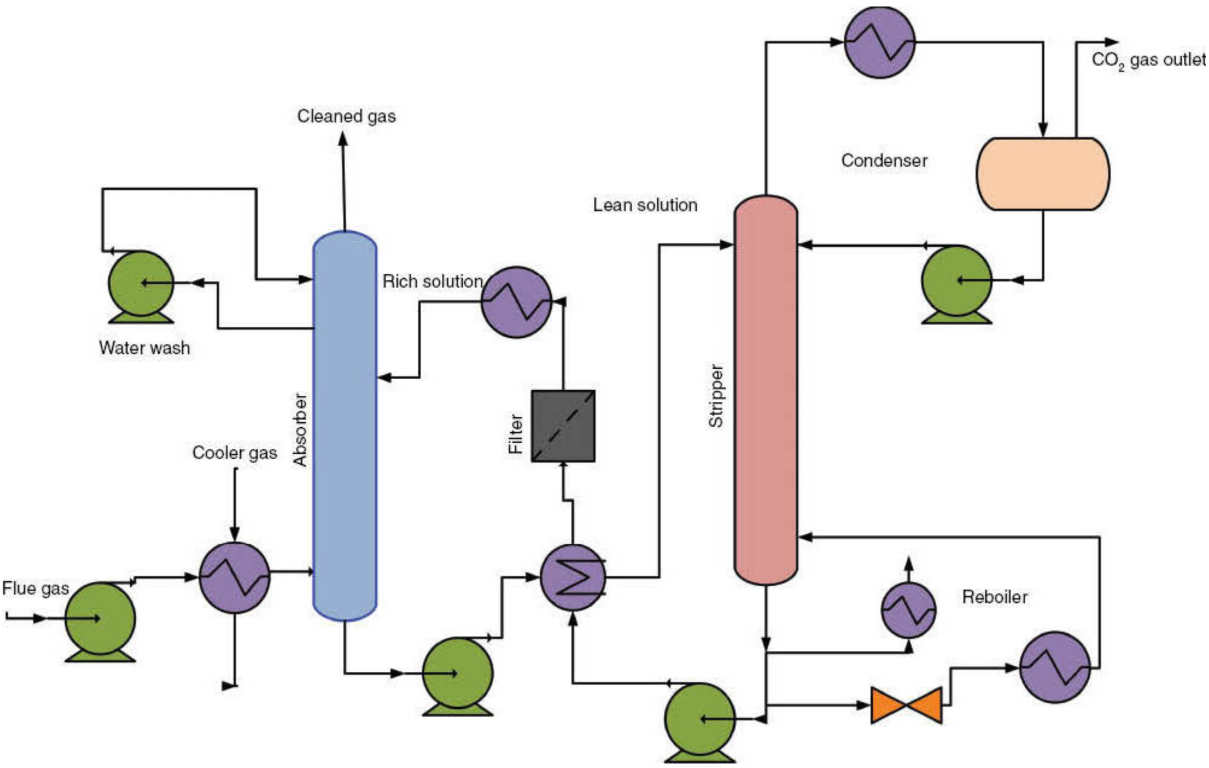

Figure 2: Basic Flowsheet Of Carbon Capture [7].

(Source:A review of CO_2 capture by absorption in ionic liquid-based solvents by S Babamohammadi, A Shamiri)

5 Modelling

5.1 Power Cycle Model

EDF power plant has 4 units, 2 with 120 MW capacity and 2 with 110 MW capacity. In this work one of the unit of power plant having 120 MW capacity is modelled using the data of power plant as on 18^{th} November 2011. The unit was operating at 84.853 MW load on that day. The model of steam cycle that simulates the performance of steam cycle of 84.8 MW unit of EDF power plant was developed. The model predicts the power output from the turbine and conditions (temperature, pressure and flow rate) of steam in the steam cycle.
The feed data of 18^{th} november 2011 was taken from EDF power plant, krakow, poland and feed specifications are as follows-:

Table 1: Steam Specification

	Units	Value
Temperature	°C	536.8
Pressure	kPa	11182
MassFlow	ton/h	296.3

The steam cycle is divided basically into 3 sections consisting of turbines, condenser and preheaters. Turbine is used in order to generate the electric energy, condenser is used to condense the steam from the outlet of LP turbine and preheaters are used in order to preheat the water flowing to the reboiler.

5.2 CO_2 Capture Model

CO_2 capture can be modelled in aspen plus in 2 ways, thermodynamic model and rate model. Thermodynamic model is used for simulation in this work. It is used in order to minimize the thermal energy required by the re-boiler and also for the easy convergence of the calculations compare to the complex rate based model. The thermodynamic model uses the E-NRTL theory which was developed by Chen and Evans (1979) and extended by Mock et al. (1986) for mixed solvent electrolyte systems. The CO_2 recovery of 85% is envisaged while modelling [10].

Two streams were specified for simulating the process, FLUE-IN and MAKE-UP. The flue gas is considered to be composed of only CO_2 , H_2O and N_2 while other components like O_2 and SO_2 are neglected. MEA make-up is added to the recycled stream before it enters into the absorber in order to compensate for the solvent loses during the absorption and stripping process. Solvent is added at atmospheric pressure and temperature.

The flue gas has a mass flow rate of 412.2 ton/h, temperature 150.1 °C, and pressure 98.8 kPa. Flue gas composition and operating conditions are taken from EDF power plant, Krakow, Poland from 18^{th} november 2011 data and is shown in table 1.

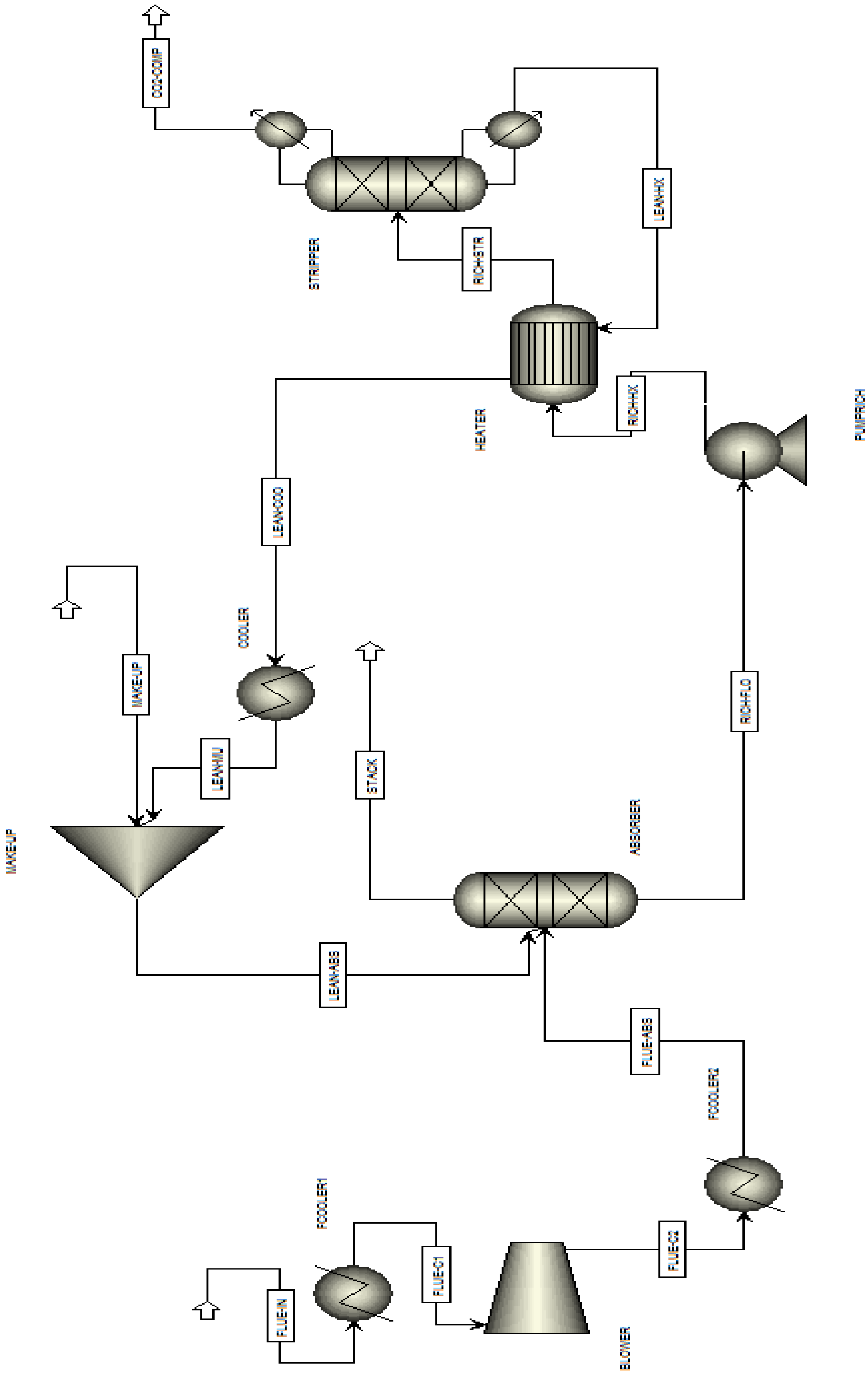

Figure 3: Aspen Plus flowsheet of CO_2 capture.

Table 2: Flue Gas Composition

Components	Flue gas mass fraction (wt%)
CO_2	18.66
N_2	77.52
H_2O	3.82
O_2	0
SO_2	0

6 Results And Discussions

6.1 CO_2 Capture Unit

The main problem with CO_2 capture is its high energy requirement.The carbon capture process needs energy mainly in 2 ways. First in the form of thermal energy in stripper re-boiler and second in the form of electric energy in the flue gas compressor. The energy requirement of the flue gas compressor is constant, since it depends mainly on the absorber pressure drop, absorber inlet pressure and the pressure at which flue gas is coming. Hence the process can be optimize only by varying the re-boiler duty requirement. So the optimal condition is one which require the minimum re-boiler duty. Energy is required in the re-boiler for 3 purposes-:

1. Generate steam from the condensed water ($Q_{steamgeneration}$).
2. Strip the CO_2 from MEA+CO_2 solution(Q_{strip}).
3. Heat the incoming solvent to the re-boiler temperature($Q_{sensibleheat}$).

$$Q_T = Q_{strip} + Q_{steamgeneration} + Q_{sensibleheat} \quad (1)$$

where Q_T = Total heat energy required by reboiler.

6.1.1 Effect of stripper pressure

Figure 4 shows how the stripper pressure affect the re-boiler duty. It can be seen that as the stripper pressure is increasing the re-boiler duty is decreasing. Since as the pressure increases there is increase in the temperature, and at higher temperature there is more H_2O and CO_2 in the gaseous phase so less amount of steam is required for stripping the CO_2 from the rich amine solvent.

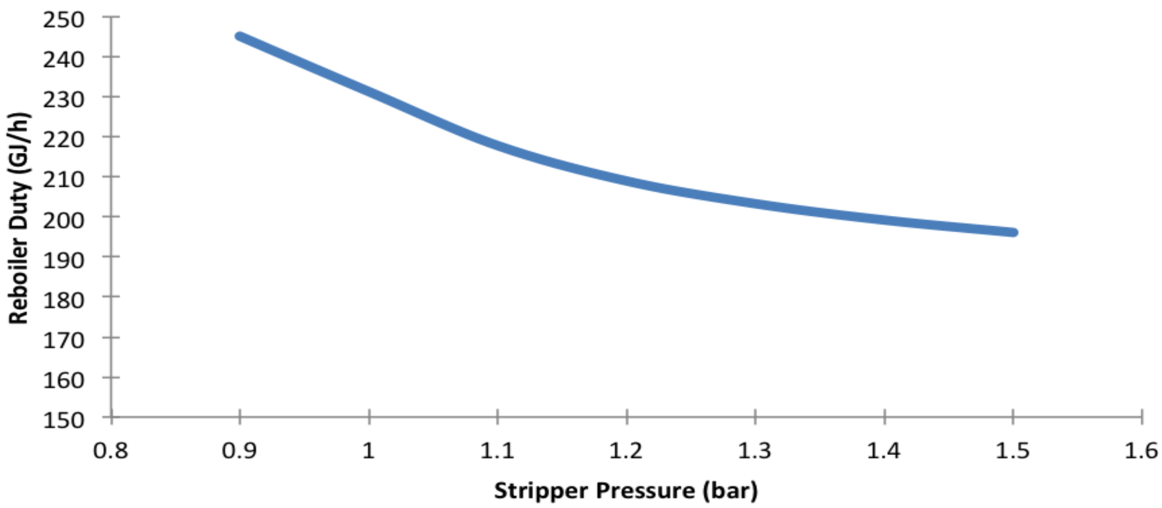

Figure 4: Effect of stripper pressure on re-boiler duty.

6.1.2 Effect of solvent flow rate and lean loading

As the solvent flow rate in the absorber is reduced the absorption rate also reduced since lean loading is increased in the absorber. Lean loading is the ratio of moles of CO_2 to moles of MEA present in the lean amine solvent. Due to the increased lean loading there is less absorption of CO_2 in the absorber so in order to keep the high absorption rate lean loading has to be kept low. But at low lean loading the re-boiler duty was much higher since more energy was required in order to heat the solvent and vaporize the water. For the optimal condition lean loading of 0.08 was kept. Due to the convergence problem, initially an open flow sheet was simulated with 30% MEA concentration in solvent and the flow rate of 624.1 ton/h.

6.1.3 Effect of CO_2 Capture Rate on Heat Duty

The capture rate is defined as the ratio of mass flow rate of CO_2 from top of stripper to mass flow rate of CO_2 in flue gases. Base case of 85% CO_2 capture utilizes 209 GJ/h of heat duty in stripper reboiler.
Mass flow of CO_2 in flue gas = 76.9 ton/h
Mass flow of CO_2 from top of stripper = 65.3 ton/h

Table 3: Effect of Carbon Capture % on Re-boiler Heat Duty.

Capture Rate (%)	Re-boiler Duty (GJ/h)
90 %	242
85 %	209
80 %	184

Table 2 depicts the effect of CO_2 capture % on the re-boiler duty. Re-boiler duty is increasing as the capture rate is increasing, since more solvent is required to capture the increased amount of CO_2 and thus more energy is required for sensible heat in the re-boiler.

6.2 Power Plant Efficiency After Capture Process

In the base case of 85% CO_2 capture compressor utilizes 8.10 MW of energy to compress the flue gas from 98.79 kPa to 157 kPa. Also a small amount of energy is required by rich amine pump which is 42.47 kW, so a total of 8.142 MW of energy is required in CO_2 capture unit. This energy requirement is satisfied by the electric power produced by the steam turbine which is about 84.4 MW. This leads to the electric power efficiency reduction of about 9.64% .

Table 4: Electric Energy Required.

Equipment	**Value**
Flue Gas Compressor	8.1 MW
Rich Amine Pump	42.47 kW

In the power plant unit about 467.5 GJ/h of heat energy is used for providing heat to district heating and 419.8 GJ/h is used for the electric energy production in turbines. Heat duty required by the re-boiler for the stripping process is 209 GJ/h, which is about 3.2 GJ/ton of CO_2 captured, this value is bit lower than the published literature value of 3.65 GJ/ton of CO_2 [11]. A part of this energy requirement is satisfied by the heat duty from the heat exchanger used to cool the flue gas. About 35.8 GJ/h is produced in flue gas cooler 1 and 44 GJ/h is produced in flue gas cooler 2 so a total of 79.8 GJ/h of heat duty is obtained.

Hence total amount of heat duty required by the re-boiler is 209 - 79.8 GJ/h i.e 129 GJ/h. Steam from LP split 1 is utilized for providing this heat duty, this steam is going to XB heat exchanger, and flowing at the rate of 94 tonnes/h , temperature 137 °C and having an enthalpy of 2754.6 kJ/kg. The amount of steam required for providing 129 GJ/h of heat duty is calculated to be 47 tonnes/h.

Thermal efficiency of the power plant is reduced by 30.8 % in providing the steam to stripper re-boiler while assuming there is no heat loss taking place in heat exchangers during transfer of thermal energy.

Table 5: Efficiency reduction after CO_2 capture process.

Energy	**Efficiency Reduction (%)**
Electric Energy	9.64
Thermal Energy	30.8

7 Conclusions

The model was designed in order to add a CO_2 capture unit in the EDF power plant, Krakow, Poland in order to capture 85% of the CO_2 which is currently emitted in the atmosphere and hence reducing the greenhouse gas emission. From the results obtained it can be seen that a large amount of thermal energy is required by the re-boiler which leads to thermal efficiency reduction of 30.8%. Hence it can be concluded that the energy penalty by capture process is too high and it is not feasible to place a capture unit in power plant. Although in the future work different solvents or different post combustion capture methods like physical adsorption method can be used to study the effect on electric and thermal efficiency of the power plant.

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