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Dipl.-Ing. Elizabeth Heischkamp,
Mülheim a. d. Ruhr

Nr. 953

Scrubbing System Design for CO_2 Capture in Coal-Fired Power Plants

LUAT Lehrstuhl für Umweltverfahrenstechnik und Anlagentechnik

Scrubbing System Design for CO_2 Capture in Coal-Fired Power Plants

Von der Fakultät für Ingenieurwissenschaften, Abteilung Maschinenbau und Verfahrenstechnik

der

Universität Duisburg-Essen

zur Erlangung des akademischen Grades

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von

Elizabeth Heischkamp
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Gutachter: Univ.-Prof. Dr.-Ing. habil. Klaus Görner
Univ.-Prof. Dr. techn. Günter Scheffknecht

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Within the last decades a continuous tightening of environmental regulations has been observed in several countries around the world. These include restriction of anthropogenic CO_2 emissions, since they are considered responsible for intensifying global warming. Coal-fired power plants represent a good possibility for capturing CO_2 before it is emitted in the atmosphere, thereby contributing to combat global warming. This work focuses on reducing the CO_2 emissions of such a power plant by 90 %. For this purpose a hard coal power plant is retrofitted with a chemical absorption using different solutions of piperazine promoted potassium carbonate. The resulting power plant's efficiency losses have been accounted for. A comparison of different scenarios such as the variation of operating parameters offer an insight in detecting suitable operating conditions that will allow to minimize efficiency penalties. Simulation details are provided along with a technical and an economic analysis.

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Mülheim an der Ruhr, 2017

Elizabeth Heischkamp

Index

Acronyms and abbreviations

AHPC	Activated Hot Potassium Carbonate
aMDEA	Activated Methyl Diethanolamine
AMP	2-Amino-2-Methyl-1-Propanol
ASU	Air Separation Unit
CaL	Calcium Looping
CAP	Chilled Ammonia Process
CAPEX	Capital EXpenditure
CLC	Chemical Looping Combustion
DCC	Direct Contact Cooler
DEA	Diethanolamine
DIPA	Diisopropanolamine
EPC	Engineering, Procurement, and Construction costs
ESA	Electric Swing Adsorption
EUA	European Emission Allowance
FG	Flue Gas
FGD	Flue Gas Desulphurisation
GDPC	Generalized Pressure Drop Correlation
GTCC	Gas Turbine Combined Cycle
GWP	Global Warming Potential
HETP	Height Equivalent to a Theoretical Plate
HP	High Pressure
HPC	Hot Potassium Carbonate
IEA	International Energy Agency
IEA GHG	IEA Greenhouse Gas R&D Programme
IGCC	Integrated Gasification Combined Cycle
IMTP	Intalox Metal Tower Packing
IP	Intermediate Pressure
IPCC	Intergovernmental Panel on Climate Change
IPFO	Interface-Pseudo-First-Order
L/G ratio	Liquid to Gas ratio
LCOE	Levelised Cost of Electricity
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
LP	Low Pressure
MAPA	Methyl Amino Propylamine

MDEA	Methyl diethanolamine (also known as N-methyl diethanolamine)
MEA	Monoethanolamine
NRTL	Non-Random Two-Liquid
OPEX	OPerational EXpenditure
PIP	Piperidine
PSA	Pressure Swing Absorption or Adsorption (as the case may be)
PYR	Pyrrolidine
PZ	Piperazine
RPP NRW	Reference Power Plant NRW
TA-Luft	Technische Anleitung zur Reinhaltung der Luft – Technical Instructions on Air Quality Control
TEA	Triethanolamine
TSA	Temperature Swing Adsorption
UOM	Unit Operation Model
VLE	Vapour-Liquid Equilibrium
WoI	Working Investment
ZEP	Zero Emissions Platform
ZEP PP	Zero Emissions Platform reference Power Plant

Nomenclature

A	[m^2]	Heat transfer area
a	[-]	Annuity factor
A_T	[m^2]	Column cross-sectional area
b	[mol/kg] also [m]	Molality
c	[mol/L] also [M]	Molarity
CaI_{fixed}	[M€]	Fixed capital investment
$CAPEX$	[€/MW]	Capital expenditure
C_{av,CO_2}	[€/t_{CO_2}]	CO_2 avoidance cost
C_{fuel}	[€/MWh]	Levelised fuel cost
$Column_i$	[M€]	Price of selected reference column
$Compressor$	[M€]	CO_2 compressor investment
CP	[$(m/s)(m^{-1})^{0.5}(m^2/s)^{0.5}$]	Capacity factor (packed towers)
C_s	[m/s]	C-factor based on tower superficial cross-sectional area
d	[m]	Column diameter
DC_{total}	[M€]	Total direct cost
E	[kJ/kmol]	Activation energy
e_b	[t_{CO_2}/MWh]	Specific CO_2 emission factor for hard coal
$e_{CO_2,CC}$	[t_{CO_2}/MWh]	Specific CO_2 emissions of RPP NRW with carbon capture
$e_{CO_2,ref}$	[t_{CO_2}/MWh]	Specific CO_2 emissions of RPP NRW
F	[$m/s(kg/m^3)^{0.5}$]	F-factor for gas loading
F_{LG}	[-/-]	Flow parameter
F_p	[m^{-1}]	Packing factor
F_p	[m^{-1}]	Packing factor
G	[$kg/(s \cdot m^2)$]	Gas phase mass velocity
h	[h]	Operating hours
h	[m]	Packing height

H_u	[kJ/kg]	Lower heating value
i	[mol/L]	species *i* concentration
IC_{total}	[M€]	Total indirect cost
$ISBL$	[M€]	Inside the battery limits
k	[mol/(l·s)]	Pre-exponential factor (independent of temperature)
k	[W/m^{2}K]	Heat transfer coefficient
k_a	[-]	Activity-based rate constant
k_c	[-]	Concentration-based rate constant
L	[kg/(s·m^2)]	Liquid mass velocity
L/G	[l/m^3]	Liquid to gas ratio
$LCOE_{CC}$	[€/MWh]	Cost of electricity with carbon capture
$LCOE_i$	[€/MWh]	Levelised cost of electricity
$LCOE_{ref}$	[€/MWh]	RPP NRW's levelised cost of electricity
$\dot{m}_{CO_2}$	[kg/s]	CO_2 mass flow rate
$\dot{m}_{fuel}$	[kg/s]	Fuel mass flow rate
n	[-]	Temperature exponent
N_i	[kmol/(m^{2}s)]	species *i* molar flux
$OPEX$	[€]	Operational expenditure
$OSBL$	[M€]	Outside the battery limits
P	[W]	Power
$P_{compression}$	[kW]	Electric demand by compression
p_{des}	[bar]	Desorber pressure (gauge)
$P_{expansion}$	[kW]	Electric demand by expansion
P_i	[MW]	Power plant net output
p_{ref}	[bar]	Reference pressure
$\dot{Q}$	[W]	Heat duty, heat transfer capacity (heat exchanger)
r	[mol/(l·s)]	Reaction's rate
r	[-]	Interest rate

R_{CC}	[%]	CO_2 capture rate (0% < R < 100%)
R_{CO_2}	[kJ/kg·K]	CO_2 gas constant
$Solvent$	[M€]	Solvent cost
$Startup$	[M€]	Start-up cost
T	[K]	Reference temperature (298.15K)
T	[-]	Plant life
T_{amb}	[bar]	Ambient temperature
u_s	[m/s]	Superficial gas velocity
$\dot{V}_G$	[m^3/s]	Gas rate
V_{new}	[m^3]	New column's packing volume
V_{ref}	[m^3]	Reference column's packing volume (MEA Case I)
w_{comp}	[kJ/kg]	Specific compressor work
x_i	[-]	species *i* fraction of reactant
x_i	[-]	reactant species *i* mole fraction
x_i	[kmol/kmol]	species *i* liquid phase mole fraction
y_i	[kmol/kmol]	species *i* gas phase mole fraction

Greek symbols		
α	[$mol_{acid\ gas}/mol_{alkalinity}$]	Loading
α_i	[-]	species *i* reaction order
α_{lean}	[$mol_{CO_2}/mol_{alkalinity}$]	Lean loading
α_{rich}	[$mol_{CO_2}/mol_{alkalinity}$]	Rich loading
δ	[m]	film thickness
ρ_G	[kg/m^3]	Gas density
ρ_L	[kg/m^3]	Liquid density
$\Delta\theta$	[K]	Temperature difference
$\Delta\eta$	[% points]	Efficiency losses due to CCS
γ	[-]	activity coefficient

η	[-]	Efficiency
η_i	[-]	Power plant net efficiency
η_{is}	[-]	Isentropic efficiency
η_{ref}	[%]	RPP NRW's net efficiency
ν	[m^2/s]	Kinematic viscosity of liquid

Subscripts	
el	electric
flood	at flood
i	RPP NRW or carbon capture (CC)
PZ	Piperazine

Superscripts	
B	bulk
gross	gross value
G	gas
i	species i
I	interface
L	liquid
net	net value
ref	reference