Markus Junk

Technical and economical assessment of various carbonate looping process configurations



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Technical and economical assessment of various carbonate looping process configurations

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Preface

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Nomenclature

<u>Latin symbols</u>

а	Decay constant of the solid fraction in the lean phase	1/m
Α	Carbonator cross section	m^2
AD	Annual depreciation	€/a
AEP	Annual electricity production	MWh
AEP_n	Electricity production in the year n	MWh
AH	Annual hours of operation	h
b	Decay constant of the contact efficiency in the lean phase	1/m
С	Concentration	-
СС	Capital costs	€
CC_n	Capital costs in year n	€
c _{CO2}	Average CO_2 concentration in the carbonator	mol/m³
$c_{CO2}*$	Equivalent CO ₂ concentration in the carbonator	mol/m³
D	Carbonator diameter	m
d_p	Particle diameter	m
DP	Depreciation period	а
d_p*	Dimensionless particle diameter (K-L Model)	-
Ε	CO ₂ capture efficiency	-
Ea	Activation energy	J/mol
<i>e</i> _{max}	Average carbonate layer thickness on the calcium oxide	m
F_0	Molar make-up-flow (CaCO ₃)	mol/s
f_a	Fraction of active CaO in the carbonator	-
F _{Ash}	Molar ash flow introduced into the CL process	mol/s
FC	Fuel costs	€
f_{Calc}	Average calcination efficiency	-
f_{Carb}	Average carbonation in the carbonator	-
FC_n	Fuel costs in the year n	€
F_{CO2}	Molar CO ₂ flow to the carbonator	mol/s
f_{m} , f_{w}	Limestone specific parameter	-
FOC	Fixed operating costs	€

FOC_n	Fixed operating costs in the year n	€
FP	Fuel price	€/t
F_R	Molar CaO flow in the solid loop	mol/s
F _{R,Ash}	Molar ash flow in the solid loop	mol/s
$F_{R,S}$	Molar calcium sulfate flow in the solid loop	mol/s
F_{Rt}	Molar solid circulation flow between reactors	mol/s
F_S	Molar calcium sulfate flow introduced into the CL process	mol/s
g	Gravity	m/s ²
G_s	Specific mass flow at the carbonator exit	kg/m²*s
h	Specific enthalpy	J/kg
Н	Enthalpy	J/mol
H_d	Height of the dense phase	m
H_l	Height of the lean phase	m
HP	Heating price	€/MWh _{th}
HP_n	Heating price in the year n	€/MWh _{th}
H_t	Total height of the carbonator	m
i	Full cylces without make-up introduction	-
<i>IC_{Total}</i>	Total investment costs	€
IDC	Interest during construction	€
I_n	Interest payment in the year n	€
k	Deactivation constant of the sorbent	-
Κ	Equilibrium constant	-
<i>k</i> '''	Reaction rate constant of a first order reaction (K-L model)	-
k'	Reaction rate constant	-
k_0	Reaction constant of the Arrhenius equation	-
K _{cw}	Exchange coefficient (core-wall)	1/s
k_r	First order reaction rate constant of the carbonation reaction	m³/mol*s
k_{ri}	Average reaction velocity of the carbonation reaction of the active sorbent particel	1/s
k_s	Intrinsic reaction rate constant of the carbonation reaction	m ⁴ /mol*s
LAR	Levelized asset retirement costs	€/MWh
LC	Levelized costs of the respective cost component	€/MWh

LCC	Levelized capital costs	€/MWh
LCOE	Levelized costs of electricity	€/MWh
$LCOE_{PP}$	LCOE of reference plant without IHCL process	€/MWh
$LCOE_{PP+IHCL}$	LCOE of reference plant with IHCL process	€/MWh
LFC	Levelized fuel costs	€/MWh
LFOC	Levelized costs of electricity	€/MWh
LHV	Lower Heating Value	MJ/kg
LVOC	Levelized variable operating costs	€/MWh
∆LCOE	Difference of the LCOE (reference plant with and without IHCL)	€/MWh
т	Mass	kg
'n	Mass flow	kg/s
Μ	Molar mass	g/mol
n	Mole	mol
Ν	Number of cycles	-
N_{age}	Number of full carbonation/calcination	-
NPV	Added net present values of the respective cost component	€/MWh
ОС	Owner costs	€
р	Pressure	Pa
Р	Electrical power	W
p_{CO_2}	Price of CO ₂ certificate	€/t CO ₂
P _{el,gr}	Electrical Gross Power	$\mathrm{MW}_{\mathrm{el}}$
PR	Performance ratio	-
Q	Heat flow	W
R	Universal gas constant	J/kmol*K
$r_{Fo,}$	Age structure at the last make-up introduction	-
r _N	Fraction of the particles in cycle N	-
<i>r</i> _{Nage}	Fraction of particles with $\mathrm{N}_{\mathrm{age}}$ full carbonation/calcination cycles	-
S	Active reaction surface	
S_0	Initial active reaction surface	m^{2}/m^{3}
S_N	Specific active reaction surface of one particle in cycle N	m^{2}/m^{3}
sp.AR	Specific costs for asset retirement	€/MW _{el,gr}

sp.FOC _n	Specific fixed operating costs in the year n	€/MWh _{el,gr}
$sp.TC_n$	Specific total costs in the year n	€/ MWh _{el,gr}
sp.VOC _n	Specific variable operating costs in the year n	€/MWh _{el,gr}
Т	Temperature	° C
t	Time	S
TC_n	Total costs in the year n	€
t _{lim}	Time that is necessary to reach full conversion	S
TPC	Total Plant Costs	€
и	Gas velocity	m/s
u_0	Superficial gas velocity	m/s
u_t	Terminal velocity	m/s
u_t^*	Dimensionless terminal velocity	-
V	Volume	m ³
<i>॑</i> V	Volume flow	m³/s _{i.Br.}
v/r	Reaction rate	1/s
V_M	Molar volume	m³/mol
VOC	Variable operating costs	€
VOC_n	Variable operating costs per year	€
W	Velocity	m/s
W_s	Solid inventory carbonator	kg
Χ	Particle conversion	-
X _{ave}	Average sorbent conversion	-
x_i	Mole fraction	-
X _{max,ave}	Average maximum sorbent conversion	-
X_N	Maximum conversion at the end of the fast reaction phase	-
X_r	Particle end conversion after a high number of cycles	-
у	Volume fraction	-
Z	Height	m

Greek symbols

δ	Core volume fraction of the dense phase	-
Δx_{CaSO4}	Average sulfated sorbent fraction per cycle	-
е*	Asymptotic solid volume fraction	-
\mathcal{E}_0	Particle porosity	-
Е	Solid volume fraction or auxiliary electrical power	-
η	Efficiency	-
μ	Viscosity	kg/m*s
ξ	Volume ratio of Ca particles to all particles in the system	-
ρ	Density	kg∕m³
τ	Average residence time (space time)	S
$ au_a$	Active space time	S
Ψ	Pore structure parameter	-

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Indices

0	Make Up
а	Potential active fraction
ave	Average
Calc	Calciner
сар	Captured
Carb	Carbonator
CL	Carbonate Looping
cond	Condenser
d	Dense phase
diss	Dissipated
el	Electric
eq	Chemical equilibrium
evap	Evaporator
F	Fuel
g	Gas phase
in	Input parameters



1	Lean phase
LS	Loopseal
max	Maximum
mf	Minimal Fluidization
NB	New Built
out	Outlet flow
PHR	Preheated Retrofit
R	Retrofit
\$	Solid phase
th	Thermal
tot	Total
W	Wall region of the fluidized bed

Most used chemical symbols

С	Carbon
C_3H_8	Propane
Ca(OH) ₂	Calcium hydroxide
CaCO ₃	Calcium carbonate (limestone)
CaO	Calcium oxide (burnt lime)
CH ₄	Methane
СО	Carbon monoxide
CO_2	Carbon dioxide
H_2	Hydrogen
H_2O	Water
N_2	Nitrogen
N_2O	Nitrous oxide
NO _x	Nitrous oxide
O_2	Oxygen
SO_2	Sulfur dioxide

Abbreviations

AG	Aktiengesellschaft (Stock company)
BFB	Bubbling Fluidized Bed
Cal	Calciner
Car	Carbonator
CCS/U	Carbon Capture and Storage/Utilization
CFB	Circulating Fluidized Bed
CFD	Computational Fluid Dynamics
CL	Carbonate Looping
CLC	Chemical Looping Combustion
COORETEC	CO ₂ -Reduktions-Technologien (Initiative of BMWi)
DEA	Diethanol-Amine
DEM	Discrete Element Method
EB	Entrained Bed
EPC	Engineering, Procurement and Construction
EPRI	Electric Power Research Institute
Eqs	Equation
EST	Institute for Energy Systems and Technology (TU Darmstadt)
EU	European Union
FAU	Friedrich-Alexander Universität Nürnberg
FGD	Flue Gas Desulfurization Unit
Fig	Figure
GKM	Grosskraftwerk Mannheim
GPU	Gas Processing Unit
Gt	Gigatonne
GW	Gigawatt
HE	Heat Exchanger
I/O	Input/output
IEA	International Energy Agency
IEAGHG	IEA Greenhouse Gas R&D Programme
IFK	Institut für Feuerungs- und Kraftwerkstechnik (Stuttgart)

IGCC	Integrated Gasification Combined Cycle
IHCL	Indirectly Heated Carbonate Looping Process
IHCL _{NP}	Indirectly Heated Carbonate Looping Process (New Build Plant)
IHCL _{PHR}	Indirectly Heated Carbonate Looping Process (Preheated Retrofit)
IHCL _R	Indirectly Heated Carbonate Looping Process (Retrofit)
INCAR-CSIS	Instituto Nacional del Carbón - CSIC
INDC	Intended Nationally Determined Contributions
IR	Imputed interest rate
IR _{AR}	Imputed interest rate for asset retirement
ITRI	Industrial Technology Research Institute (Taiwan)
K-L	Kunii-Levenspiel
$kW_{th} \\$	Kilowatt (thermal)
LP	Low Pressure
LT	Lifetime
M&E	Mass and Energy Balance
MEA	Monoethanol-Amine
MP	Medium Pressure
MW	Megawatt
n	Operating year
OECD	Organization for Economic Co-operation and Development
Ppm	Parts Per Million
PSD	Particle Size Distribution
RFCR	Research Fund For Coal and Steel
RK	Rotary Kiln
SCL _R	Standard Carbonate Looping (Retrofit)
SCR	Selective Catalytic Reduction (DeNO _x)
TGA	Thermogravimetric analysis
TUD	Technische Universität Darmstadt
UNFCCC	United Nations Framework Convention on Climate Change

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