Waste-To-Energy with carbon capture via Molten Carbonate Fuel Cells

Session XVII: Waste-to-Energy, 28 June 2019

S. Consonni, F. Viganò, M. Spinelli, L. Mastropasqua, S. Campanari

LEAP s.c.ar.l., Piacenza, Department of Energy, Politecnico di Milano
Motivation

Terminology: Waste-To-Energy (WTE) ↔ Energy from Waste (EfW)

1) Energy recovery is an essential ingredient of sustainable waste management

2) EfW with grate combustors and steam Rankine cycle dominates the production of electricity and heat from waste

3) Net Life-Cycle fossil CO\(_2\) emissions from EfW plants are low - even negative in several instances - but the goals set by the Paris agreement call for further efforts

4) Reducing direct CO\(_2\) emissions from EfW plants can further improve their environmental compatibility and improve their acceptance by the public opinion

5) Post-combustion CO\(_2\) capture appears the most suitable technology to reduce direct CO\(_2\) emissions from EfW plants

6) This work aims at assessing the performances achievable by post-combustion capture via Molten Carbonate Fuel Cells (MCFC)
### EfW plant

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal thermal capacity, $W_{LHV}$</td>
<td>200.0</td>
</tr>
<tr>
<td>No. of parallel lines</td>
<td>3</td>
</tr>
<tr>
<td>Design LHV, MJ/kg</td>
<td>10.34*</td>
</tr>
<tr>
<td>Waste throughput, t/h</td>
<td>69.6</td>
</tr>
<tr>
<td>Treatment capacity (@ 8,000 h/y), kt/y</td>
<td>557.0</td>
</tr>
<tr>
<td>Steam pressure, bar(a)</td>
<td>50.0</td>
</tr>
<tr>
<td>Steam temperature, °C</td>
<td>440</td>
</tr>
<tr>
<td>Nominal steam production, t/h</td>
<td>233.9</td>
</tr>
<tr>
<td>Nominal condensing pressure, bar(a)</td>
<td>0.05</td>
</tr>
<tr>
<td>Nominal gross power, $W_E$</td>
<td>63.0</td>
</tr>
<tr>
<td>Nominal net power, $W_E$</td>
<td>56.1</td>
</tr>
</tbody>
</table>

### “Only electricity” mode

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross el. eff., $%_{LHV}$</td>
<td>31.5</td>
</tr>
<tr>
<td>Net el. eff., $%_{LHV}$</td>
<td>28.1</td>
</tr>
<tr>
<td>Estimated R1</td>
<td>0.75</td>
</tr>
</tbody>
</table>

### Expected emission levels*

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Concentration, mg/m$_N$$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>5.0</td>
</tr>
<tr>
<td>SO$_2$</td>
<td>0.5</td>
</tr>
<tr>
<td>NO$_X$</td>
<td>35.0</td>
</tr>
<tr>
<td>HCl</td>
<td>2.0</td>
</tr>
<tr>
<td>HF</td>
<td>0.1</td>
</tr>
<tr>
<td>PM</td>
<td>0.3</td>
</tr>
</tbody>
</table>


- Grate combustor with integrated boiler.
- Dry Air Pollution Control (APC) system with use of NaHCO$_3$.
- Low temperature (~180 °C) “tail end” SCR with NH$_3$ solution.
Molten Carbonate Fuel Cell

**ELECTROLYTE**

\[
\frac{1}{2} O_2 + CO_2 + 2e^- \rightarrow CO_2^2- 
\]

**CATHODE (+)**

\[
H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^- 
\]

**ANODE (-)**

\[
CO_2 + H_2O + \text{unreacted fuel (CO + H}_2\) 
\]

**Temperature range:** 600-650°C

- Overall REDOX
- Steam reforming
- Water gas shift

\[
H_2 + \frac{1}{2} O_2 + CO_{3, cathode} \rightarrow H_2O + CO_{2, anode} + \text{heat} 
\]

\[
C_nH_m + nH_2O + \text{heat} \rightarrow \left(\frac{m}{2} + n\right)H_2 + nCO 
\]

\[
CO + H_2O \leftrightarrow H_2 + CO_2 + \text{heat} 
\]

\[
\eta_{el,MCFC} \propto V_{cell} = E_{Nerst} - \Delta V_{losses} 
\]

\[
E_{Nerst} = \frac{\Delta G}{nF} + \frac{RT}{nF} \ln \left( \frac{x_{H_2an} x_{O_2cath}^{0.5}}{x_{H_2Oan} x_{CO_2an}} \right) 
\]
Basic features of the MCFC

In a MCFC carbonate ions (CO$_3^{2-}$) permeate through a Li-K solid matrix electrolyte supported by porous aluminate (LiAlO$_2$) for stability and strength increase. H$_2$ is fed to the anode (Ni), O$_2$ and CO$_2$ to the cathode (NiO)

- High efficiency (>50% LHV)
- Suitable for CCS applications in power and industrial plants
- Operating temp. (650°C) favors internal reforming → cheap catalyst
- Internal reforming increases fuel flexibility (variety of hydrocarbons)
- Low NO$_x$ (electro-reduction) and SO$_2$/H$_2$S (must be removed upstream)
- Costs and durability

![Diagram of MCFC process]

**CO$_2$ + O$_2$**
Input to cathode

**H$_2$ + CO + CO$_2$ + H$_2$O**
from anode

**NG + Steam**
to anode

**580°C**

**Reforming layer**

**600°C**

Pre-reformed fuel

**CO$_2$-poor flow**
from cathode
Commercial MCFC

Plant configuration of system offered by Fuel Cell Energy (FCE)

Pre-reformer

Burner

Air blower

CO₂ loop

Sulfur removal

Natural gas

Exhausts vent

Water supply

CO₂ rich stream

Liquid water

Combustion gas

Air

Natural gas / syngas
From commercial MCFC to carbon capture

*Flows not to scale*
From commercial MCFC to carbon capture

Flows not to scale

Plant generating $CO_2$

$CO_2$ Processing Unit (CPU)

Storage

MCFC cathode

Carbon not captured

Stack

Carbon in flue gases

Carbon in NG

MCFC anode

Natural Gas inlet

Carbon Captured

*$Flows not to scale$
CO₂ Capture by MCFCs

Molten Carbonate Fuel Cells for Retrotfitting Postcombustion CO₂ Capture in Coal and Natural Gas Power Plants

The state-of-the-art conventional technology for postcombustion capture of CO₂ from fossil-fueled power plants is based on chemical solvents, which requires substantial energy consumption for regeneration. A promising alternative, available in the near future, is the application of molten carbonate fuel cells (MCFC) for CO₂ separation from postcombustion flue gases. Previous studies related to this technology showed both high efficiency and high carbon capture rates, especially when the fuel cell is thermally integrated in the flue gas path of a natural gas-fired combined cycle or an integrated gasification combined cycle plant. This work compares the application of MCFC-based CO₂ separation process to pressurized coal-fired steam cycles (PCC) and natural gas combined cycles (NGCC) as a retrofit to the original power plant. Mass and energy balances are calculated through detailed models for both power plants, with fuel cell behavior simulated using a 0D model calibrated against manufacturers’ specifications and based on experimental measurements, specifically carried out to support this study. The resulting analyses include a comparison of the energy efficiency and CO₂ separation efficiency as well as an economic comparison of the cost of CO₂ avoided (CCA) under several economic scenarios. The proposed configurations result in promising performance, exhibiting very competitive efficiency and economic metrics in comparison with conventional capture technologies. Application as a MCFC retrofit yields a very limited (>80%) decrease in efficiency for both power plants (PCC and NGCC), a strong trade-off (25-40%) in CO₂ emission and a competitive cost for CO₂ avoided (25-40 €/ton).

[DOI: 10.1155/1.0358061]

Application of Molten Carbonate Fuel Cells in Cement Plants for CO₂ Capture and Clean Power Generation

Maurizio Spinelli*, Matteo C. Romano**, Stefano Consonni*, Stefano Campanari*  
Maurizio Marchilb, Giovanni Cintib

*Politecnico di Milano, Department of Energy, Via La Mbrtachini 4, 20156 Milano, Italy  
**CITE - Cimento Group, via Cernusco 124, 24121 Bergamo, Italy

Molten Carbonate Fuel Cells retrofits for CO₂ capture and enhanced energy production in the steel industry

Luca Mastropasquab,*, Lorenzo Pierangeloab,*, Maurizio Spinelliab, Matteo C. Romanoab, Stefano Campanariab, Stefano Consonniab  
*Politecnico di Milano, Department of Energy, Via La Mbrtachini 4, 20156 Milan, Italy  
**LEAP s.r.l., Via Nino Bixio 27C, 20121, Milano, Italy

CO₂ capture from combined cycles integrated with Molten Carbonate Fuel Cells

Stefano Campanari*, Paolo Chiesa, Giampaolo Manzolini  
Politecnico di Milano, Dipartimento di Energia, Via La Mbrtachini 4, 20156 Milano, Italy
Flue gas pre-heating

EfW Plant

EfW flue gases

Air

Waste

Natural gas & steam

Unconverted fuel

EfW power output

MCFC power output

CO\textsubscript{2}-rich gases

CO\textsubscript{2}-poor gases

CO\textsubscript{2} to storage

EfWflue gases

MCFC

Cathode

Anode

CO\textsubscript{2}

CPU Power input

CO\textsubscript{2}

Processing Unit (CPU)
Flue gas preheating ahead of MCFC

Option 1 - LJUNGSTROM REGENERATOR

- Hot flow
- Cold flow

Option 2 - COMPACT HEAT EXCHANGER

INDUSTRIAL REFERENCE:
Heat exchanger type like Solar Mercury 50 GT's recuperator

Features:
- Stamped and folded metal foil
- Chessboard arrangement - Square matrix
- Counter-flow configuration
**CO₂ Processing Unit (CPU)**

- **Exhausts from MCFC ANODE**
- **T = 75°C**
  - **p = 1 bar**
  - \( x_{\text{CO}_2} = 40-45\% \)
- **T = -50°C**
  - **p = 20 bar**
- **Knock out drum 2**
- **T = -29°C**
  - **p = 25 bar**
- **Knock out drum 1**
- **T = 30°C**
  - **p = 26 bar**
  - \( x_{\text{CO}_2} = 80-85\% \)

**Syngas**

**T = 30°C**
- **p = 110 bar**
- \( x_{\text{CO}_2} = 98-99\% \)
**Assumptions**

**MCFC operating conditions**
- Current density: 1500 A/m²
- Voltage: 0.65-0.72 V
- Fuel utilization factor: 75%
- Steam to carbon ratio: 2
- Inlet temperature (pre-reformer layer): 450°C
- Inlet temperature (anode): 600°C
- Inlet temperature (cathode): 575°C
- Outlet temperature (anode and cathode): 645°C
- Pressure losses on anode / cathode sides: 3 kPa / 2 kPa
- Heat losses (% input thermal power): 1%
- DC/AC electrical efficiency: 97%
- Minimum CO₂ molar fraction at cathode outlet: 1%
- Minimum O₂ molar fraction at cathode outlet [%]: 2.5%

**EfW Operating conditions**
- Primary energy input, MW
  \[ W_{LHV} \] = 200
- Net electric power, MW
  \[ e \] = 54.9

**EfW Effluents properties**

<table>
<thead>
<tr>
<th>Flow rate</th>
<th>Temperature</th>
<th>Pressure</th>
<th>Composition, %vol</th>
</tr>
</thead>
<tbody>
<tr>
<td>kg/s</td>
<td>°C</td>
<td>bar</td>
<td>Ar</td>
</tr>
<tr>
<td>137.9</td>
<td>61.3</td>
<td>1.01</td>
<td>0.8</td>
</tr>
</tbody>
</table>
# Results

<table>
<thead>
<tr>
<th></th>
<th>Ref. EfW</th>
<th>EfW+1 MCFC</th>
<th>EfW+2 MCFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>EfW gross electric power*, MW</td>
<td>63.0</td>
<td>64.1</td>
<td>64.1</td>
</tr>
<tr>
<td>EfW net electric power*, MW</td>
<td>56.1</td>
<td>54.9</td>
<td>54.9</td>
</tr>
<tr>
<td>MCFC gross electric power, MW</td>
<td>-</td>
<td>47</td>
<td>50.2</td>
</tr>
<tr>
<td>CO(_2) capture and other auxiliary consumptions, MW</td>
<td>-</td>
<td>-14.4</td>
<td>-12.8</td>
</tr>
<tr>
<td>Overall net electric power, MW</td>
<td>56.1</td>
<td>87.5</td>
<td>92.3</td>
</tr>
<tr>
<td>Natural gas consumption, MW(_{LHV})</td>
<td>-</td>
<td>79.5</td>
<td>79.4</td>
</tr>
<tr>
<td>1(^{st}) law energy efficiency, %(_{LHV})</td>
<td>28.1</td>
<td>31.3</td>
<td>33.0</td>
</tr>
<tr>
<td>NG marginal efficiency, %(_{LHV})</td>
<td>-</td>
<td>39.5</td>
<td>47.1</td>
</tr>
<tr>
<td>Biogenic CO(_2) released by waste combustion(^+), kg/s</td>
<td>9.7</td>
<td>9.7</td>
<td>9.7</td>
</tr>
<tr>
<td>Captured CO(_2), kg/s</td>
<td>-</td>
<td>21.6</td>
<td>21.7</td>
</tr>
<tr>
<td>Emitted CO(_2), kg/s</td>
<td>19.1</td>
<td>1.90</td>
<td>1.9</td>
</tr>
<tr>
<td>Fossil CO(_2) emission, kg/s</td>
<td>9.4</td>
<td>-7.8</td>
<td>-7.8</td>
</tr>
<tr>
<td>Avoided fossil CO(_2) emission(^§), kg/s</td>
<td>-</td>
<td>10.8</td>
<td>11.2</td>
</tr>
<tr>
<td>Primary energy consumption for CO(<em>2) capture(^§), MW(</em>{LHV})</td>
<td>-</td>
<td>27.2</td>
<td>19.1</td>
</tr>
<tr>
<td>SPECCA(^§), MJ(_{LHV}/kg CO_2)</td>
<td>-</td>
<td>2.52</td>
<td>1.70</td>
</tr>
</tbody>
</table>

* Including extra power production due to heat recovery from additional flue gas cooling and extra consumption due to the increased head of the ID fan.

\(^+\) By assuming 51% of carbon in the waste is biogenic.

\(^§\) By assuming reference efficiency for electricity from NG of 60%\(_{LHV}\).
1) The use of MCFCs as post-combustion capture technology for EfW plants can yield interesting outcomes in terms of both carbon capture and performances

2) For a large scale EfW plant, fossil CO2 emissions become negative, making the EfW+MCFC plant a CARBON SINK rather than a carbon emitter

3) For the case study considered here - EfW with combustion power 200 MW_{LHV} - net power production increases by 55-65%, at the expense of a natural gas consumption for the MCFC of about 80 MW_{LHV}, i.e. about 40% of the energy input from waste

4) Crucial issue to be verified for technical feasibility is the capability to achieve EfW flue gas purity compatible with the requirements of the fuel cell

5) Additional crucial issue to be verified for industrial feasibility is capital and operating costs
Thank you
for your attention!

www.mater.polimi.it