FUEL CONVERSION IN FLUIDIZED DUAL-REACTOR SYSTEMS

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THIS PRESENTATION WILL GIVE EXAMPLES ON REACTORS AND MODELLING
REACTORS
EXAMPLES OF DUAL-REACTOR FUEL-CONVERSION SYSTEMS

- Fluidized catalytic crackers
- Chemical looping conversion
- Pressurised FBC for coal conversion.
- Conversion of biomass to high-(medium) value gas.
- Pyrolysis-combustion plants for waste fuels.
ARRANGEMENTS: The coupled reactors could be:

A. Circulating

B. Sequential

C. Gravitational
A. CIRCULATING SYSTEMS: VARIOUS PROPOSALS HAVE BEEN MADE FOR BIMASS GASIFICATION
ADD-ON GASIFIER/CFB BOILER FOR BIOMASS GASIFICATION (The Chalmers unit [6])

Heat, Electricity, Steam

Flue gas

Fuel

Air

Hot bed material

Heat, Electricity, Steam

Flue gas

Bio Product Gas

Biomass

Fluidization gas (Steam or Bio Producer Gas or …)

Air

Fuel

Hot bed material
Principle scheme: Chemical Looping Combustion (CLC)

Particulate material and heat are brought from one reactor to the other
CLC WITH LIME FOR BIOMASS GASIFICATION [8]

Reactor 1:
CaCO₃ + heat $\rightarrow$ CaO + CO₂
High-temperature combustion and calcination $\rightarrow$ CO₂ release

Reactor 2:
CaO + CO₂ $\rightarrow$ CaCO₃ + heat
Low-temperature gasification.
CO₂ is bound by CaO $\rightarrow$ H₂

because the water-gas shift reaction is dominant in biomass gasification

\[ \text{CO} + \text{H}_2\text{O} \leftrightarrow \text{CO}_2 + \text{H}_2 \]
To improve conversion efficiency dual-reactor systems were proposed (for coal gasification in fluidised bed).

There were many proposals, for instance, the "Cogas" gasifier (1974)
B. SEQUENTIAL REACTORS FOR WASTE CONVERSION

Many arrangements follow the general layout:

- Prepared fuel, waste
- Devolatilisation 500-600 °C
  - Coarse ash separation
  - Metals, glass
- Combustion 1300-1500 °C
  - Char
- Heat transfer
- Flue gas cleaning
- Oxygen
- Product gas
- Gasification 1000-2000 °C
  - Fine ash (molten?)
- Steam process
  - Alternatively
  - Ash (molten?)
Example: WASTE COMBUSTION, EBARA
C. GRAVITY TYPE OF GAS GENERATORS

Blauer Turm, Muehlen

Biomass Heat pipe Reform, J. Karl

Hydrogasification of coal for methane production 1974 IGT [9]
THE HEAT-PIPE REFORMER

Abbildung 9: Schema des Heatpipe Reformers
Dual-reactor systems (recirculating or once-through) are proposed for many applications

Advantages

- High efficiency (high char conversion)
- High heating-value gas
- Opens up possibilities in waste conversion, CO$_2$ removal, H$_2$ production

Drawbacks

- Increased complexity
- Not well developed so far, although known for a long time
MODELLING

The simplest possible model presented in a survey comprising 400 references will be explained.

COMPARISON BETWEEN DIRECT AND INDIRECT GAS GENERATORS BY HEAT AND MASS BALANCES

Autothermal or direct

Allothermal or indirect
COMPOSITION OF SOLID FUELS

FUEL (as delivered) = b + w + a

SOLID PART (daf)

- b: COMBUSTIBLES (daf)
- a: ASHES

W MOISTURE

 FIXED

- x_c: FIXED

 VOLATILES

- x_v: VOLATILES
METHOD OF ANALYSIS

The comparison is based on heat and mass balances of the entire reactors plus a few assumptions. The fuel analysis is given.

ASSUMPTIONS

• Devolatilisation \( x_v \) and drying take place in the gasifier

• The char \( x_c = 1 - x_v \) is gasified to an assumed extent \( \phi_{\text{gas}} \).

• The autothermal case: remaining char is a loss and volatiles are burnt for heating

• The allothermal case: remaining char is burnt in the combustor and volatiles are only burnt if the char is completely consumed
### THE FUEL

\[ m_{f,in} = m_f (1 + \xi_u + \xi_b) \]  

(4)

\( \xi_u \) is the loss of fuel kg/kg fuel converted due to incomplete conversion  
\( \xi_b \) is fuel consumed to produce heat, expressed in kg/kg fuel converted.

This gives

\[ m_{f,in} = m_f a (1 + \xi_u + \xi_b) + \text{ashes} \]

\[ + m_f w (1 + \xi_u + \xi_b) + \text{moisture} \]

\[ + m_f b (1 + \xi_u + \xi_b) + \text{combustibles} \]

(5)

The combustible part is

- \( m_f b \) gas from volatiles and gasification of char  
- \( m_f b \xi_u \) conversion loss, mostly unreacted char  
- \( m_f b \xi_b \) consumption to maintain reactor temperature

The combustible part consists of char \( x_c \) and volatiles \( x_v \) (from fuel analysis).  
Then the heating value of the volatiles is

\[ H_{u,v} = \left( H_{u,b} - x_c H_{u,c} \right) / x_v \]  

(3)
The amount of gas produced (kg gas/s) is

\[ m_{\text{gas}} = m_f b + \text{Volatile} + \text{gas from gasified char}, m_f b x_c \phi_{\text{gas}}, + m_{f,\text{in}} w + \text{Fuel moisture} + m_f b \xi_b g_0 \text{ Combustion gas in the autothermal reactor} \]

Additional assumption for the autothermal reactor: the flue gas \( g_0 \) and air demand \( l_0 \) are those of combustion of fuel with char withdrawn.
HEAT AND MASS BALANCES

\[ m_f b \xi b H_{h,b} = \]
\[ = m_{f,in} \left\{ c_{pmf}(T_b - T_0) + wH_w \right\} \]
\[ + m_f b x_c \varphi_{gas} \left\{ c_{pm,H2O}(T_b - T_0) + H_{C,H} \right\} \]
\[ + m_f b \xi b \ell_0 c_{pm,air}(T_b - T_0) \]
\[ + \text{radiation losses from reactor} \]

where

\[ H_{u,b} = H_{u,v} \text{ in an autothermal reactor and } H_{u,b} = H_{u,c} \text{ in an allothermal one} \]

and \( T_b \) is the bed temperature

Input of energy with fuel burnt

Heating of fuel + evaporation of moisture

Heating of gasification vapour + heat for production of gas

Heating of combustion air

(neglected here)
PERFORMANCE CHARACTERISTICS

The heating value of the gas
\[ m_{gas} H_{u,gas} = m_f b H_{u,v}(1- x_c) + H_{C,H} x_c \phi_{gas} \]

The cold gas efficiency of gasification
\[ \eta_g = \frac{m_{gas} H_{u,gas}}{(bm_{f,in} H_{u,f})} \]

The fraction of the combustibles burnt
\[ \xi_b = \frac{m_{f,in} \left( c_{pmf} \Delta T + H_w \right) + m_f b x_c \phi_{gas} \left( c_{pmH_2O} \Delta T + H_{C,H} \right)}{m_f b (H_{u,b} - \ell_o c_{pmair} \Delta T)} \]
GASIFIER EFFICIENCY AND HEATING VALUE OF EXIT GAS VS REACTOR TEMPERATURE

Zero moisture ($w=0$) and no gasification of char ($\phi_{gas}=0$) in auto- and allothermal gas generators.
1) Various moisture contents in the fuel (\(w\) varies) and no gasification of char (\(\phi_{\text{gas}} = 0\)).
2) No moisture (\(w = 0\)) and various \(\phi_{\text{gas}}\) are also shown.
FRACTION OF FUEL NEEDED TO ATTAIN A CERTAIN GASIFIER TEMPERATURE, $m_f b \xi_b$.

Degree of gasification

Moisture content

Autothermal

Allothermal

Autothermal

Allothermal
AIR RATIO BASED ON FUEL ADDED.

\[ \lambda = \frac{m_f b \xi_b l_o}{m_{f,in} b l_o} \xi_b / (1 + \xi_u + \xi_b) \]
With fuel burnt \( m_b \xi_b = B \) and flue gas \( B_{fgv} = F_{f, gas} \), the heat transferred between the two reactors 1 and 2 is

\[
BH_{u,b} = F_s c_{pms} (T_1 - T_2) + F_{f, gas} c_{pmg} (T_1 - T_0)
\]

With the adiabatic temperature \( T_{ad} = H_{u,b} / (F_{f, gas} c_{pmg}) + T_0 \)

The flow of solids between the reactors

\[
F_s = F_{f, gas} c_{pmg} \frac{(T_{ad} - T_1)}{(T_1 - T_2)} c_{pms}
\]
ENERGY TRANSPORT BETWEEN COUPLED REACTORS

Mass flow of bed material kg/s kg fuel

Temperature difference between reactors, deg

Fuel burned in the combustion reactor B kg/kg fuel
CONCLUSIONS

A simple balance model can be used for performance analysis

The limitations are:

1. The amount of char gasification $\varphi_{\text{gas}}$ has to be estimated by more advanced modelling.

2. The gas composition has to be predicted by additional models, e.g. equilibrium models in combination with species balances. However, the formulation gives this information with a low resolution: produced gas + water vapour from moisture + combustion gas.

3. Fluidisation conditions and reactor dimensions have to be determined
CONCLUSION REGARDING THE PERFORMANCE

• The energy in the char is about equal to the quantity of heat required for the gasifier. So, no gasification is really needed, only devolatilisation.

• There is an effort to design autothermal reactors to avoid the predominant combustion of volatiles and instead burn char.

• The location of the control surface for balance has to be considered (what is to be included/excluded).

• In the allothermal case just one point of operation balances the fuel burnt and the heat requirement. In all other points there is either too much char (loss) or too little char (additional fuel is needed).
REFERENCES