# Politecnico di Milano

## School of Industrial Engineering

Energy Engineering for an Environmentally Sustainable World

*Bioenergy and Waste-to-Energy Technologies*

Academic Year 20XX/XX

# Midterm Exam Example

## Time: 1.5 h (90 min)

**PLEASE NOTICE**

1) Books, notes, cell phones, laptops, tablets are NOT allowed
2) Answer clearly ONLY to the questions posed by the problem sets. Additional considerations and/or developments will NOT be considered.
3) For open questions, the answer MUST fit within the available space.
4) Fill these sheets and return them together with your solutions.
5) Write your name below and mark each sheet of the solution with your name and page number.

FIRST NAME……………………………………FAMILY NAME…………………………………………..

## Problem 1 (10 points)

A biomass-fired power plant is designed for the chipped woody feedstock here described:
Ash content: 2% by mass on wet basis
Moisture content: 40% by mass
LHV: 10 MJ/kg on wet basis
Flue gas production at stack: 7.6 $m_n^3/kg_{\_DAF}$
At rated conditions, biomass consumption is 28 t/h, gross electric production 20 MW and stack temperature 165°C. The gross electric efficiency of the steam cycle is 30%.
However, due to storage conditions, the biomass supplied to the plant is the same described above, but with a moisture content of 50% by mass. Assuming 7500 equivalent working hours per year, determine:

1) the gross electric efficiency of the plant at design conditions;
2) the annual consumption of biomass, productions of ash and flue gas at design conditions;
3) the energy efficiency of the boiler at design conditions;
4) the energy efficiency of the boiler when the plant is fed with the actual biomass (consider that the extra moisture produces steam with a Cp = 2.2 kJ/kg-K, excess air remains the same as well as the stack temperature; all the losses different from the stack remain constant);
5) the annual consumption of biomass, productions of ash and flue gas when the plant is fed with the actual biomass and produces the same gross electric power as at rated conditions;
6) the gross electric efficiency of the plant at the conditions of points 4, 5.

## Problem 2 (10 points)

An example of MSW composition is reported in the table:

| **Waste categories** | **%<br>on weight** | **Moisture<br>(% on weight)** | **LHVd<br>(kJ $kg_d^{-1}$)** |
|---|---|---|---|
| Food waste | 40 | 60 | 16700 |
| Paper/cardboard | 25 | 15 | 21000 |
| Plastic | 15 | 10 | 37600 |
| Glass/inert materials | 7.5 | 0 | 0 |
| Fine fraction | 12.5 | 20 | 14600 |

1. Evaluate the waste LHV and LHVd
2. If the glass and the inert materials are collected at the source with an efficiency of 75%; paper and food waste are collected with an efficiency of 40% and plastic is collected with an efficiency of 25%, evaluate the efficiency of the separate collection and the moisture and the LHV (kJ $kg^{-1}$) of the residual waste.

FIRST NAME…………………………………FAMILY NAME………………………………………..

## Question 1 (5 points)

Explain why the evaporation pressure in waste-fired boilers is typically quite limited.

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## Question 2 (5 points)

Give a brief description of the plastic recycling process.

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Solution to problem 1 - Midterm exam - 11/05/2012

① The gross electric efficiency of the plant at design conditions can be promptly determined as:

$$\eta_{el,gross} = \frac{P_{gross}}{\dot{m}_{fuel} \cdot LHV_{fuel}} = \frac{20\ MW}{28\ t/h \cdot \frac{1\ kg/s}{3{,}6\ t/h} \cdot 10\ \frac{MJ}{kg}} = 25.71\ \%$$

Reference has been made to the rated biomass flowrate of 22 t/h, which is equivalent to:

$$\dot{m}_{fuel} = 28\ t/h \cdot \frac{1\ kg/s}{3{,}6\ t/h} = 7.78\ \frac{kg}{s}$$

② Since the moisture and ash contents of design biomass are expressed on wet basis, the production of ash can be readily determined:

$$\dot{m}_{Ash} = \dot{m}_{fuel} \cdot Ash\% = 7.78\ \frac{kg}{s} \cdot 2\% = 0.156\ \frac{kg}{s}$$

The production of flue gas depends on the flowrate of Dry-Ash-Free biomass:

$$\dot{m}_{fuel\ DAF} = \dot{m}_{fuel} \cdot (100\% - Ash\% - Moisture\%) =$$

$$= 7.78 \cdot (100\% - 2\% - 40\%) = 4{,}512\ \frac{kg}{s}$$

$$\text{Flue gas}_{DAF} = 4.512\ \frac{kg_{fuel\_DAF}}{s} \cdot 7.6\ \frac{m_N^3}{kg_{fuel\,DAF}} = 34.29\ \frac{m_N^3}{s}$$

The moisture brought about by biomass is:

$$\dot{m}_{Moisture} = \dot{m}_{fuel} \cdot Moisture\ \% = 7.78 \cdot 40\% = 3.11\ \frac{kg}{s}$$

Its equivalent, in terms of flue gas production is:

$$\text{Flue gas}_{Moisture} = 3.11\ \frac{kg}{s} \cdot \frac{1\ kmol}{18\ kg} \cdot \frac{22{,}414\ m_N^3}{1\ kmol} = 3.875\ \frac{m_N^3}{s}$$

The overall flue gas production is:

$$Flue\ gas_{total} = Flue\ gas_{DAF} + Flue\ gas_{Moisture} =$$

$$= 34.29 + 3.875 = 38.17 \frac{m_N^3}{s}$$

On annual basis:

$$\text{Biomass consumption} = 7.78 \frac{kg}{s} \cdot \frac{3.6\ t/h}{kg/s} \cdot 7500 \frac{h}{y} = 210'060 \frac{t}{y}$$

$$\text{Ash production} = 0.155 \frac{kg}{s} \cdot \frac{3{,}6\ t/h}{kg/s} \cdot 7500 \frac{h}{y} = 4'185 \frac{t}{y}$$

$$\text{Flue gas production} = 38.17 \frac{m_N^3}{s} \cdot \frac{3600\ s}{h} \cdot 7500 \frac{h}{y} = 1.03 \cdot 10^9 \frac{m_N^3}{y}$$

(3) Since the gross power output of the steam cycle is 20 MW and its gross electric efficiency is 30 %, the thermal power to the cycle is:

$$P_{IN,SC} = \frac{P_{el,gross}}{\eta_{SC,gross}} = \frac{20MW}{0.30} = 66.67\ MW$$

The thermal input of the boiler is:

$$P_{IN,PLANT} = m_{fuel} \cdot LHV = 7.78 \cdot 10 = 77.8\ MW$$

$$\eta_{Boiler} = \frac{P_{IN,SC}}{P_{IN,PLANT}} = \frac{66.67}{77.8} = 85.69\ \%$$

Boiler losses amount to:

$$\text{Boiler losses} = P_{IN,PLANT} - P_{IN,SC} = 77.8 - 66.67 = 11.13\ MW$$

(4) With Feedstock that differs from the design biomass only for moisture content, the only difference with respect to the design conditions is an extra stack loss due to the extra steam produced during combustion.

For simplicity reference is made to 1 kg/s of DAF biomass:

$\dot{m}fuel_{DAF} = 1\ kg/s$

The ash content in dry-basis is:

$$Ash\%_{DRY} = \frac{Ash\%_{WET}}{1-Moisture\%} = \frac{2\%}{1-40\%} = 3.33\%$$

Whit the new moisture content.

$$Ash\%_{WET} = Ash\%_{DRY} \cdot (1 - Moisture\%) =$$

$$= 3.33\% \cdot (1 - 50\%) = 1.67\%$$

Thus the biomass flowrate that corresponds to 1 kg/s of biomass on DAF basis is.

$$\dot{m}fuel = \frac{\dot{m}fuel_{DAF}}{1 - Ash\% - Moisture\%} = \frac{1}{1-1,67\%-50\%} = 2.069\ \frac{kg}{s}$$

$$\Rightarrow \dot{m}_{Moisture} = \dot{m}fuel \cdot Moisture\% = 2.069 \cdot 50\% = 1.035\ \frac{kg}{s}$$

This amount of moisture refers to 1 kg/s of DAF biomass.
With design biomass this figure was:

$$\dot{m}fuel_{DAF-Design} = \dot{m}fuel_{-Design} \cdot (1 - Moisture\%_{Design} - Ash\%_{Design}) =$$

$$= 7.78 \cdot (1 - 40\% - 2\%) = 4.51\ kg/s$$

$$\Rightarrow \left(\frac{\dot{m}_{Moisture}}{\dot{m}fuel_{DAF}}\right)_{Design} = \frac{3.11}{4.51} = 0.69$$

The extra moisture for each kg/s of DAF biomass produces extra steam in flue gas, which, in turn, increases the stack loss.

$$\left(\frac{\dot{m}_{moisture}}{\dot{m}_{fuel-DAF}}\right)_{extra} = 1.035 - 0.69 = 0.345$$

As a consequence, in addition to the previous production of flue gas, there will be:

$$\text{Flue gas}_{extra-moisture} = 0.345\,\frac{kg}{s} \cdot \frac{1\,kmol}{18\,kg} \cdot \frac{22.414\,m_N^3}{kmol} = 0.43\,\frac{m_N^3}{s}$$

The extra stack loss due to this extra flowrate can be estimated as:

$$\text{Boiler}_{extra-loss} = \dot{m}_{moisture-extra} \cdot c_p \cdot \left(T_{stack} - T_{REF}\right) =$$

$$= 0.345\,\frac{kg}{s} \cdot 2.2\,\frac{kJ}{kg\text{-}K} \cdot \left(165 - 25\right) = 106.26\,kW$$

$T_{REF} = 25\,°C$ is the reference temperature for LHV definition.

The boiler losses in design conditions per kg/s of DAF biomass are:

$$\left(\frac{\text{Boiler losses}}{\dot{m}_{fuel\,DAF}}\right)_{Design} = \frac{11.13\,MW}{4.51\,kg/s} = \frac{2.47\,MW}{kg/s}$$

With actual biomass this figure becomes:

$$\left(\frac{\text{Boiler losses}}{\dot{m}_{fuel\,DAF}}\right)_{Actual} = \left(\frac{\text{Boiler losses}}{\dot{m}_{fuel\,DAF}}\right)_{Design} + \left(\frac{\text{Boiler extra loss}}{\dot{m}_{fuel\,DAF}}\right) =$$

$$= \frac{2.47\,MW}{kg/s} + \frac{106.26\,kW}{kg/s} = \frac{2.57\,MW}{kg/s}$$

The LHV of actual biomass depends on $LHV_{DAF}$:

$$LHV = LHV_{DAF}(1 - Ash\% - Moisture\%) + LHV_{Moisture} \cdot Moisture\%$$

$$\Rightarrow LHV_{DAF} = \frac{LHV - LHV_{Moisture} \cdot Moisture\%}{1 - Ash\% - Moisture\%} =$$

$$= \frac{10 - (-2.442) \cdot 40\%}{1 - 2\% - 40\%} = 18.93 \frac{MJ}{kg}$$

$$\Rightarrow LHV_{Actual} = 18.93(1 - 1.67\% - 50\%) + (-2.442) \cdot 50\% =$$

$$= 7.93 \frac{MJ}{kg}$$

Thermal power input per kg/s of DAF biomass is:

$$\frac{P_{IN,PLANT}}{\dot{m}_{fuel\,DAF}} = \frac{\dot{m}_{fuel} \cdot LHV}{\dot{m}_{fuel\,DAF}} = \frac{2.069 \cdot 7.93}{1} = \frac{16.41\ MW}{kg/s}$$

Thermal input to steam cycle:

$$P_{IN,SC} = P_{IN,PLANT} - \text{Boiler losses} = 16.41 - 2.57 = \frac{13.84\ MW}{kg/s}$$

$$\Rightarrow \eta_{Boiler} = \frac{P_{IN,SC}}{P_{IN,PLANT}} = \frac{13.84}{16.41} = 84.34\%$$

5 The real flowrate of actual biomass can be determined in order to warrant the production of 20 MW electric gross:

$$\left(\frac{P_{EL,GROSS}}{\dot{m}_{fuel\,DAF}}\right) = \left(\frac{P_{IN,SC}}{\dot{m}_{fuel\,DAF}}\right) \cdot \eta_{SC} = 13.84 \cdot 30\% = \frac{4.152\ MW}{kg/s}$$

$$\Rightarrow \dot{m}_{fuel\,DAF} = P_{EL,GROSS} \Big/ \left(\frac{P_{EL,GROSS}}{\dot{m}_{fuel\text{-}DAF}}\right) = \frac{20}{4.152} = 4.817 \frac{kg}{s}$$

$$\Rightarrow \dot{m}_{fuel} = \dot{m}_{fuel\,DAF} \cdot \left(\frac{\dot{m}_{fuel}}{\dot{m}_{fuel\_DAF}}\right) = 4.817 \cdot 2.069 = 9.966 \ \frac{kg}{s}$$

$$\dot{m}_{Ash} = \dot{m}_{fuel} \cdot Ash\% = 9.966 \cdot 1.67\% = 0.166 \ \frac{kg}{s}$$

$$Flue\ gas = \left\{\left(\frac{Flue\ gas}{\dot{m}_{fuel\,DAF}}\right)_{Design} + \left(\frac{Flue\ gas}{\dot{m}_{fuel\,DAF}}\right)_{extra}\right\} \cdot \dot{m}_{fuel\,DAF} =$$

$$= \left\{\frac{38.17}{4.51} + 0.43\right\} \cdot 4.817 = 42.84 \ \frac{m_N^3}{s}$$

On annual basis:

$$Biomass\ consumption = 9.966 \ \frac{kg}{s} \cdot \frac{3.6\ t/h}{kg/s} \cdot 7500 \ \frac{h}{Y} = 269'082 \ \frac{t}{Y}$$

$$Ash\ production = 0.166 \ \frac{kg}{s} \cdot \frac{3.6\ t/h}{kg/s} \cdot 7500 \ \frac{h}{Y} = 4482 \ \frac{t}{Y}$$

$$Flue\ gas\ production = 42.84 \ \frac{m_N^3}{s} \cdot \frac{3600\,s}{h} \cdot 7500 \ \frac{h}{Y} = 1.157 \cdot 10^9 \ \frac{m_N^3}{Y}$$

(6)

$$\eta_{EL,GROSS} = \frac{P_{EL,GROSS}}{\dot{m}_{fuel} \cdot LHV} = \frac{20}{9.966 \cdot 7.93} = 25.31\%$$