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Fuel moisture soft-sensor and its validation for the industrial BioGrate boiler

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Contents

- Objectives
- Description of the Biograte process
- Fuel moisture soft-sensor
- Decription of the testing environment
- The test results of the fuel moisture soft-sensor
- Conclusions

Objectives of the advanced control of the plant

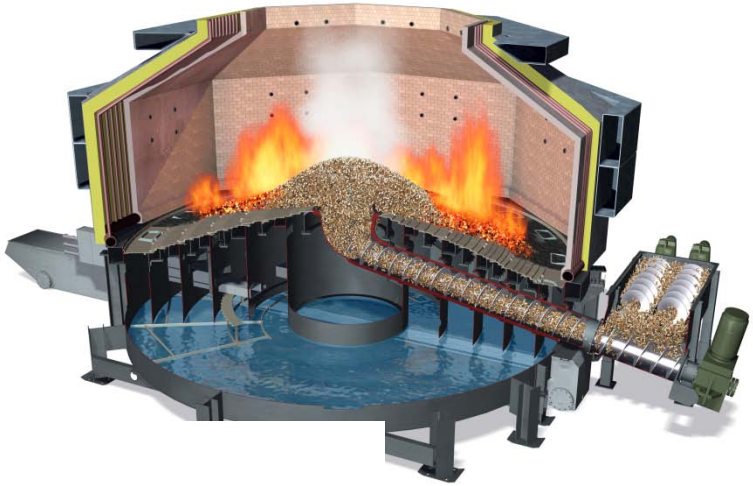
- The main objective is to control the plant and avoid shutdowns while burning wide variety of problematic bio fuels with fluctuating fuel quality and moisture
- To keep constant power production with fluctuating fuel quality and moisture
- To react sudden changes of power demand
  - with fluctuating fuel quality and moisture
  - with long time delays

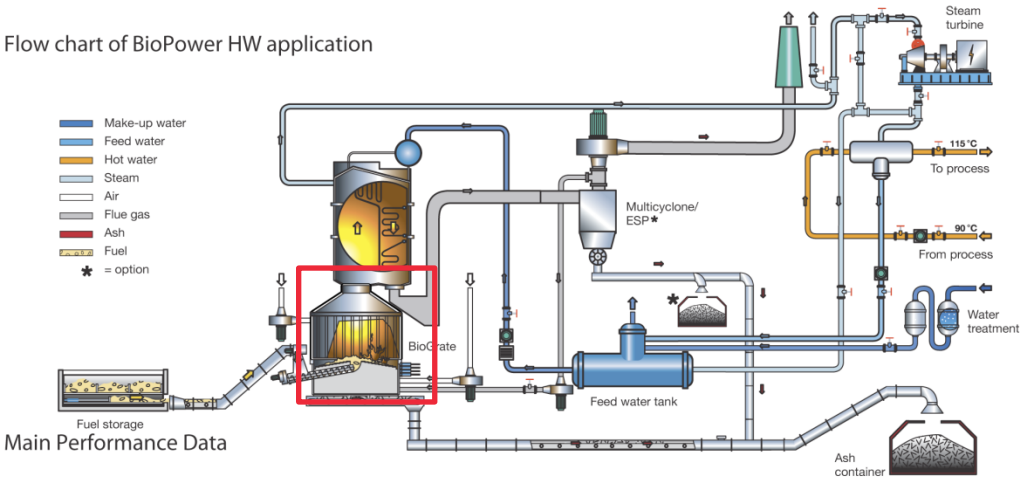
Objectives of the fuel moisture soft-sensor

- The fuel moisture soft-sensor is needed to achieve control objectives
  - Robust control is not efficient because fuel moisture is not measured and process dynamics contain long delays
  - Estimating fuel moisture allows control to compensate the affect of moisture variation

Description of the Biograte process

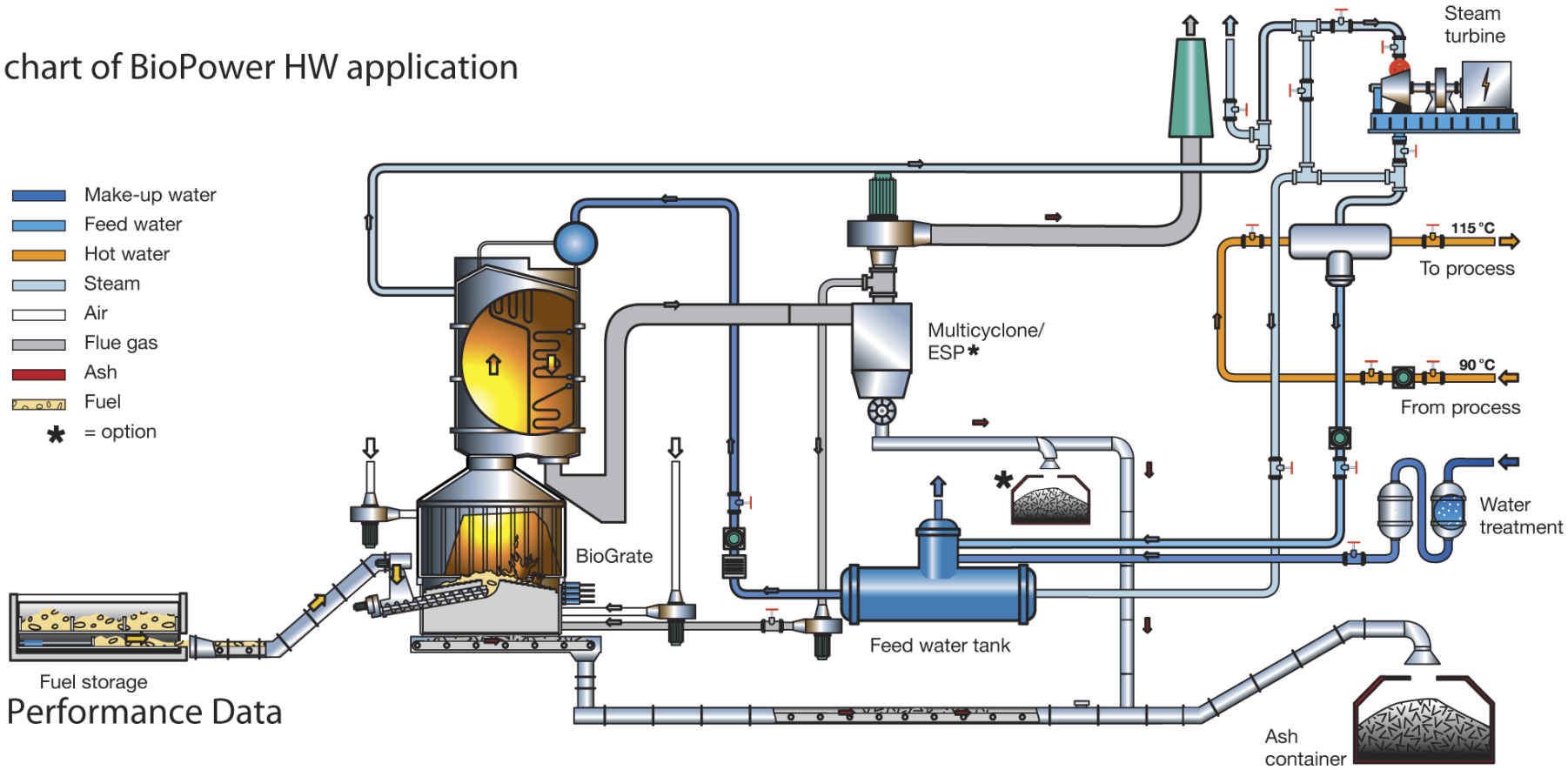
- The fuel is fed onto the center of a grate from below by a stoker screw.
- Alternate rotating rings are pushed clockwise or counterclockwise respectively.





Description of the Biograte process

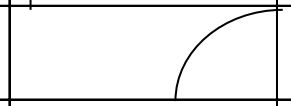
Flow chart of BioPower HW application



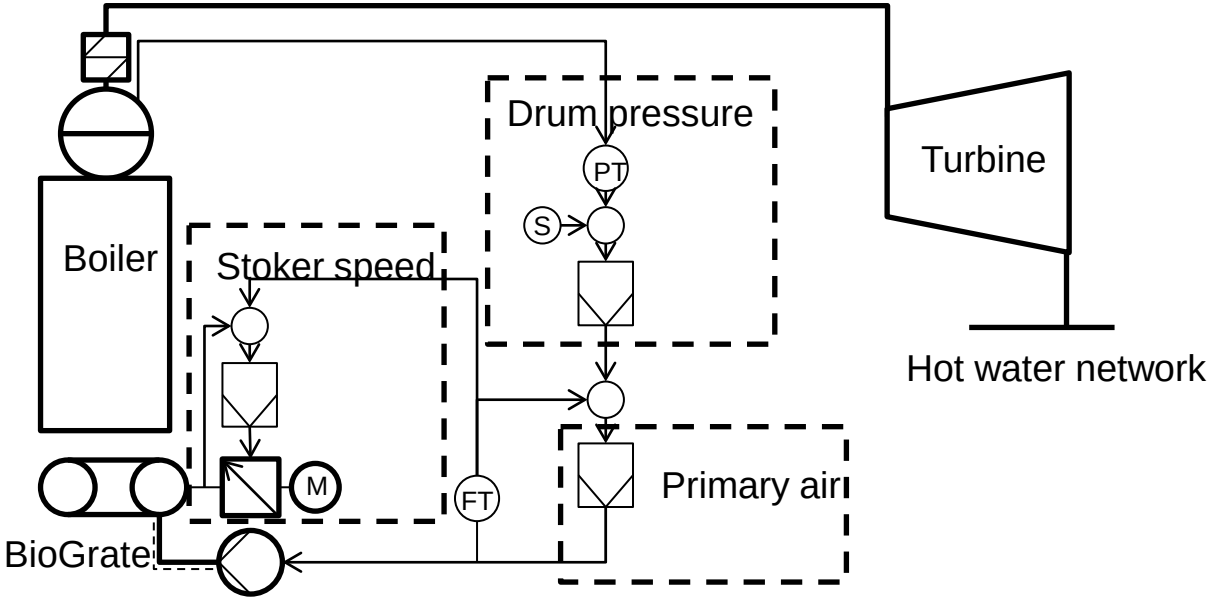
Main Performance Data

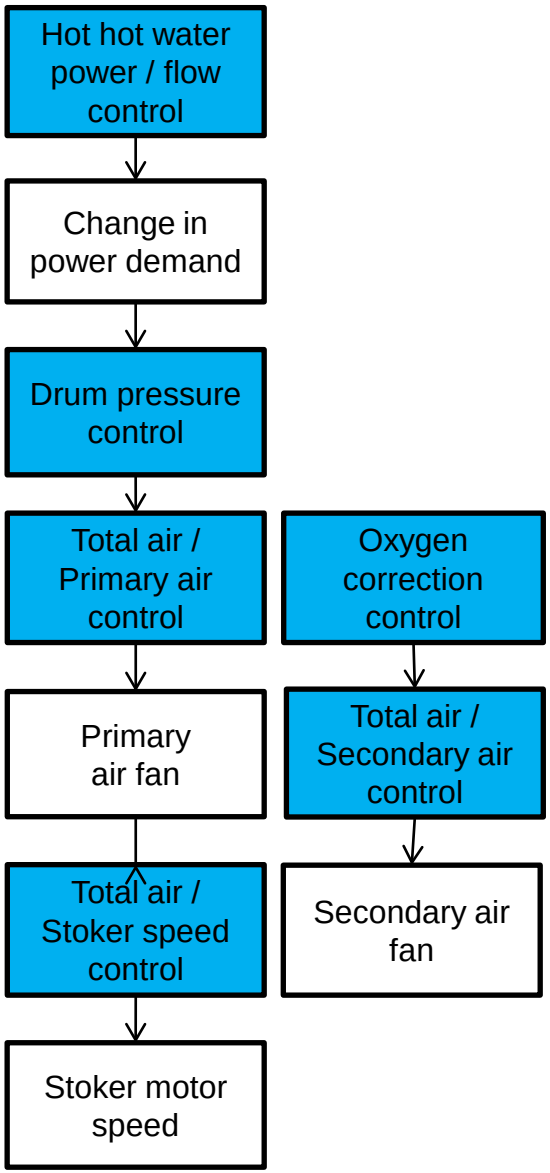
Description of the delays in the Biograte process

- The BioGrate process is characterized by large time constants and long dead times

Input variable	Output variable	Step response	Dead time	Time constant
Primary air flow	Combustion power		30s	2s
Moisture in fuel feed flow	Combustion power		15min	10min
Combustion power	Drum pressure		4s	20min
Combustion power	Secondary superheater		1s	1.5min
Combustion power	Fuel moisture soft-sensor		4s	<1min
Combustion power	Combustion power Estimation		4s	<1min

Control of BioGrate boiler





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Fuel moisture soft-sensor

- The fuel moisture disturbance *w* is estimated with least squares

$$\min J(w) = \sum_{i=0}^{N} \left| h_2(i) - \hat{h}_2(i|w) \right|^2$$

where h_2 is the output enthalpy of the secondary superheater

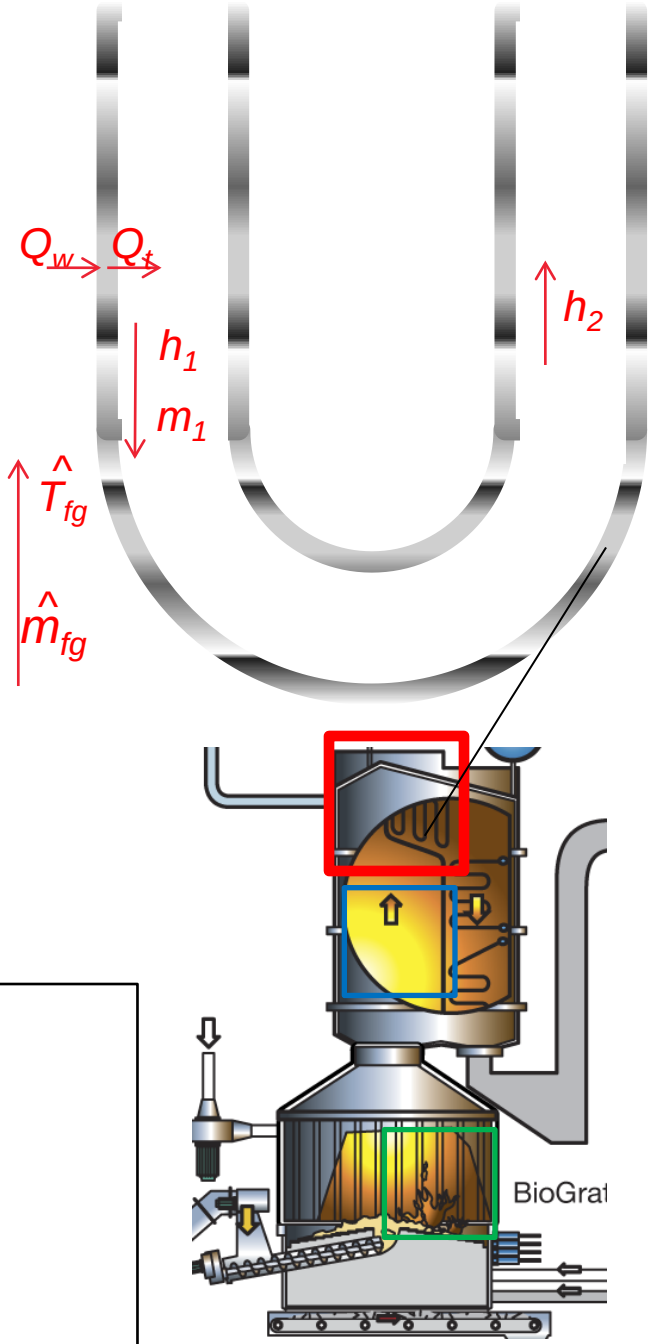
- The fuel moisture soft-sensor is based on following sub models
  - **Superheater model** estimates the output enthalpy h_2 of the secondary superheater
  - **Flue gas model** estimates flue gas flow m_{fg} and flue gas temperature T_{fg}
  - **Combustion model** estimates fuel flow $m_f(w)$

$$\frac{d\hat{h}_2}{dt} = \frac{1}{\rho V}\left(Q_t + m_1 h_1 - m_2 \hat{h}_2\right)[MJ/s]$$

$$Q_t = \alpha_c m_2^{0.8}(T_w - T)[MJ/s]$$

$$\frac{T_w}{dt} = \frac{1}{m_t C_p}(Q_w - Q_t)[K/s]$$

$$Q_w = \alpha_w \hat{m}_{fg}^{0.65}\left(\hat{T}_{fg} - T_w\right) + k_w\left(\hat{T}_{fg}^4 - T_w^4\right)[MJ/s]$$



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Fuel moisture soft-sensor: Flue gas

- Flue gas flow is:

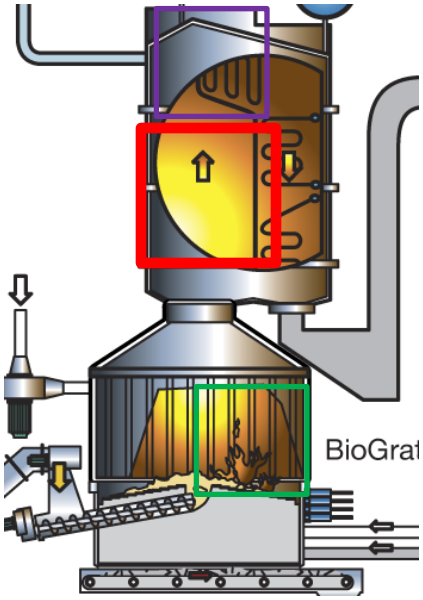
  $\hat{m}_{fg}=\hat{m}_f(w)\cdot N_{fg}\,[kg/s]$

  and N_{fg} is flue gas flow for one kilogram of fuel (mol/kg).

- Flue gas temperature is:

$$\hat{T}_{fg}=\frac{q_f+0.21\left(F_{Air}/\left(22.41\cdot 10^{-3}\cdot \hat{m}_f(w)\right)C_{O_2}\right)+0.79\left(F_{Air}/\left(22.41\cdot 10^{-3}\cdot \hat{m}_f(w)\right)C_{N_2}\right)}{n_C C_{CO_2}+n_S C_{SO_2}+\left(n_{H_2O}+n_{H_2}\right)C_{H_2O}+\left(3.76\cdot N_{O_2}^{g}+n_{N_2}\right)C_{N_2}+0.21\cdot N_{ExAir}C_{O_2}+0.79\cdot N_{ExAir}C_{N_2}}$$

  where $q_{f\ is}$ is effective heat value of wet fuel, F_{air} is total air flow (m^3/s), C_i is specific heat capacity (J/molT), and N_{ExAir} is excess air (mol/kg)

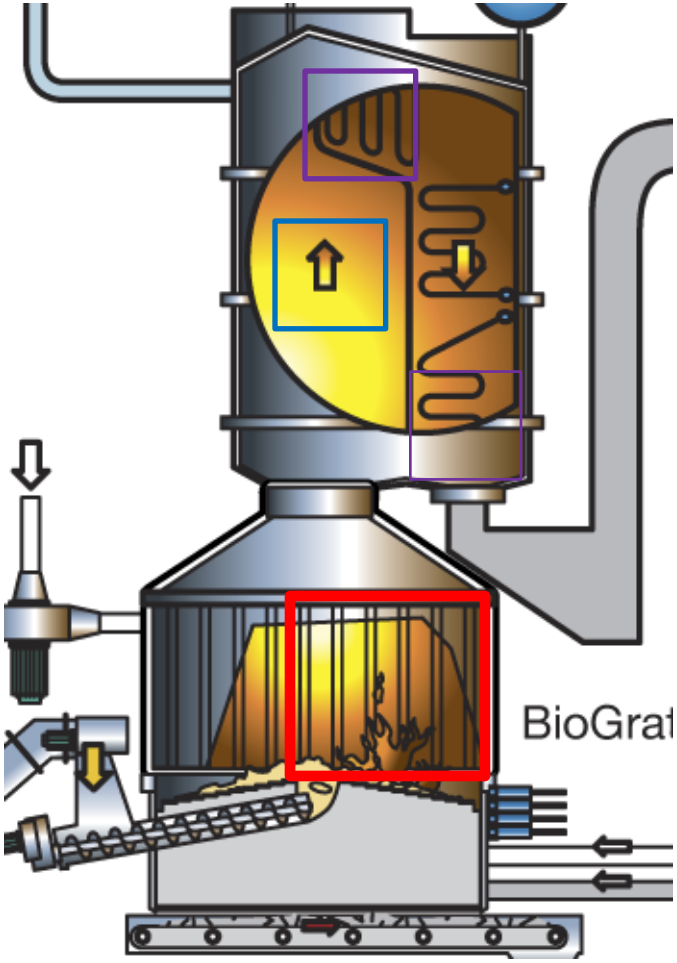


Fuel moisture soft-sensor: Combustion

- The fuel flow $m_f(w)$ is given as follows:

$$\hat{m}_f(w) = \frac{\left(0.21 - \frac{X_{O_2}}{100}\right) n_{Air}}{N_{O_2}^g + \frac{X_{O_2}}{100}\left(N_{fg} - 4.76 \cdot N_{O_2}^g\right)} [kg/s]$$

where X_{O_2} is oxygen content of flue gas (%),
n_{Air} is total air flow (mol/s),
$N_{O_2}{}^g$ oxygen needed to burn 1 kilogram of fuel (mol/kg), and
N_{fg} is flue gas flow for one kilogram of fuel (mol/kg)



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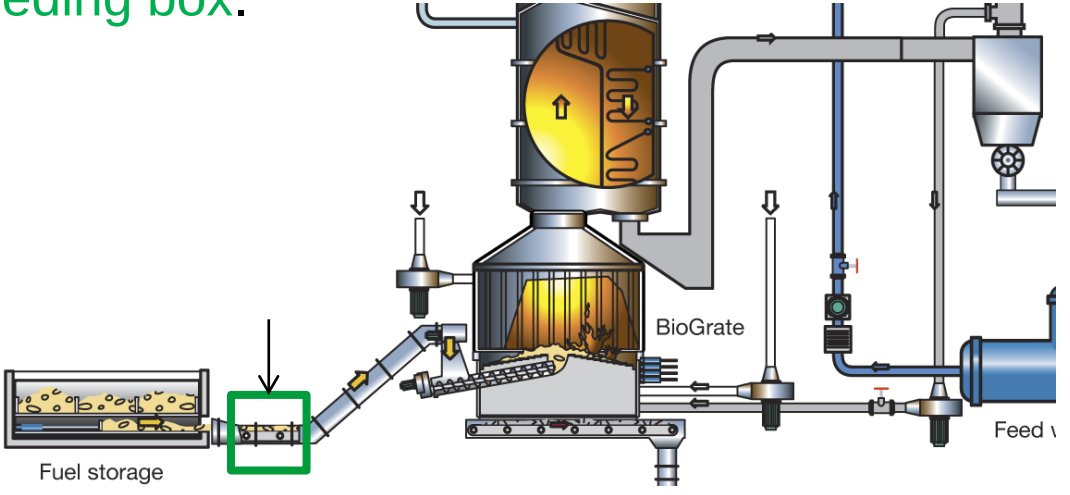
Decription of the testing environment

- The experiments were conducted at the BioPower 5 CHP plant that produce 13.5 MW heat and 2.9 MW electricity.

  Two fuels were used:

1. spruce bark with the moisture content of 57%
2. dry woodchips (spruce) with the moisture content of 20%

- Dry biomass was fed manually into the screw conveyor between wet fuel through the extra feeding box.



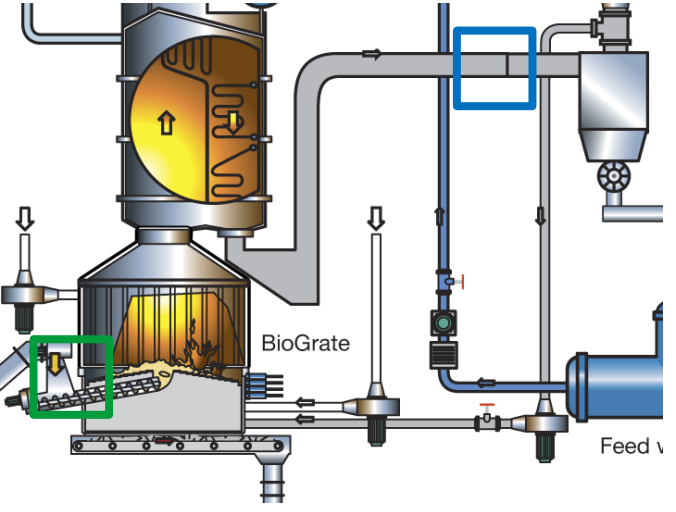
Decription of the testing environment

The accuracy of the fuel moisture soft-sensor was investigated by

- Sampling fuel feed every 5 minutes.
- Servomex 2500 FT-IR flue gas moisture analyzer. Samples were recorded every second.

Measurement set-up for fuel feed samping

Measurement set-up for the FT-IR analyzer in the flue gas duct



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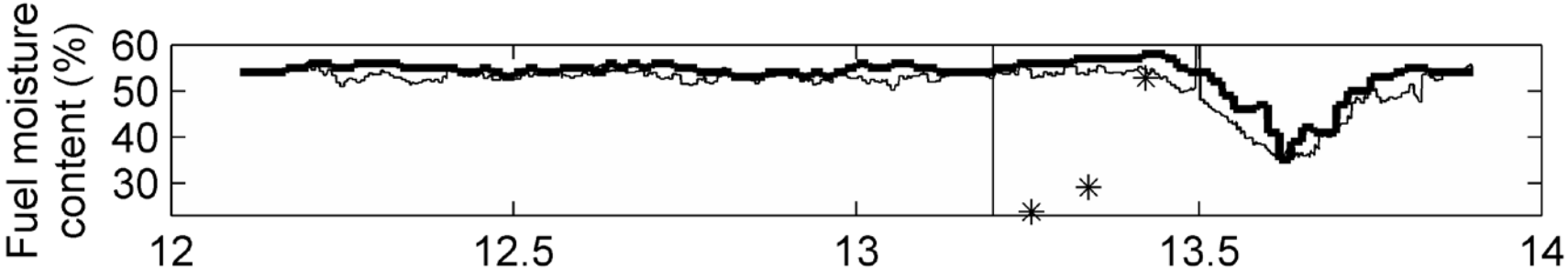
The test results of the fuel moisture soft-sensor: Accuracy

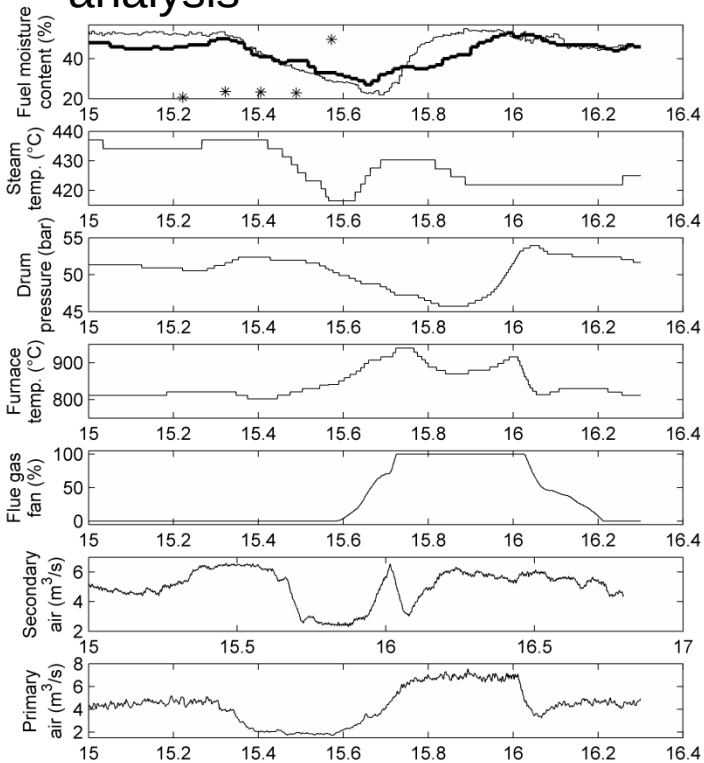
- According to the fuel sampling, the wet fuel contained 54.4% moisture per kg fuel on average
  The fuel moisture soft-sensor content resulted in an average fuel moisture content of 54.6% per kg fuel.
- Dry fuel contained 25.9% moisture per kg fuel on average
  The fuel moisture soft-sensor content resulted in an average fuel moisture content of 27% per kg fuel



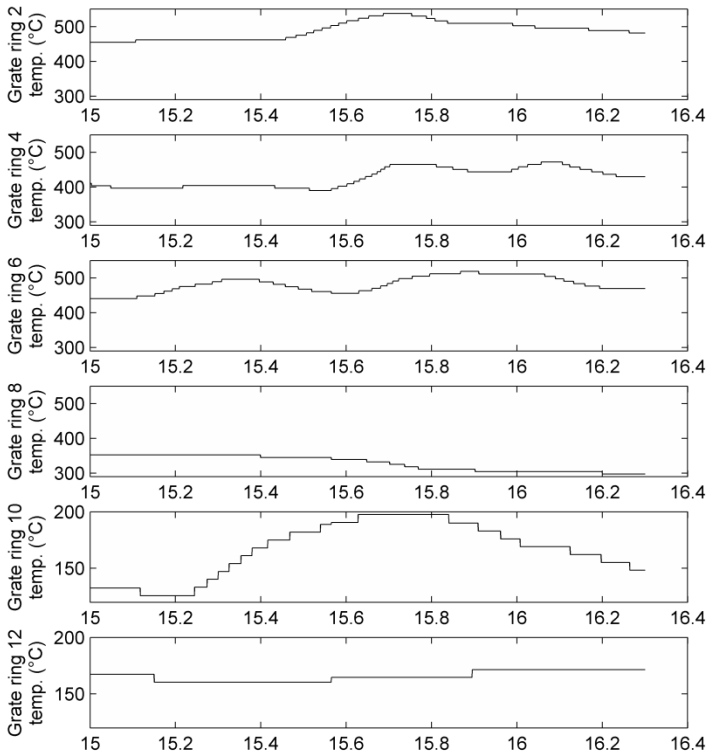
Fuel moisture soft-sensor (thick line), sampled fuel moisture (stars), and fuel moisture calculated from the FT-IR measurement (thin line) for comparison.

The test results of the fuel moisture soft-sensor: Dynamic behaviour

- The fuel moisture soft-sensor responds to step changes within 1 minute compared with FT-IR according to the test results and cross-correlation analysis



Fuel moisture soft-sensor (thick line), sampled fuel moisture (stars), and fuel moisture calculated from the FT-IR measurement (thin line) for comparison.



Grate temperatures during the test. The grate rings are numbered from the center (Grate ring 2) to the edge of the grate (Grate ring 12)

Conclusions

- Fuel moisture soft-sensor opens new possibilities to control combustion:
  - Fuel moisture soft-sensor shows a decrease in fuel moisture 20 minutes before drum pressure drops
  - Fuel moisture soft-sensor responds to step changes within 1 minute compared with FT-IR.
- Fuel moisture soft-sensor value and the sampled moisture content matches well
- In 15 MW BioPower CHP plant average 0.5 million euros is saved yearly