COPECOM - Control potential of different operating methods in small-scale wood pellet combustion

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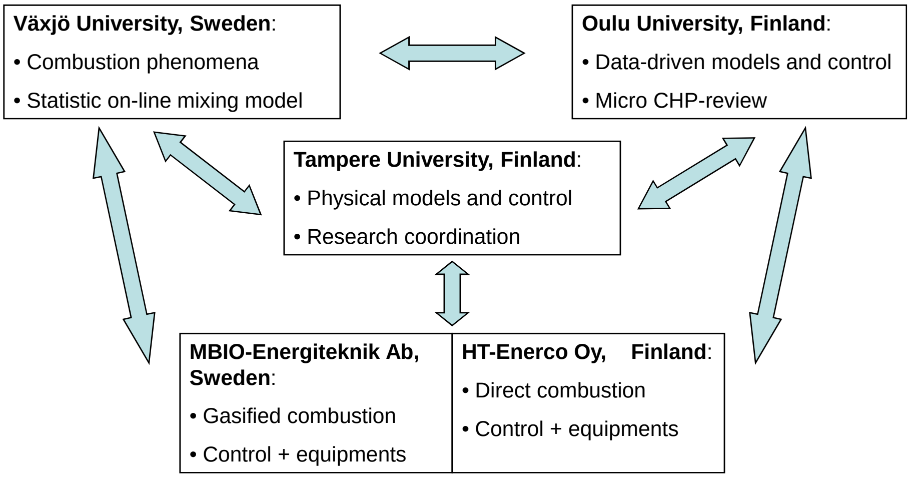
COPECOM
Research focus and targets

- Control potential of pellet burners – research on gasified and direct combustion, *experimental*
- Physical + data-based modelling and control development, *experimental/theoretical*
- An analysis of integrated small-scale power production and storage, *theoretical*

Research consortium



Växjö University, Sweden:
- Combustion phenomena
- Statistic on-line mixing model

Oulu University, Finland:
- Data-driven models and control
- Micro CHP-review

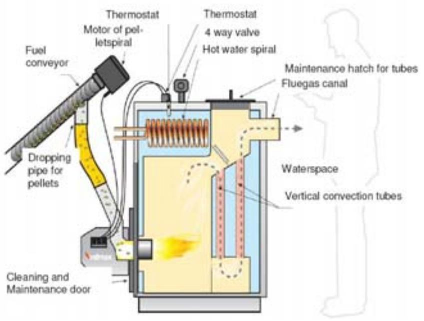
Tampere University, Finland:
- Physical models and control
- Research coordination

MBIO-Energiteknik Ab, Sweden:
- Gasified combustion
- Control + equipments

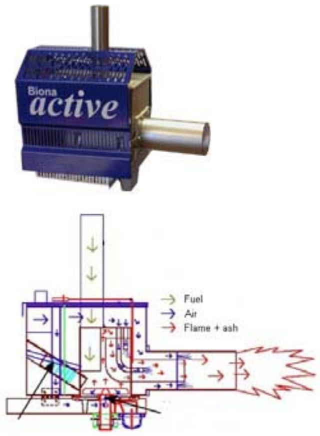
HT-Enerco Oy, Finland:
- Direct combustion
- Control + equipments

Burners

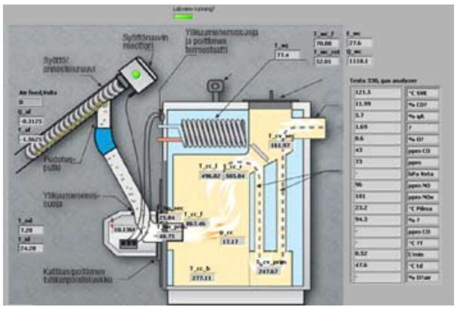
Velmax



Biona



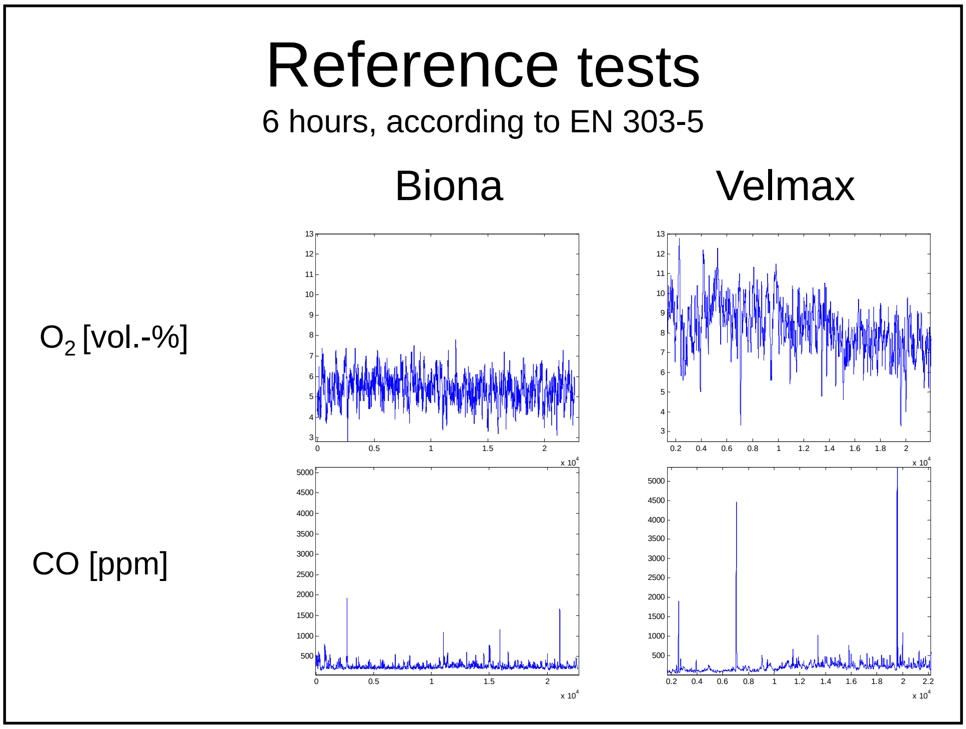
The Finnish subproject



Reference tests

6 hours, according to EN 303-5

	Biona	Velmax
Boiler output, kW, (mean value ± std)	**15.3 ± 2.7**	**15.3 ± 4**
Burner output (fuel), kW, (mean value)	**19.7**	**17.5**
Total efficiency, %, (from fuel to water)	**78**	**87.4**
O2, %, (mean value ± std)	**5.4 ± 0.7**	**8.2 ± 1.3**
CO, ppm (mean value @ 10% O2 ± std)	**184 ± 92**	**191 ± 588**
NOx, ppm, (mean value @ 10% O2 ± std)	**73 ± 4.2**	**97 ± 11.5**



Reference tests

6 hours, according to EN 303-5

Biona

Velmax

O_2 [vol.-%]

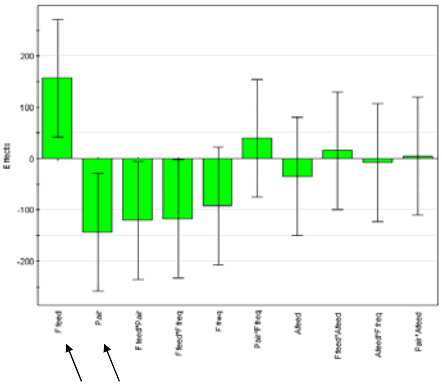
CO [ppm]

Design of Experiments

- In search for effects and interactions
- Selected control variables
  - fuel power
  - draft
  - air feed
  - fuel feeding period
- Full factorial design
- Partial Least Square (PLS) modelling

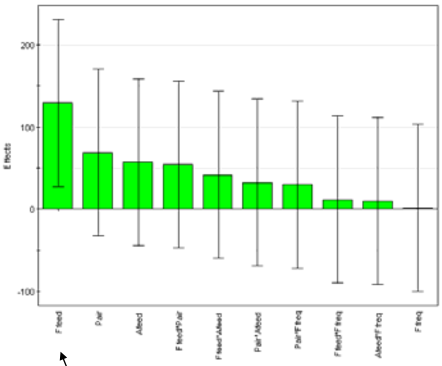
Main effects, CO

Biona



Fuel power, Draft

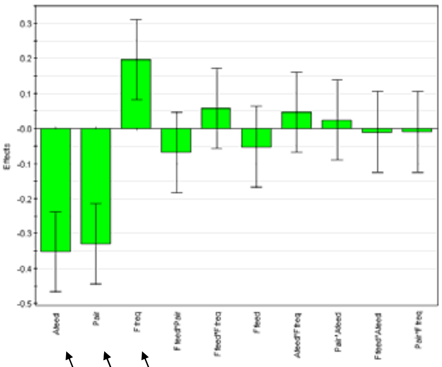
Velmax



Fuel power

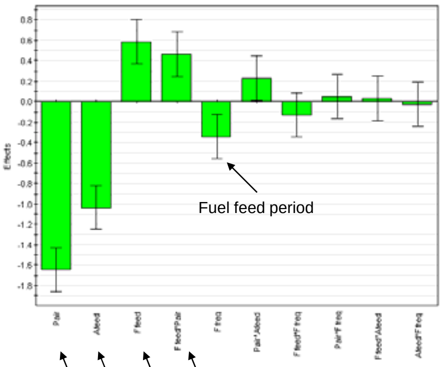
Main effects, total efficiency

Biona



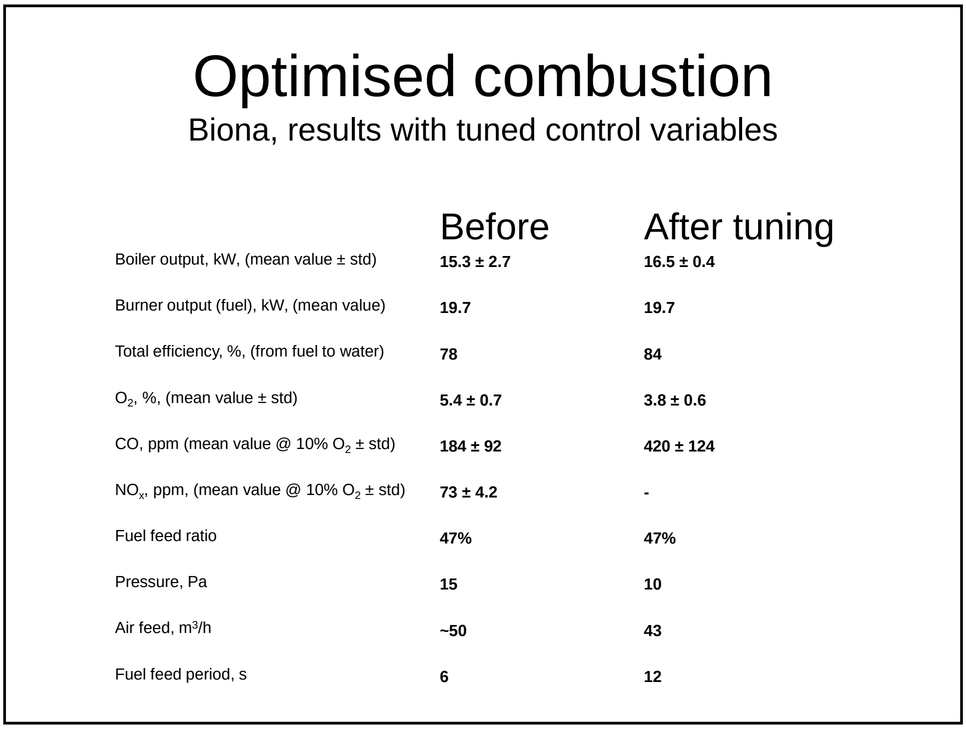
Air feed, Draft, Fuel feed period

Velmax



Fuel feed period

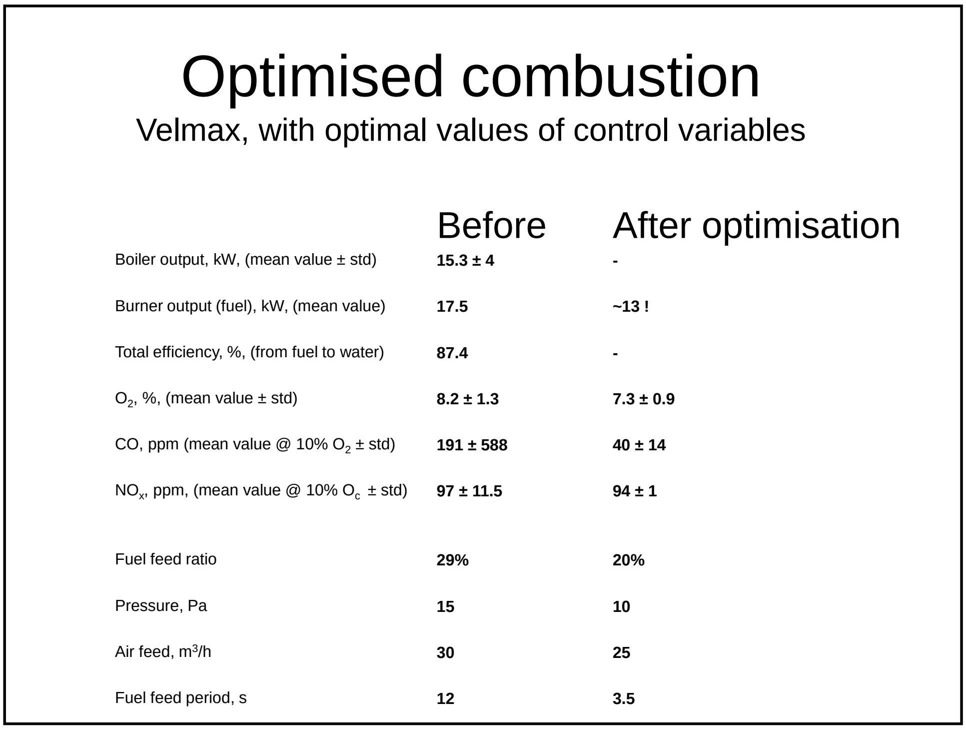
Draft, Air feed, Fuel power+Draft,



Optimised combustion

Biona, results with tuned control variables

	Before	After tuning
Boiler output, kW, (mean value ± std)	**15.3 ± 2.7**	**16.5 ± 0.4**
Burner output (fuel), kW, (mean value)	**19.7**	**19.7**
Total efficiency, %, (from fuel to water)	**78**	**84**
O_2, %, (mean value ± std)	**5.4 ± 0.7**	**3.8 ± 0.6**
CO, ppm (mean value @ 10% O_2 ± std)	**184 ± 92**	**420 ± 124**
NO_x, ppm, (mean value @ 10% O_2 ± std)	**73 ± 4.2**	**-**
Fuel feed ratio	**47%**	**47%**
Pressure, Pa	**15**	**10**
Air feed, m^3/h	**~50**	**43**
Fuel feed period, s	**6**	**12**



Optimised combustion

Velmax, with optimal values of control variables

	Before	After optimisation
Boiler output, kW, (mean value ± std)	**15.3 ± 4**	**-**
Burner output (fuel), kW, (mean value)	**17.5**	**~13 !**
Total efficiency, %, (from fuel to water)	**87.4**	**-**
O_2, %, (mean value ± std)	**8.2 ± 1.3**	**7.3 ± 0.9**
CO, ppm (mean value @ 10% O_2 ± std)	**191 ± 588**	**40 ± 14**
NO_x, ppm, (mean value @ 10% O_c ± std)	**97 ± 11.5**	**94 ± 1**
Fuel feed ratio	**29%**	**20%**
Pressure, Pa	**15**	**10**
Air feed, m^3/h	**30**	**25**
Fuel feed period, s	**12**	**3.5**

Discussion of experiment results

- Explored control variables have effect on combustion
- Stable and proper chosen values for variables important
- Air feed control disturbs combustion (primary + secondary air changes simultaneously)
- Combination of optimal values can reduce emissions and increase total efficiency

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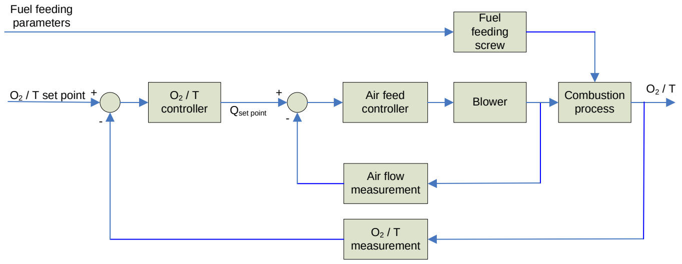
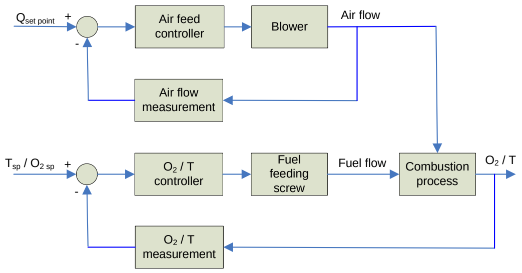
A control concept



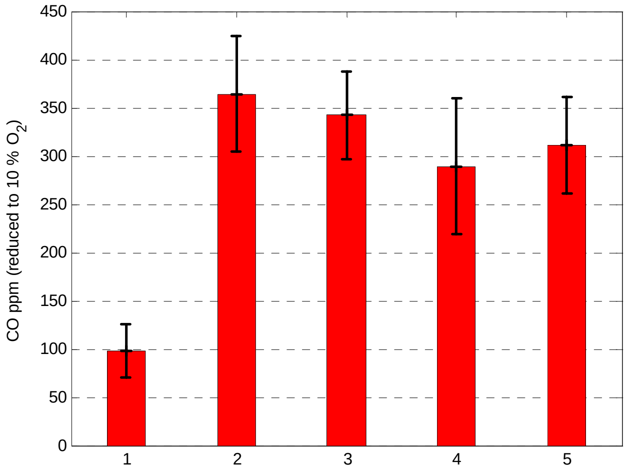
- Excess air stabilisation
- Results in power fluctuation
- Not suitable as the primary and secondary air feeds cannot be separated with burners with one air fan
- Note: Constant air flow do not stabilize the combustion

Proposed control concept



- Power stabilisation
- Settles the fuel feed to air feed
- Enables power level control
- Both Velmax and Biona (with constant power)

CO with different control strategies (Velmax)



1. Excess air stabilisation, lambda sensor + air flow control
2. Power stabilisation, lambda sensor + air flow control
3. Power stabilisation, lambda sensor
4. Power stabilisation, temperature sensor + air flow control
5. Power stabilisation, temperature sensor

Conclusions

- Requirements for clean combustion
  - Draft
  - Air feed
  - Fuel feed
  - Other parameters (e.g. fuel feeding period)
- The combustion properties vary with different systems
- Active control can compensate variations in combustion conditions
- Controllable process and proper instrumentation is needed
- Emission and efficiency requirements determines the automation level

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Modelling approach

Fundamental thoughts behind approach:

- Domestic pellet burners may not be of optimal design – nor operating under optimal conditions – for environmentally friendly combustion, though they are carbon-dioxide neutral
- The emissions of unburned hydrocarbons may be radically reduced by the application of modern control technology
- To achieve this, a model that can avoid sudden peak values is necessary.

Statistical modelling, Växjö experiments

Two (*main*) questions:

1: What are the average values?

2: How big is the variation?

Hypothesis:

The variation in analysis can probably be related to imperfections in the mixing along the gas pathway.

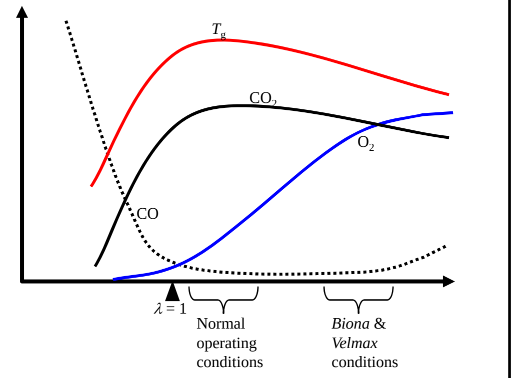

Figure 10: Over all behavior of oxygen, unburnt and temperature in combustion applications as functions of the air factor

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Statistical modelling, Växjö experiments

Results:

1: Mean values measured: TOO HIGH!!

2: Variation in CO (meas):
Biona 455, $\sigma = 219$ ppm
Velmax 404, $\sigma = 279$ ppm

(Biona 455, $\sigma = 220$ ppm
Velmax 400, $\sigma = 280$ ppm)

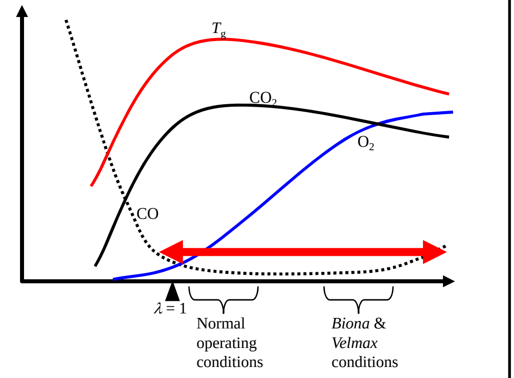

Figure 10: Over all behavior of oxygen, unburnt and temperature in combustion applications as functions of the air factor

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Statistical modelling, Växjö experiments

Results:

1: Mean values: TOO HIGH!!

2: Variation in CO (meas):
Biona 455, σ = 220 ppm
Velmax 400, σ = 280 ppm

Model results:

Biona 600, σ = 400 ppm
Velmax 0, σ = 300 ppm

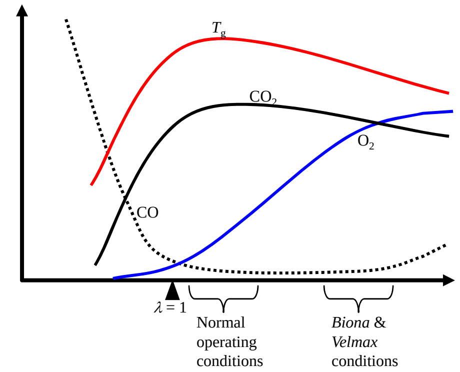

Figure 10: Over all behaviour of oxygen, unburnt and temperature in combustion applications as functions of the air factor

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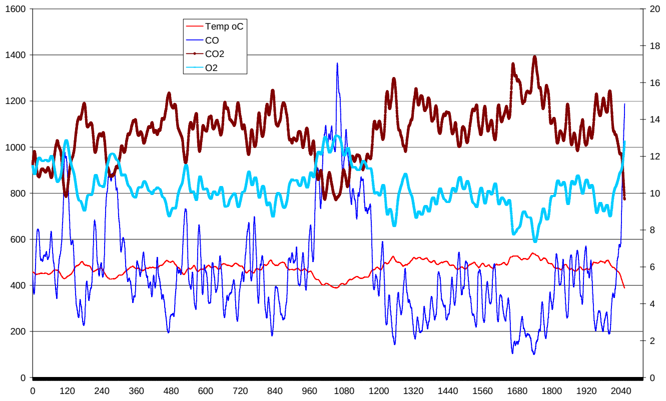
Statistical modelling

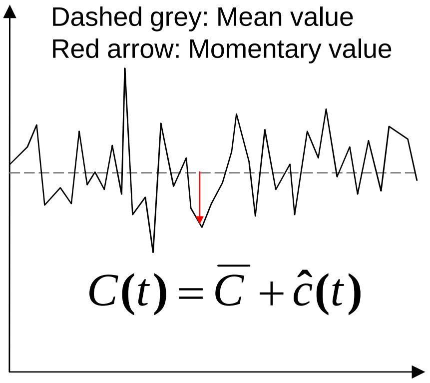
The model results seem to indicate that statistical modelling can be used to reproduce the variations in CO as well as its over-all behaviour.

- How does the statistical model work?

Time data for gas analysis, 35 min exp:



Time data for local gas analysis:



Dashed grey: Mean value
Red arrow: Momentary value

$$C(t) = \overline{C} + \hat{c}(t)$$

The mean value can be calculated from a simple mass balance.

The momentary value needs more consideration...

Resolved data for gas analysis:

Two major ways to attack the problem:

1) Make time averages and solve the Navier-Stokes and continuity equations for node points in space
   This yields space-resolved concentration distributions and is the classical method used in CFD modelling.
2) Assume constant averages across macroscopic volumes and introduce functions for the successive development of the distribution as a function of time.
   This yields approximate distributions at the exit from each computational volume.

Resolved data for gas analysis:

The third way to attack the problem:

3) Solve the Navier-Stokes and continuity equations for node points in space and following turbulent disturbances though time.
   This yields space-and-time-resolved concentration distributions and is quite CPU-intensive and time consuming.

This is probably not reasonable for on-line control…

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Statistical modelling

Resolved data for gas analysis:

The second way is sufficient in this case, since the aim is to reproduce the general behaviour of the gas analysis, i.e. the frequency (and thus the total, time-integrated amounts) of harmful emissions.

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Statistical modelling

Resolved data for gas analysis:

The main weakness of this treatment are that it must be based on correlations rather than on thorough models and that it can only treat the gas phase while the solid phase must be extremely simplified.

The second way is sufficient in this case, since the aim is to reproduce the general behaviour of the gas analysis, i.e. the frequency (and thus the total, time-integrated amounts) of harmful emissions.

Step 1
Define a time series for the fuel-air mixture at the inlet

Resolved data for gas analysis:

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Step 1
Define a time series for the fuel-air mixture at the inlet

Step 2
Modify the time series according to predetermined functions

Resolved data for gas analysis:

The main weakness of this treatment is that it must be based on correlations rather than through models that can only by the gas phase while the solid phase must be extremely simplified.

The second way is sufficient in this case, since the aim is to reproduce the general behaviour of the gas analysis, i.e. the frequency (and thus the total time-integrated amounts) of harmful emissions.

Step 1
Define a time series for the fuel-air mixture at the inlet

Step 2
Modify the time series according to predetermined functions

Step 3
Modify the time series with respect to additional air

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Statistical modelling

Resolved data for gas analysis:

The main weaknesses of this treatment are that it must be based on correlations rather than on thorough models and that it can treat only the gas phase while the solid phase must be extremely simplified.

Step 1	**Step 2**	**Step 3**	**Step 4**
Define a time series for the fuel-air mixture at the inlet	Modify the time series according to predetermined functions	Modify the time series with respect to additional air	Iterate 2 and 3 over all volumes until finished

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Statistical modelling

Step 0

Find one parameter to be followed:

The air factor – λ – has the disadvantage of being defined on an open interval, [0 , ∞ [, which makes it difficult to use.

Use the mixing factor instead: $f_{mix,air} = \dfrac{\lambda \cdot m^0_{air,stoichiometric\ need}}{\lambda \cdot m^0_{air,stoichiometric\ need} + 1 + m_{inert}}$

where m^0_{air} is the stoichiometric need of air in kg/kg wet fuel and m_{inert} is the momentary amount of flue gases in kg/kg wet fuel.

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Statistical modelling

Step 1

Set up an initial time series:

At the inlet, there can be only fuel ($f_{\text{mix}} = 0$) or air ($f_{\text{mix}} = 1$).

Hence, we define a randomized series 1100010011110100100... with the correct mean value and with a frequency representing a typical frequency of small-scale turbulence for the geometry.

The frequency is chosen as $\nu = \frac{\overline{U}}{d_P}$, where $\overline{U}$ is the mean gas velocity and d_P is the mean particle diameter.

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Statistical modelling

Step 2

Modify the time series successively:

As the series of eddies passes the physical volumes, the small eddies dissipate, representing a shift from higher to lower frequencies.

This is modelled by digital filtering using the response time function – which is the frequency characteristic of the volume – as the filter function.

Filtering does not affect the mean value but only the frequency spectrum.

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Statistical modelling

Step 3

Insert additional air at inlets:

Additional air – secondary, tertiary... – adds momentum and adds mass.

Momentum is added by decreasing the Peclet number in the filter functions (i.e. increasing the effective, turbulent, diffusion).

Mass is added by randomly inserting 1’s into the time series so as to change the mean value of the mixing factor f_{mix} in accordance with the physical reality.

To represent the increase in velocity, the total time is maintained as the number of eddies increase. Thus the frequency increases.

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Step 4

Iterate:

The time series – successively with more and more points as more and more air is injected – is followed downstream.

For each mixing factor value in the time series, the change from inlet to outlet is evaluated and recalculated into gas composition.

These values yield a change in gas heating value, and thus a heat release, in that volume. This is used to calculate a new gas temperature and a residence time in the volume. This is iterated in each volume with respect to the heat losses.

After the final volume, a time series for the exit gas is obtained.

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Statistical modelling

Back-calculate

The air factor:

From the last gas volume, a time series representing the mixing factor $f_{mix}(t)$ is now known, as is the gas temperature.

From $\lambda = \frac{f_{bo}}{1-f_{mix,air}} + \frac{1}{m^0_{air,st}} \cdot \frac{f_{mix,air}}{1-f_{mix,air}}$, this can be used to calculate $\lambda(t)$.

Knowing $\lambda(t)$, the gas composition can be readily calculated.

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Statistical modelling

Back-calculate

Gas composition when $\lambda < 1$ (IV):

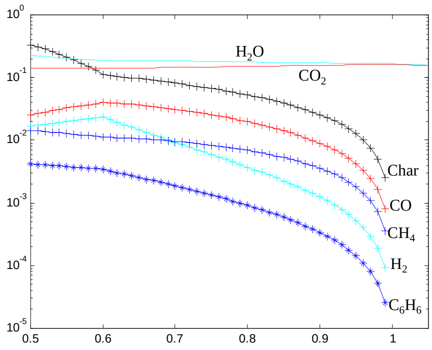


Figure 1: Distribution of hydrocarbons as a function of the air factor at sub-stoichiometric conditions

Sample calculation showing the fractions of the different components as a function of λ at sub-stoichiometric conditions.

Statistical modelling

Back-calculate

Gas composition when $\lambda \geq 1$:

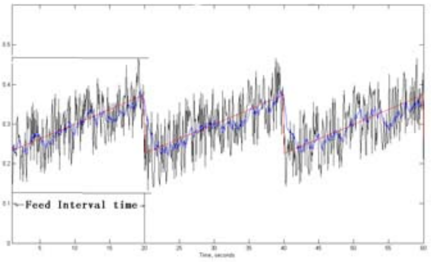
In case of over-stoichiometric conditions, simple stoichiometry is used to calculate the gas composition from the air factor.

Statistical modelling

Example

The Biona burner, gasifier volume:

In the Biona, pellets are fed batch-wise creating a saw-tooth pattern for the air factor in the primary zone:



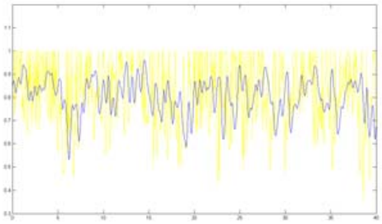
Red: λ mean baseline

Black: λ randomised to input

Blue: λ at exit of volume 1

The Biona burner, combustion chamber:

The last air in the Biona is injected just at the inlet to the boiler combustion chamber:



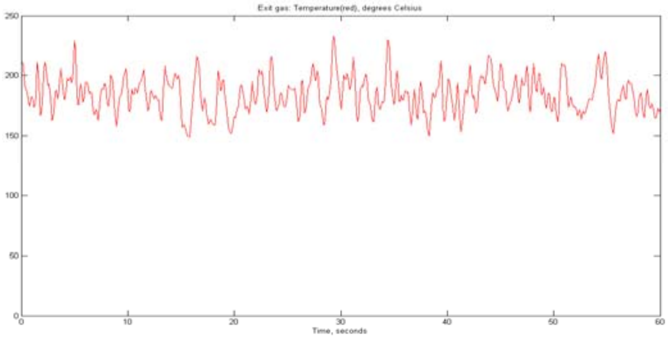
Yellow: f_{mix} at air inlet

Blue: f_{mix} at fireplace exit

This represents the flue gas

The Biona burner, results:

The diagram shows the simulated gas temperatures at the boiler exit during 1 minute:



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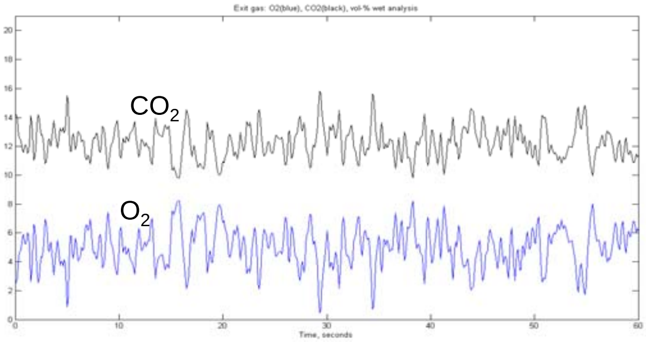
Statistical modelling

Example

The Biona burner, results:

The diagram shows the simulated gas analysis (CO_2 and O_2) at the boiler exit during 1 minute (*wet analysis*):



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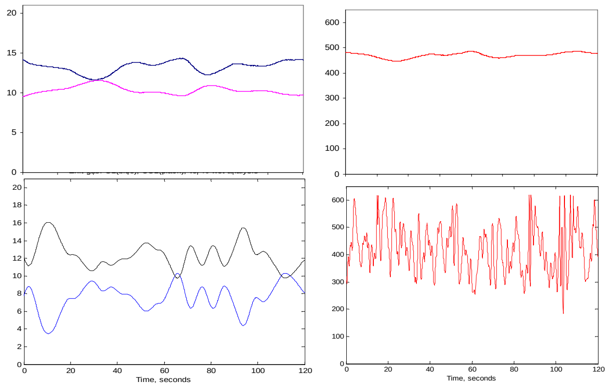
Statistical modelling

Example

The Biona burner, comparison, 2 min:



Measured CO_2, O_2 and temperature

Simulated CO_2, O_2 and temperature

Analyzer system dampens variations

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Statistical modelling
Example

The Biona burner, five simulations:

$O_{2,mean}$	σ_{O2}	$CO_{2,mean}$	σ_{CO2}	CO_{mean}	σ_{CO}
7.8	1.0	12.0	0.9	842	459
8.1	1.3	11.8	1.4	676	635
7.6	1.6	12.3	1.5	562	203
7.7	1.3	12.2	1.2	758	371
7.8	1.0	12.0	1.0	557	206
7.8	1.3	12.1	1.2	679	409

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Statistical modelling
Complementary experiments

Burner vs. Combustion chamber:

Experiments in a Baxi boiler showed incomplete combustion from both burners.

Experiments in an axisymmetric, insulated, combustion chamber also demonstrated incomplete burnout – though better.

Simulations confirm the trend.

Thus, the over-all behaviour of the statistical model seems correct within the limits set by the simplifications used.

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Statistical modelling

Over-all conclusions (I)

The statistical model in general:

The suggested statistical model can:

- Reasonably well predict an over-all gas analysis containing several % O_2 in combination with several hundred ppm CO
- Reasonably well reproduce the variation in CO-emissions as a measure of total unburnt
- Describe how changes in geometry from one to another will influence the over-all mixing and burnout, as long as the changes are not too radical

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Statistical modelling

Over-all conclusions (II)

The statistical model in general:

The suggested statistical model can ***not***:

- A priori – i.e. without adoption to experimental values – predict the behaviour of a burner/boiler combination
- Predict effects primarily caused by chemical kinetics
- Extrapolate to very large changes

Statistical modelling
Over-all conclusions (III)

The statistical model in general:

The suggested statistical model can thus:

- Be used as a predictor in a control system, pointing out the correct direction for adjustments to improve the burnout
- Improve its own predictive power by collecting data successively

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COPECOM: Developed control framework

- Temperature measurement information is enriched by mathematical modelling
  - Models to determine emissions and efficiency (UO + TUT)
  - They are used with statistic mixing model to gain information in which direction the process should be driven (VXU)
  - The result is combination of models
  - The enriched information is the foundation for control

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- MBIO Energieteknik Ab

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