Effect of alternative fuel properties on NO_x reduction

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Introduction

Today we see a substantial increase in the use of alternative fuels in the cement industry. The prospect of reduction in fuel costs and the environmental benefits of waste to energy conversion are the driving forces. For several years Norcem have steadily increased their use of alternative fuels such as refuse derived fuel (RDF), liquid hazardous waste (LHW), solid hazardous waste (SHW), animal meal (AM) and waste oil (WO). Alternative fuels behave differently compared to e.g. coal during combustion, which is a factor that may influence the clinker quality, kiln operation, energy consumption and emissions. Scancem International ANS and Telemark University College has therefore initiated a research program to provide a better basis for characterization and understanding of alternative fuels in cement kilns. The study focus on the effect of alternative fuel properties on NO_x reduction by advanced reburning and reburning in conjunction with CO emission.

A laboratory circulating fluidized bed combustor (CFBC) is applied, in addition to full scale experiments at kiln 6 Norcem Brevik. Furthermore, computational fluid dynamic (CFD) simulations with the aid of Fluent ® on the flow regime of the precalciner at kiln 6 Norcem Brevik is performed. This paper will summarize the findings including results from full-scale experiments with advanced reburning, animal meal and solid hazardous waste as a reburning fuel and with comparable tests in the CFBC reactor.

Full scale experiments

The precalciner kiln 6 in Brevik is a so called "in-line calciner" (ILC), where the off-gas from the kiln is led through the precalciner. A sketch of the precalciner kiln is shown in Figure 1. Table 1, 2 and 3 show the characteristics of the kiln, the fuels and the emissions of kiln 6, respectively.

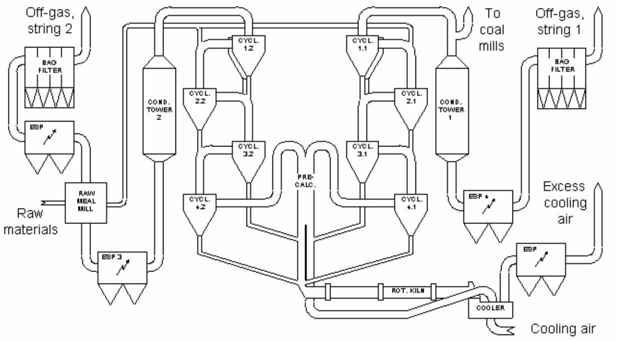

Figure 1: *Precalciner kiln 6, Brevik*

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[1] Part of Heidelberg Cement

Table 1: *Characteristics of kiln 6,Brevik.*

Kiln length	68 m
Outer kiln diameter	4.4 m
Nominal production capacity	3300 tons clinker/day
Typical specific fuel consumption	3300 kJ/kg clinker
Approximate static pressure loss in the preheater	7000 Pa
Specific cooler load at nominal production capacity	48 tons clinker/m²day

Table 2: *Fuel characteristics of kiln 6,Brevik.*

Parameters	**Unit**	**Coal**	**LHW**	**SHW**	**RDF**	**AM**	**WO**
Moisture	% (As rec.)	2.80	45.70	10.70	25.00	4.50	0.00
Volatiles	%	31.60	100.00	46.30	53.0	59.70	100.00
C.fix	%	45.5	0.00	7.70	10.50	7.50	0.00
Ash	%	20.1	0.00	35.30	11.50	28.30	0.00
LHV	MJ/kg (as rec.)	24.74	17.88	15.75	18.0	15.80	41.60
O/N	Molar ratio	2.30	11.89	36.65	34.60	1.57	-

Table 3: *Emission characteristics of kiln 6,Brevik.*

Emission component	**SFT limit value**[2] mg/Nm^3@ 11 % O_2	**2000** mg/Nm^3@ 11 % O_2
Dust	40	5
Total organic carbon (TOC)	10	6.5
Chlorine compound calculated as HCl	10	6.6
Fluorine compound calculated as HF	1	0.1
SO_x calculated as SO_2	300	170
NO_x calculated as NO_2		707
Sum Cd + Tl	0.1	0.081
Mercury	0.1	0.002
Sum of other metals[3]	1.0	1.913
Dioxines	0.1[4]	0.025[5]

Execution of full scale experiments

The experiments in the precalciner have been executed in two campaigns in order to obtain reburning and advanced reburning, according to Table 4, 5 and 6. Henceforth, refereed to as experiment 1 to 7 for the experiments in February and 8 to 17 for the experiments in April.

Advanced reburning is obtained with urea pellets fed into the precalciner at the kiln gas side with the alternative fuel (SHW). The proportioning of urea pellets are executed with a screw feeder into the alternative fuel feed stream.

The reburning fuels are solid hazardous waste and animal meal.

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[2] The Norwegian State Pollution Control Agency (SFT)

[3] Sb, As, Pb, Cr, Co, Cu, Mn, Ni, V, Sn

[4] I-TE ng/Nm^3

[5] I-TE ng/Nm^3

Table 4: *Average fuel- and solid feed into the precalciner kiln 6 during experiments in February 2001.*

Parameters		**No feed**	**SHW**	**SHW + 38 kg/h urea**	**SHW + 153 kg/h urea**	**SHW + 269 kg/h urea**	**SHW + 386 kg/h urea**	**AM**
		#1	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**
Coal$_{\text{Primary Burner}}$	t/h	4.1	3.6	3.8	3.8	3.6	3.5	4.2
Coal$_{\text{Precalciner}}$	t/h	9.9	9.0	9.7	8.8	9.2	9.0	8.9
LHW	t/h	1.5	1.7	1.8	1.8	1.8	1.8	1.5
SHW	t/h	0.0	3.0	3.0	3.0	3.0	3.0	0.0
RDF	t/h	2.9	2.5	2.0	2.3	2.0	2.0	3.1
AM$_{\text{Precalciner}}$	t/h	0.0	0.0	0.0	0.0	0.0	0.0	2.6
AM$_{\text{Primary Burner}}$	t/h	0.0	0.0	0.0	0.0	0.0	0.0	0.0
WO	t/h	2.5	2.6	2.2	2.2	2.5	2.7	2.5
Raw Meal	t/h	238	238	237	224	237	237	239

The reference condition is no feed of alternative fuel into the kiln gas side of the precalciner, with reference to experiment 1 and 8. Experiment 3, 4, 5 and 6 as well as experiment 10, 11, and 12 show increasing feed of urea to obtain advanced reburning (AR) rich with a 30 minutes interval.

Table 5: *Average fuel- and solid feed into the precalciner kiln 6 during experiments in April 2001.*

Parameters		**No feed**	**SHW**	**SHW + 153 kg/h urea**	**SHW + 386 kg/h urea**	**SHW + 770 kg/h urea**	**AM**
		# 8	**# 9**	**# 10**	**# 11**	**# 12**	**# 13**
Coal$_{\text{Primary Burner}}$	t/h	6	8	8	8	8	8
Coal$_{\text{Precalciner}}$	t/h	8	5	6	5	6	6
LHW	t/h	2	0	0	0	0	0
SHW	t/h	0.0	4	4	4	4	0.0
RDF	t/h	4	6	5	6	6	6
AM$_{\text{Precalciner}}$	t/h	2.0	0.0	0.0	0.0	0.0	3
AM$_{\text{Primary Burner}}$	t/h	0.0	0.0	0.0	0.0	0.0	0.0
WO	t/h	0	0	0.0	0.0	0	2
Raw Meal	t/h	220	218	220	220	220	226

It is accomplished two longer trials with advanced reburning rich in experiment 16 and 17 at two and one hour interval, respectively. It is essential to investigate the effect of reburning with SHW in comparison to the advanced reburning, shown in experiment 2 and 9. Utilization of animal meal in the precalciner is shown in experiment 7 and 13. In experiment 16 and 17 the effect of animal meal in the main burner is shown with and without urea in combination with SHW in the precalciner.

Table 6: *Average fuel- and solid feed into the precalciner kiln 6 during experiments in April 2001.*

Parameters		**SHW**	**SHW + 386 kg/h urea**	**SHW + 153 kg/h urea**	**SHW + 386 kg/h urea**
		# 14	**# 15**	**# 16**	**# 17**
Coal$_{\text{Primary Burner}}$	t/h	7	6	7	7
Coal$_{\text{Precalciner}}$	t/h	5	4	5	4
LHW	t/h	1	1	1	2
SHW	t/h	4	4	4	4
RDF	t/h	6	6	5	6
Coal$_{\text{Precalciner}}$	t/h	0.0	0.0	0.0	0.0
Coal$_{\text{Primary Burner}}$	t/h	2	2	0.0	0.0
WO	t/h	1	0	0	0
Raw Meal	t/h	213	220	220	220

Results and discussion of the full scale experiments

The principal trend from the campaign in February (experiment 1 to 7) and April (experiment 8 to 13) can be seen in Figure 2 and 3. Where, the principal development shows decreasing NO_x emissions and increasing CO emissions.

The decreasing NO_x emission can be explained with:

- reburning with SHW (experiment 2 and 9),
- increasing supply of urea together with SHW (advanced reburning rich) in experiment 3 to 6 and 10 to 12, and
- utilization of animal meal in experiment 7 and 13.

Additional supply of animal meal into the main burner during reburning and advanced reburning showed additional NO_x reduction in experiment 16 and 17.

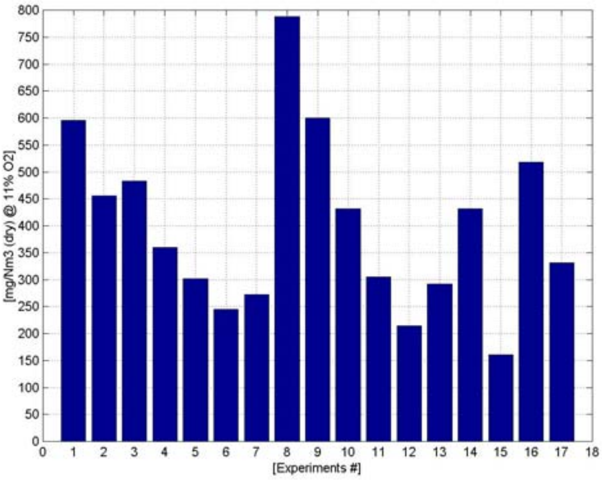

Figure 2: *NO_x emitted from kiln 6 during experiment 1 to 17.*

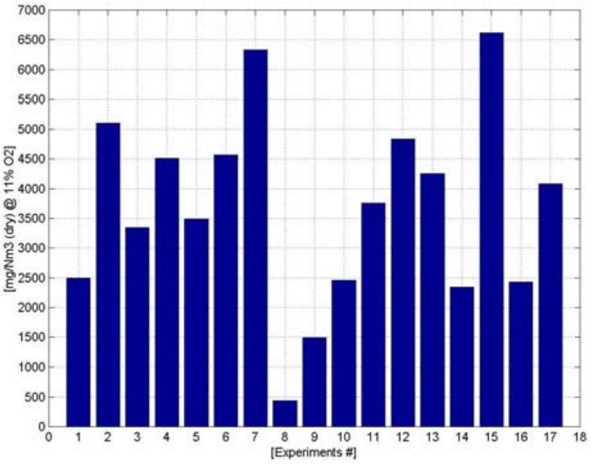

Figure 3:*CO emitted from kiln 6 during experiment 1 to 17.*

The full-scale experiments showed that:

- advanced reburning and combustion of animal meal in the precalciner is well suited for NO_x reduction in the precalciner kiln 6 at Norcem Brevik, and
- combustion of animal meal in the main burner gives additional overall NO_x reduction and lower NO_x emissions at the kiln inlet although it result in a significant increase of fuel-nitrogen supply.

An increasing development of the molar ratio (urea/$NO_{\text{kiln inlet}}$) lower the NO_x emissions and that an optimum NO_x reduction is at a ratio between 2.6 to 3, which is lower compared to previous experiments /1/.

The assumption is that combustion of animal meal follows a similar reduction route as advanced reburning or selective non-catalytic reduction because of a low HCN/NH_4 ratio.
Hämäläinen (1995) showed that the/NH_3 ratio in pyrolysis gases decreases with the fuel O/N ratio /2/. It can be seen from Table 2 that the O/N ratio is low for animal meal and coal in comparison with solid hazardous waste (SHW) and refuse derived fuel (RDF), which signify a smaller HCN/NH_3 ratio. Experiments showed that up to 86 % of the nitrogen in animal meal is released during pyrolysis, compared to only 4 % in the coal.
Experiments executed by Zevenhoven et al. (2000) showed that smaller HCN/NH_3 ratio favour NO_x reduction /3/. Comparing experiments made by Desroches-Ducarne et al. (1998) to experiment 7 and 13, shows that adding a fuel with low HCN/NH_3 ratio in combination with RDF lowers the NO_x emissions /4/. Hence, NO_x reduction with animal meal is most likely to originate from NH_3 released during volatilisation.

The CO and TOC emissions follow the same pattern, as it is a result of incomplete combustion.
The increased CO emissions are probably due to the increasing amount of NH_3 in the process during supply of urea and animal meal in experiment 1 to 17.
Equation 1 and 2 are the primary reduction reactions for NH_3 and CO, respectively. It can be seen from Figure 4 that the primary abstraction reaction constant for NH_3 is about ten times faster than the CO oxidation. Hence, the competition for the OH radical between Equation 1 and 2 are probably the reason for the increased CO emissions.
The increased TOC emissions can probably be due to the formation of e.g. NH_4Cl.

$$CO + OH \rightarrow CO_2 + H \tag{1}$$

$$NH_3 + OH \rightarrow NH_2 + H_2O \tag{2}$$

The ammonia slip is about 34 % of the NO_x reduction during combustion with animal meal. Furthermore, the ammonia slip is a minor part, 0.8 %, of the NO_x reduction when animal meal is supplied into the main burner.

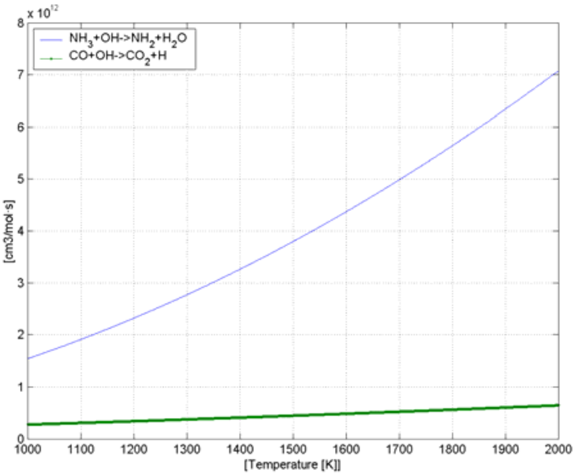

Figure 4: *Comparison between the reaction rate constants for reaction:* $NH_3+OH\text{->}NH_2+H_2O$ *and* $CO+OH\text{->}CO_2+H$ */5/.*

Laboratory experiments

Laboratory experiments have been accomplished at Telemark University College with the use of a laboratory CFBC reactor. The main purpose is to investigate different fuels characteristics during:

- reburning,
- advanced reburning and
- combustion without circulating mass.

The laboratory CFBC reactor are designed and operated in order to obtain similar conditions as in a precalciner /5/. The CFBC reactor has a physical design of about 6 meter in height and 100 mm diameter.
A literature review showed that there is a similarity between the CFBC reactor and the precalciner regarding the phenomena of:

- gas- and solid mixing,
- core-annulus flow,
- micro flow structure and
- effects of particles on turbulence.

There is a similarity between the CFBC reactor and the precalciner at Norcem Brevik regarding the dimensionless groups applied, which roughly obtains the same:

- fluidization regime,
- riser solids hold-up by volume fraction and
- macroscopic movements of solid.

The largest difference between the CFBC reactor and the precalciner is the turbulence. The consequence of not achieving similar turbulence will probably affect the particle retention time and the diffusion of oxidizer to the fuel particle.

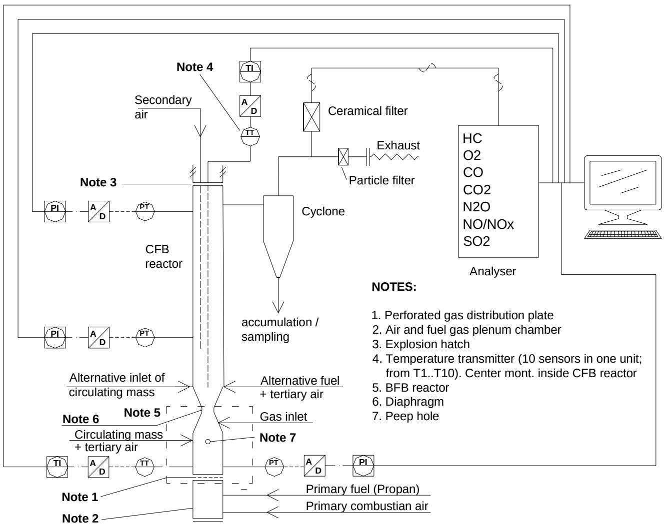

Figure 5: *Sketch of the CFBC reactor /7/.*

Execution of laboratory CFBC experiments

In the experiments with reburning and advanced reburning it was of interest to investigate alternative fuels behavior in a precalciner environment i.e. with circulating mass[6] and supply of up to 2000 mg/Nm³ of NO into the CFBC reactor. In the experiments without circulating mass fuel specific differences were expected.

It was decided to vary the supply of NO in four steps for the experiments with advanced reburning and combustion without circulating mass to investigate the impact of increasing supply of NO.
The reburning experiment was executed with virginal and blends of fuels, which was the main object with this set of experiments. The reburning experiment was executed with only one step of NO supplied (about 1930 mg/Nm³).
Table 7 show the principal operating conditions during the experiments including the levels of SO_3, Cl and the calcination degree.

It was chosen to run the reburning and advanced reburning experiments with a particle size less than 1 mm. The experiment without circulating mass was tested with two sets of particle sizes, namely less than 1 and 2 mm, to investigate the impact on combustion behavior.

Table 7: *Principal results from the reburning, advanced reburning and combustion without circulating mass experiments.*

Parameters	Unit	Reburning	Advanced reburning	Comb. without circ. mass
λ	[-]	1.11 - 1.21	1.12 - 1.26	1.52 - 1.82
Alt. fuel	% energy	49 - 64	36 - 56	28 - 57
q	kW	37.5 - 53.1	35.7 - 55.8	20 - 29
τ_g	sec.	0.64 - 0.69	0.63 - 0.67	0.86 - 1.06
v_{riser}	m/s	6.3 - 6.8	5.9 - 6.8	4.0 - 5.0
Re	[-]	5300 - 5700	5570 - 5670	4520 - 4810
ε_{riser}	[-]	0.99996	0.99996	-
G_s	kg/h	29	29	-
$NO_{supplied}$	mg/Nm³	1931	72 - 1457	74 - 1450
Calsination	%	70 - 86	83 - 87	-
SO_3	wt%	0.36 - 0.6	0.075 - 0.45	-
Cl	wt%	0.01 - 0.14	0.01 - 0.01	-

Results and discussion of the laboratory experiments

The principal laboratory experiments showed:

- almost no connection between the level of NO supplied and the CO and TOC emissions,
- that larger particle size gave increased CO emissions,
- that increasing the particle size changes the ranking of fuels with highest CO emittance and
- increasing CO and TOC emissions during reburning with animal meal in contrast to combustion in a lean environment (without circulating mass).

Combustion of animal meal showed increased CO and TOC emissions similar to the full-scale experiments. However, when animal meal is burnt in a lean environment the CO and TOC emissions are low and the competition between Equation 1 and 2 seems to be of minor importance.

A probable cause is that:

- for lean flames, the critical amine free radical NH_2 is reduced directly or through the NNH intermediate, and/or
- the increased amount of hydrogen radicals increases the production of OH radicals.

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[6] The experiments were executed with circulating mass that had a mixture of 50/50 raw meal and Millisil®M6. The loading of circulating mass was about 67 % of the theoretical input in comparison to the precalciner /7/.

Reburning

The reburning experiment was executed with the following fuels and mixtures:

- refuse derived fuel (RDF),
- animal meal (AM),
- coal,
- RDF/AM (75/25 wt %),
- coal/AM (75/25 wt %), and
- CC/AM (25/75 wt %).

The experiments were executed with about 1930 mg /Nm³ of NO supplied into the riser inlet. The development between the reburning fuels is shown in Figure 6.

The reburning experiments showed, at conditions similar to a precalciner, the following order of optimal NO reducing fuels and mixtures:

- RDF/AM (up to 41.4 % improvement related to coal),
- RDF (up to 39.5 % improvement related to coal),
- CC/AM (up to 34.5 % improvement related to coal),
- AM (up to 25 % improvement related to coal),
- coal/AM (up to 18.3 % improvement related to coal), and
- coal.

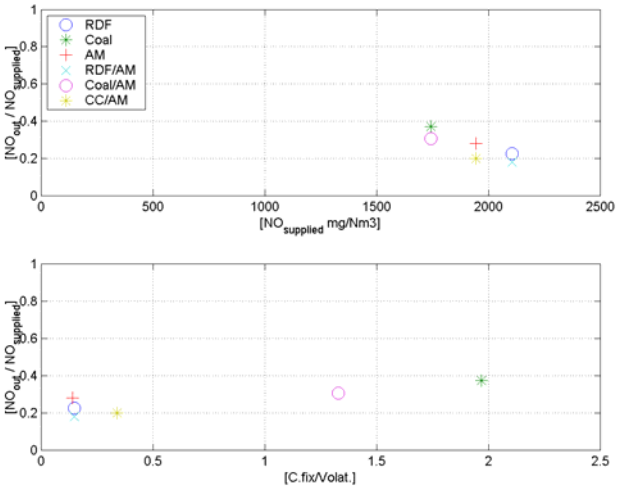

Figure 6: *Main plot: $NO_{supplied}$ with respect to $NO_{out}/NO_{supplied}$ ratio during reburning experiments with RDF, coal, AM, RDF/AM, coal/AM and CC/AM. Subplot: C.fix/Volat. ratio with respect to $NO_{out}/NO_{supplied}$ ratio.*

Advanced reburning
The advanced reburning rich experiment was executed with:

- 25 wt % urea and RDF (RDF_{25}),
- 5 wt % urea and RDF (RDF_5), and
- 5 wt % urea and coal ($coal_5$).

The experiments were executed with a four-step variation in the NO supplied (72 - 1457 mg /Nm³) with the development shown in Figure 7. Figure 8 show the urea/$NO_{supplied}$ ratio with respect to NO_{out}.

The advanced reburning experiments showed that:

- the surplus of urea, which did not contribute to a reduction in the NO and emitted as ammonia, is found as a increase in the NO_2 and N_2O,
- RDF is a better fuel for advanced reburning compared to coal,
- increased amount of $NO_{supplied}$ improves (lower) the ratio NO_{out} / $NO_{supplied}$ and
- the NO reduction depends on the ratio of (urea/ $NO_{supplied}$), with an optimum NO_x reduction larger than 5, see Figure 8.

The advanced reburning showed, at conditions similar to a precalciner (1000 mg/Nm³ $NO_{supplied}$), the following order of optimal NO reducing fuels and urea mixtures:

- RDF_5 (up to 60 %),
- RDF_{25} (up to 50 %), and
- $coal_5$(up to 8 %)

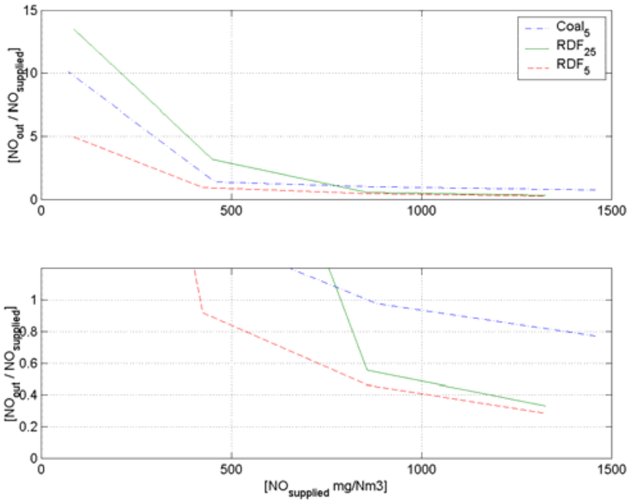

Figure 7: *Main plot: $NO_{supplied}$ with respect to $NO_{out}/NO_{supplied}$ ratio during advanced reburning experiments with 25 wt % urea and RDF; 5 wt % urea and RDF; 5 wt % urea and coal. Subplot: Close-up of the main plot.*

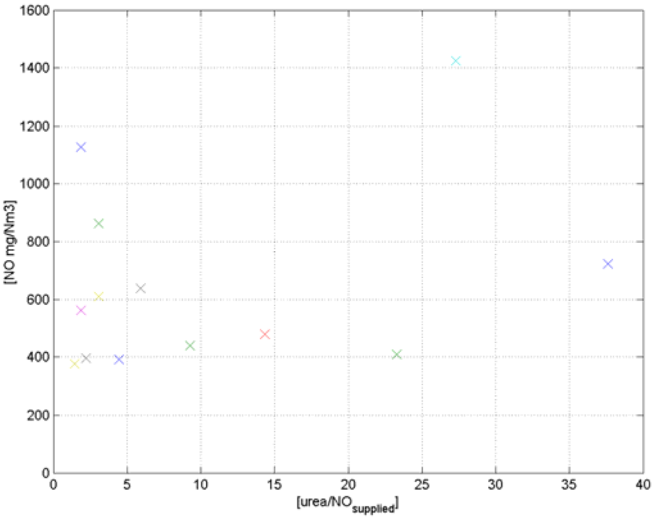

Figure 8: *The urea/NO$_{supplied}$ ratio with respect to NO$_{out}$ without consideration of types of alternative fuel.*

Combustion without circulating mass
The experiments without circulating mass was executed with:

- RDF,
- coal,
- AM, and
- SHW.

The experiments were accomplished with a four-step variation of the NO supplied (74 - 1450 mg /Nm³). There was no supply of tertiary air during the experiments without circulating mass. The overall excess air ratio was 1.52 to 1.82. Figure 9 and 10 show the development of the experiment without circulating mass.

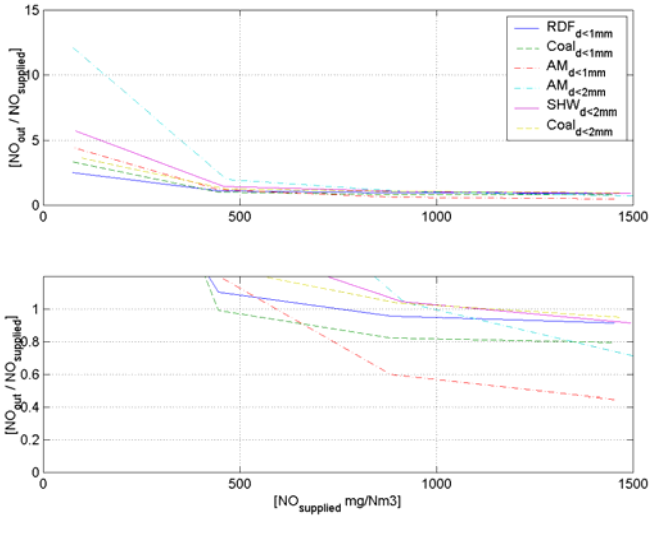

Figure 9: *Main plot: NO$_{supplied}$ with respect to NO$_{out}$/NO$_{supplied}$ ratio during experiments without circulating mass. Experiments with RDF$_{d<1mm}$, Coa$_{d<1mm}$, AM$_{d<1mm}$, SHW$_{d<2mm}$, Coal$_{d<2mm}$, AM$_{d<2mm}$. Subplot: Close-up of the main plot.*

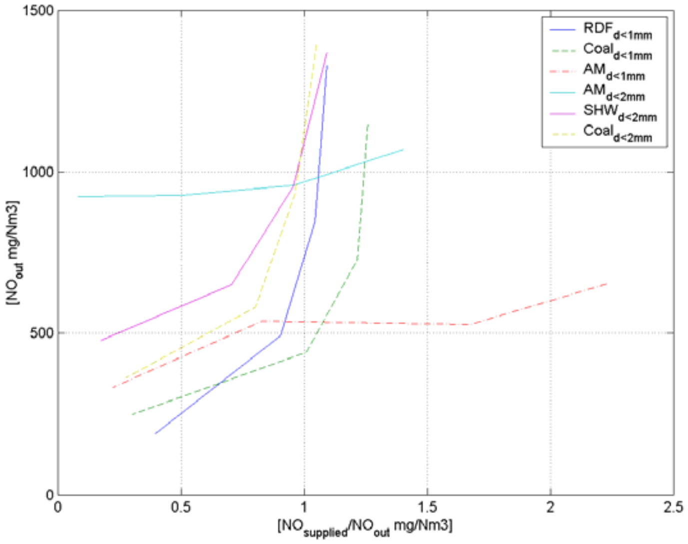

Figure 10: *$NO_{supplied}/NO_{out}$ ratio with respect to NO_{out} during experiments without circulating mass. Experiments with $RDF_{d<1mm}$, $Coal_{d<1mm}$, $AM_{d<1mm}$, $SHW_{d<2mm}$, $Coal_{d<2mm}$, $AM_{d<2mm}$.*

Two sets of particle sizes were tested to investigate the impact on combustion behaviour. The particles was ground down into two groups:

- $d_{p<1}$, and
- $d_{p<2}$ mm

The combustion without circulating mass experiments showed that:

- smaller particles gave larger NO reduction - almost the double at the governing conditions,
- heterogeneous reactions are possibly the main reason for the NO reduction with increasing $NO_{supplied}$ during combustion of coal, RDF and SHW. The increased N_2O emissions during coal combustion are probably due to the heterogeneous reactions. However, a combination with homogenous reactions are likely,
- homogenous reaction is possibly the main reason for the NO reduction with increasing $NO_{supplied}$ during combustion of animal meal. Hence the increased N_2O emissions for animal meal are probably due to the homogenous reaction. Animal meal is, as mentioned above, probably governed by the ammonia released during volatilization, but a combination with heterogeneous reduction reactions are likely,
- the different behavior of animal meal is due to the assumed release of ammonia during volatilization, and
- increased amount of $NO_{supplied}$ improves (lower) the ratio $NO_{out}/NO_{supplied}$.

The combustion without circulating mass showed, at conditions similar to a precalciner (1000 mg/Nm³ $NO_{supplied}$), the following order of optimal NO reducing fuels:

- $AM_{d<1}$ (up to 45 %),
- $coal_{d<1}$ (up to 18 %) and
- $RDF_{d<1}$ (up to 6 %).

Following, $AM_{d<2}$, $SHW_{d<2}$ and $coal_{d<2}$ break even ($NO_{out}/NO_{supplied}=1$) at similar conditions.

Flow calculations

Euler-Euler granular multiphase simulations are accomplished with FLUENT 4.0 in order to verify the assumption of dilute flow and the importance of particle-particle collisions in a precalciner. Euler-Langrangian simulations of the precalciner are performed as well with FLUENT 6.0. The particle-trajectory, retention time and species concentration are calculated successfully. The simulations reveal important information for further utilization of alternative fuel in the precalciner. A structured grid are generated in GAMBIT with the number of about 240,000 cells, see Figure 11. The model height is 42.8 meter with a width at the section of inlets, and diameter at the mid- and top region of 3.56×3.27, 3.74 and 2.61 meter, respectively.

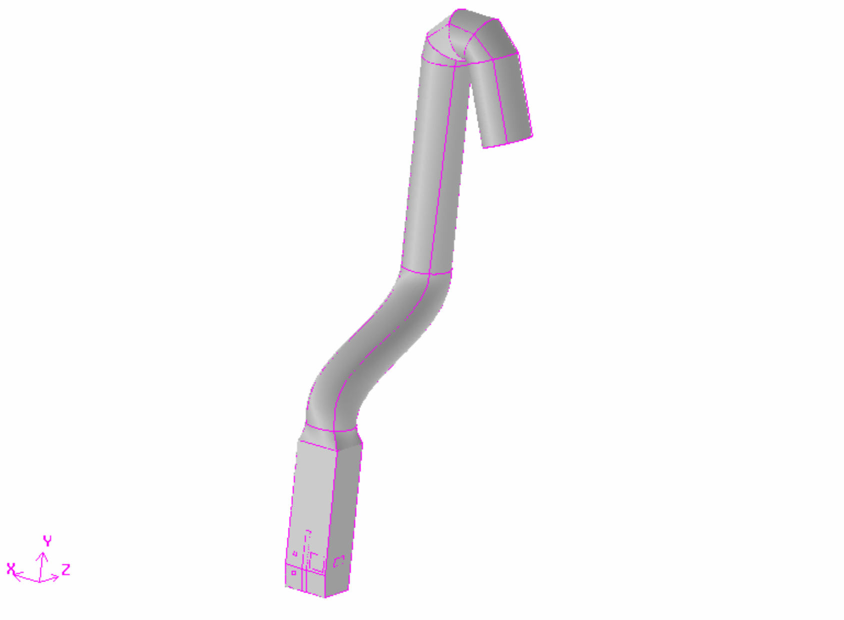

Figure 11: *The figure shows the precalciner model with its inlets and outlets. The alternative fuel and raw meal inlet on the tertiary gas side are located opposite of the corresponding inlets and is not shown in the figure.*

The Euler-Euler granular multiphase simulations showed that the particles:

- volume fraction is below $1 \cdot 10^{-3}$, which is in accordance to previous characteristics,
- rise in two plumes from the injection points until it disperse between the first and second bend and increase the particles volume fraction close to the wall,
- obstructs part of the tertiary- and kiln gas inlet, which increases the local gas velocity, before it disperse and become uniformly distributed in the upper parts and
- that the kinetic energy turbulence can be seen to follow the raw meal volume fraction. Hence, the particles seem to enhance turbulence.

The Euler-Langrangian simulations showed:

- delayed volatilization on the kiln gas side, which most likely can be due to the suppressing effect of raw meal in the up stream giving a lower heat transfer. Replacement of the raw meal inlet could improve the volatilization, since the raw meal inlet is at the similar level as the alternative fuel inlet, which is in contrary to the tertiary kiln gas side,
- low degree of mixing between the kiln- and the tertiary air gas side, which represents poor oxidizing conditions for the alternative fuel on the kiln gas with a delayed burn up, see Figure 12. However, it is necessary with a low degree of mixing to obtain a successful utilization of reburning and advanced reburning in the precalciner. A reduction (optimization) of the reburning zone will improve the delayed burnout,
- that the ratio of solids- to gas retention time τ_s/τ_g is about 2 in the precalciner and half the size compared to previous experiments in a FLS-ILC calciner /6/. A comparison between previous work on CFBC reactors and precalciners with these simulations, show that particle retention time has to be considered for the specific precalciner. The back mixing / core-annulus flow, is low in this precalciner due to the high gas velocity.

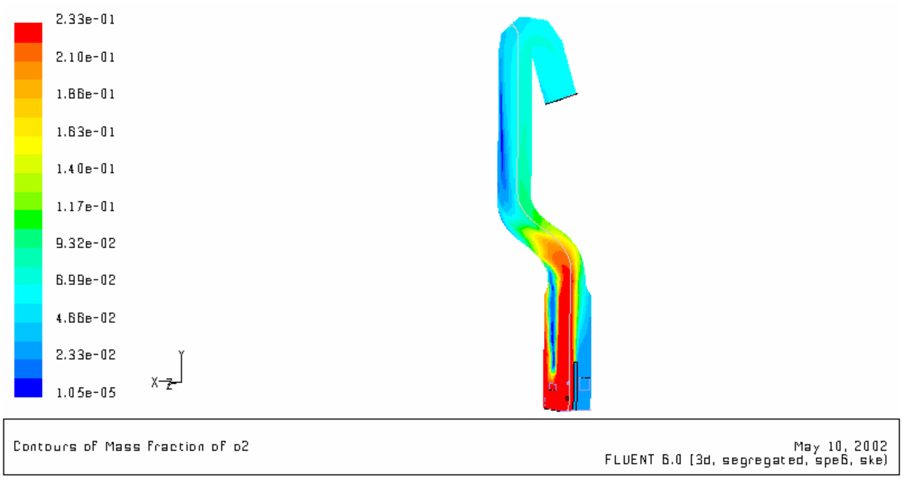

Figure 12: *Contours of mass fraction of O_2 during Euler-Langrangian simulations.*

Conclusion

It has been designed, constructed and executed experiments in a CFBC reactor accompanied with full scale experiments in the precalciner at kiln 6 in Brevik. Furthermore, it has been executed CFD simulations to verify the precalciner regime and to investigate the flow patterns influence on the burn up. Investigations on the following fuels, and blends of them, has been executed:

- Refuse derived fuel,
- Animal meal,
- Solid hazardous waste,
- Char coal, and
- Coal.

This work showed that:

- Laboratory experiments, in a similar regime as in a precalciner, demonstrate to be well suited for characterization of alternative fuels in a precalciner regime.
- Experiments with and without circulating mass in the laboratory CFBC reactor justify the importance of executing combustion experiments in similar environment to a precalciner.
- Advanced reburning and reburning are well suited for NO_x reduction in a precalciner during utilization of SHW and animal meal. RDF shows the best capacity to reduce NO_x during reburning and advanced reburning in laboratory experiments. However, previous full-scale experiments show larger NO_x reduction for animal meal compared to RDF.
- Animal meal is believed to follow the reduction route of SNCR or advanced reburning.
- Increasing amount of $NO_{supplied}$ at the reactor inlet improves the ratio of NO_{out} / $NO_{supplied}$ for all fuels during laboratory experiments with advanced reburning and combustion without circulating mass.
- Increasing ratio of urea/ $NO_{supplied}$ lower the NO_x emissions. A conclusive optimum is not possible to make without further investigations, but an assumption shows an optimum between 8 - 10 and 2.6 - 3.0 in the laboratory experiments and the full-scale experiments, respectively.
- Increased CO emissions during advanced reburning and reburning (with animal meal) is most likely to be due to the competition for the OH radical during oxidation of CO and reduction of NH_3. However, combustion of animal meal, in a lean environment without circulating mass, showed low CO emissions.
- Heterogeneous reactions reduce NO with increasing amount of $NO_{supplied}$. This was shown during combustion without circulating mass in a lean environment in the laboratory experiments. This finding emphasize that NO reduction is governed by several phenomenon.
- Smaller particles reduce CO and NO emissions.
- CFD simulations reveal important information about the flow regime and its importance to improve burn up.

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