SUOMEN SOODAKATTILAYHDISTYS
FINNISH RECOVERY BOILER COMMITTEE

Suomen Soodakattilayhdistys ry

CFD Modeling of Reduced Lignin Black Liquor Combustion

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Executive Summary and Conclusions – CFD Modeling of Reduced Lignin Black Liquor Combustion

Markus Engblom, Nikolai DeMartini

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Lignin removal by precipitation using CO_2 is a technology that is commercially available, and mills are starting to implement it. They are doing this either to obtain the lignin or as a means of reducing the load to the recovery boiler. Lignin removal will affect both the heating value of the black liquor and the amount of char carbon in the black liquor during combustion. The heating value was calculated to change from 13.2 MJ/kg d.s. for the original black liquor to 11.6 MJ/kg d.s. for the 20% reduced lignin case. Thus the HHRR was calculated to be 2.9, 2.6 and 2.3 MW/m^2 on a LHV basis for the base case, 10% reduced lignin and 20% reduced lignin cases respectively. The calculated adiabatic temperatures are 1240, 1170 and 1130 °C respectively. The amount of fixed carbon (combustible carbon in the char) was found to decrease in combustion experiments with three reduced lignin black liquors and the fraction of fixed carbon to the model was 14.3, 10.3 and 7.4% of the total dry solids for the base case, 10% reduced lignin and 20% reduced lignin cases respectively, while the volatile fraction (kg volatiles/kg d.s.) was assumed to remain the same. This is a key assumption because in addition to reducing the amount of organic material to the boiler, the fraction of that material that forms char is reduced, thus the amount of char to the walls and bed is reduced both because of the reduction in organics to the boiler and the reduction in the amount of char formed. From a practical perspective, the firing changes needed are more significant than if the removal of lignin only affected the total amount of organics to the boiler.

Thus, spraying conditions and/or air distribution will need to be adjusted to maintain the lower furnace temperature and to maintain carbon on the bed, which are needed for high reduction efficiency and low SO_2. Seven different cases were run for a CFD model of the WisaForest recovery boiler. The seven cases were:

- Case 1. Base case at 100% MCR, 3% excess O_2 (wet gases)
- Cases 2 & 3. 10% and 20% lower lignin with the same air distribution, but total air reduced to maintain 3% excess O_2 (wet gases). These runs provide information about carbon distribution in the boiler.
- Cases 4 & 5. 10% and 20% lower lignin with the same total air as cases 2 & 3, but with air redistributed to balance the carbon distribution.
- Cases 6 & 7. 10% and 20% lower lignin with the mean droplet size increased to increase the carbon to the lower furnace to balance the air in cases 2 & 3.

Without changing the air distribution or firing conditions (same droplet size distribution), the removal of lignin was calculated to result in a significant deficit in carbon delivery to the lower furnace. The calculated deficit was 13% and 37% (carbon that would be converted compared to carbon fed) for 10% and 20% lignin removal respectively (cases 2 & 3). To balance the carbon by changing the air distribution (less air to lower furnace, cases 4 & 5) or droplet size distribution (larger droplets, cases 6 & 7) alone required significant changes to these parameters, Table 1.

Table 1. Air distribution and average droplet size distribution for cases 1 and 4-7. In 4&5 the air distribution was adjusted and in 6-7 the air distribution was maintained, but the mean droplet size was adjusted.

Parameter	Case 1	Case 4	Case 5	Case 6	Case 7
Lignin reduction	0%	10%	20%	10%	20%
Primary Air	22	20	15	22	22
Secondary Air	43	40	30	43	43
Tertiary Air	35	40	55	35	35
Mean droplet size (mm)	5.7	5.7	5.7	12.5	23
Excess Temperature (°C)	18.4	18.4	18.4	13.7	6.5

Even for a 10% reduction in lignin, the calculations indicate that both air distribution and spraying conditions will need to be adjusted. To get more carbon to the lower furnace, spraying angle or nozzle will likely need to be changed, especially at lignin removal levels higher than 10%. It does not appear that adjusting black liquor firing temperature alone will be sufficient to maintain the carbon to the bed.

The calculation of additional cases would help clarify how to adjust firing conditions to maintain carbon to the lower furnace and thus maintain the lower furnace temperature. Specifically:

- Reduced lignin 10% and 20%, but with 100% MCR (runs so far have been 97% MCR and 94% MCR respectively)
- Spray tilt (10% and 20% reduced lignin)
- Combination of changes to spray (T or tilt) and air distribution
- Sensitivity analysis – Impact of distribution of carbon between volatiles and char & impact of swelling

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CFD Modeling of Reduced Lignin Black Liquor Combustion

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Åbo Akademi

SKY Lipeätyöryhmä meeting 21.1.2015

Objective and CFD runs 1-7

- CFD modeling for studying what operational changes may be needed when firing reduced lignin black liquor
- CFD modeling of Wisaforest recovery boiler
  - **Run 1:** Base Case, 100% MCR, flue gas O_2 3% (wet)
  - **Runs 2 and 3:** 10% and 20% lignin removed, total air adjusted for flue gas O_2 3% (wet), other variables unchanged
  - **Runs 4-7:** 10% & 20% lignin removed, modifications to air distribution (Runs 4&5) and liquor spraying (Runs 6&7)

Modeled Black Liquors (1/3)

	Original Black Liquor (wt% d.s.)	Lignin [1] (wt% d.s.)
C	32.2	64.5
H	3.3	6
N	0.09	0.1
Na	21.4	0.3
K	2.4	0.05
Cl	0.3	0
Tot. S	6.4	2.5
SO4	5.4	0
OH	1.74	0
HHV (MJ/kg d.s.)	13.2	26.5

Composition of reduced lignin BL based:

- Lignin content of BL: 36 wt-%
- 175 kg H_2SO_4/ton lignin precipitated [1]

1 Tomani, P. The lignoboost process. In Proceedings to The 2nd Nordic Wood Biorefinery Conf., 2-4 Sept. 2009, Helsinki, Finland, pp. 181-188.

Modeled Black Liquors (2/3)

	Original Black Liquor (wt% d.s.)	10% lower lignin (wt% d.s.)	20% lower ligning (wt% d.s.)
C	32.2	30.9	28.9
H	3.3	3.2	3.03
N	0.09	0.09	0.09
Na	21.4	22.8	23.9
K	2.4	2.6	2.7
Cl	0.3	0.32	0.34
Tot. S	6.4	7.0	7.5
SO_4	5.4	6.7	7.87
OH	1.74	1.4	1.1
HHV (MJ/kg d.s.)	13.2	12.4	11.6

Modeled Black Liquors (3/3)

	Original Black Liquor	10% lower lignin	20% lower lignin
Liquor d.s. (wt-%)	81.3	81.3	81.3
Volatiles (kg/kg d.s.)	0.337	0.337	0.337
Char-C (kg/kg d.s.)	0.143	0.103	0.074
Inorganics (kg/kg d.s.)	0.516	0.555	0.585
Na_2S (kg/kg d.s.)	0.115	0.120	0.121
Na_2SO_4 (kg/kg d.s.)	0.080	0.101	0.118
Na_2CO_3 (kg/kg d.s.)	0.320	0.335	0.345
HHV (MJ/kg d.s.)	13.2	12.4	11.6
LHV (MJ/kg liquor)	8.4	7.8	7.2

Liquor feed and combustion air (Runs 1-3)

	Original Black Liquor	10% lower lignin	20% lower ligning
Liquor feed (tds/d)	5320	5160	5000
Of MCR (%)	100	97	94
Air (kg/s)	272	256	232
Air (Nm3/s)	211	199	180
Primary	22%	22%	22%
Secondary	43%	43%	43%
Tertiary	35%	35%	35%
Target flue gas O_2 (% wet)	3.0	3.0	3.0
HHRR (MW/m^2) based on (HHV / LHV)	3.6 / 2.9	3.3 / 2.6	3.0 / 2.3
$T_{adiabatic}$	1240 °C	1150 °C	1100 °C

CFD calculation strategy

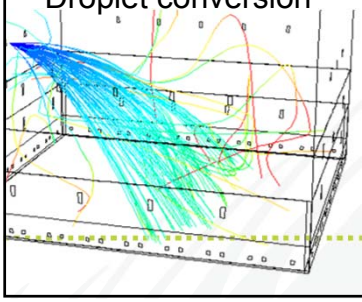
- Set up Base Case
  - Liquor and air mass flows
  - Droplet size for C-balanced situation
- Reduced lignin cases
  - liquor to 10% or 20% reduced lignin
  - total air for target 3% O_2 (wet flue gas)
  - Other variables remain the same

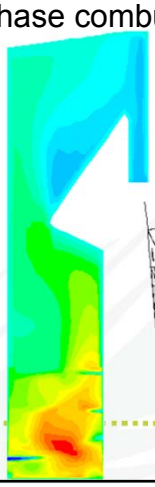
ÅA CFD Recovery Furnace Model

- **Fluent based**
- **ÅA sub-models for droplets and char bed**

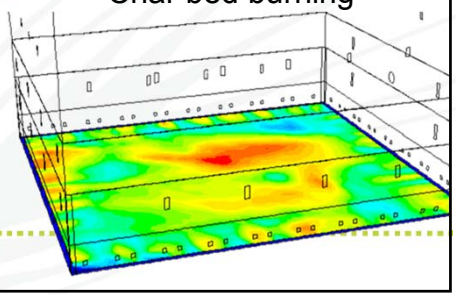
Gas phase combustion

Droplet conversion



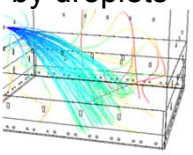


Char bed burning

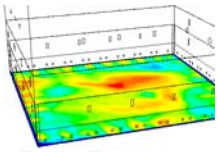


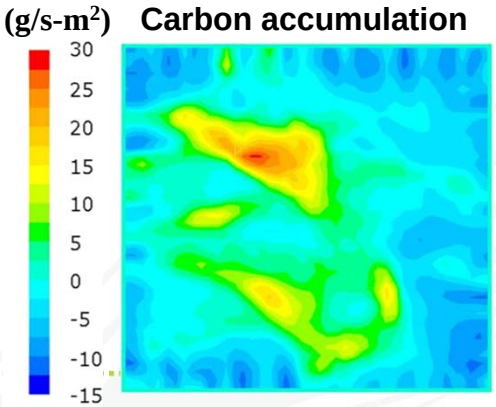
Char bed burning model

Carbon input by droplets

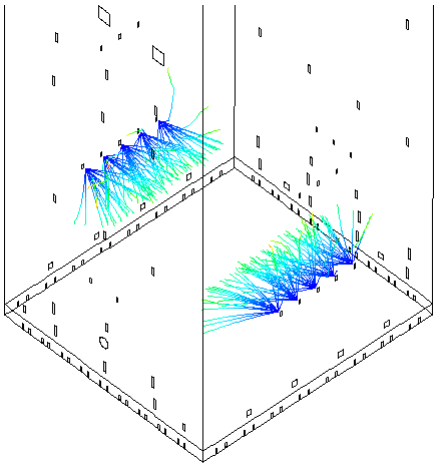


Char carbon conversion





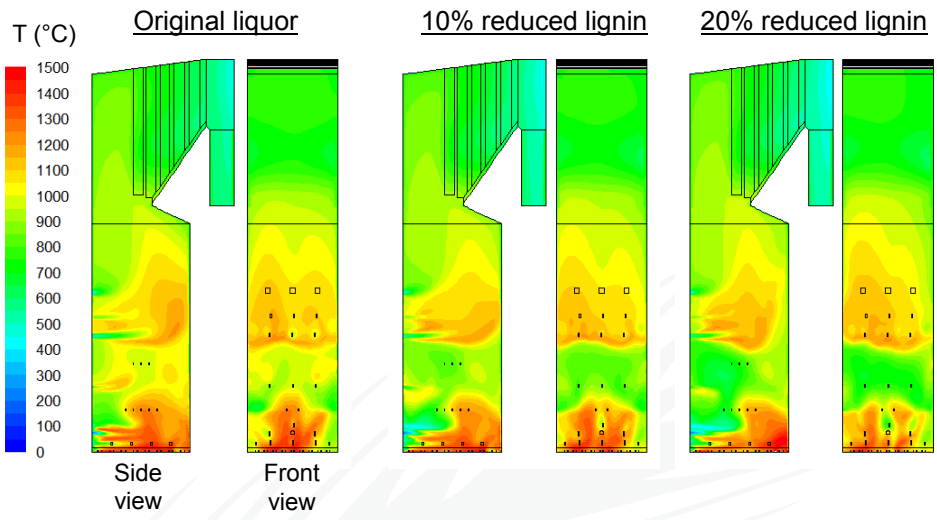
Wisa liquor gun locations



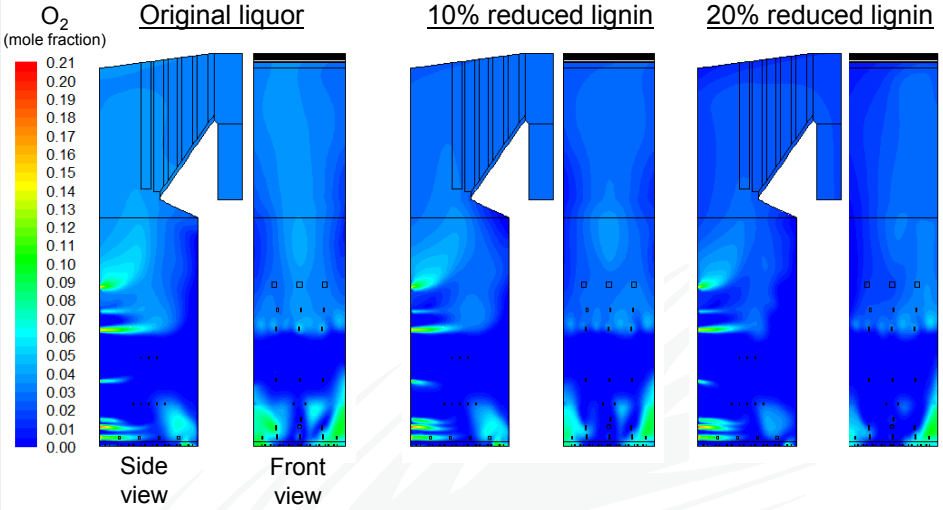
Guns on left and right wall; 5 guns/wall

CFD results

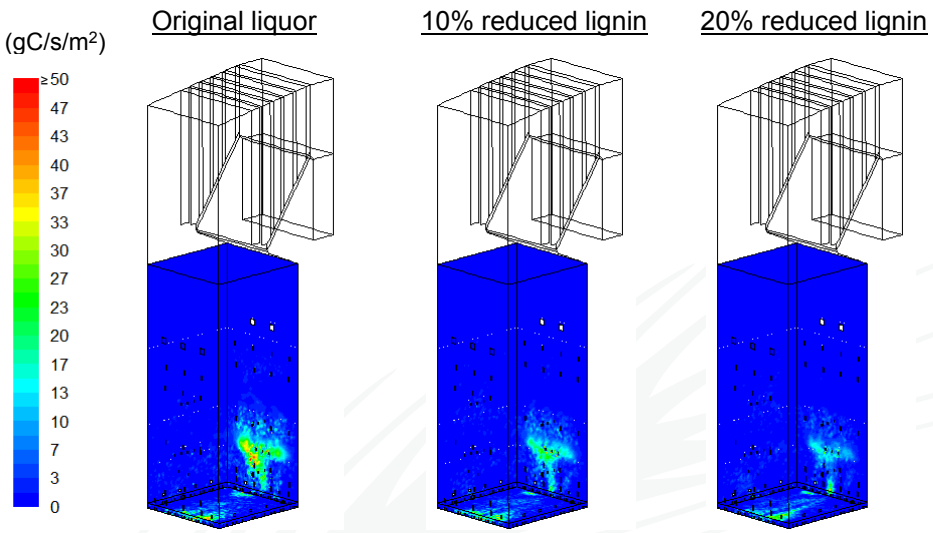
Temperature



O_2 concentration

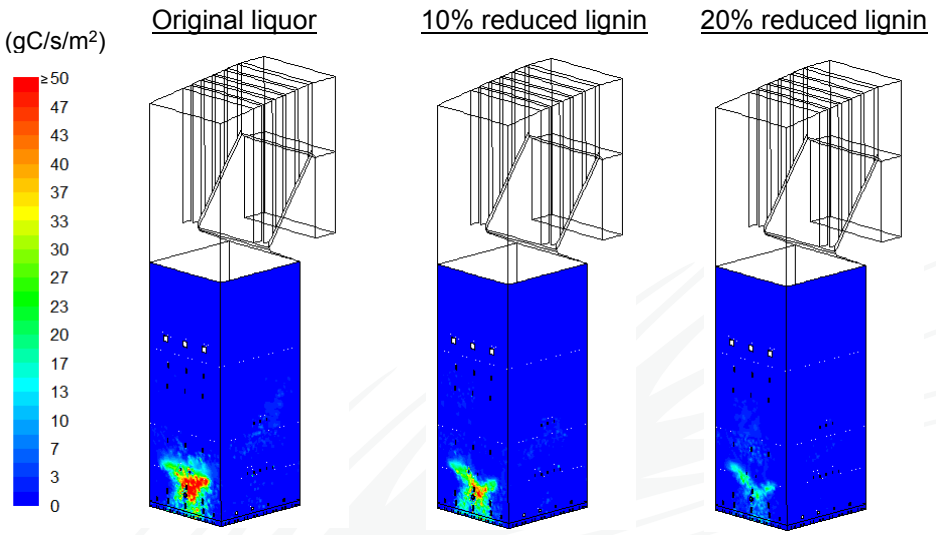


Carbon to walls/bed



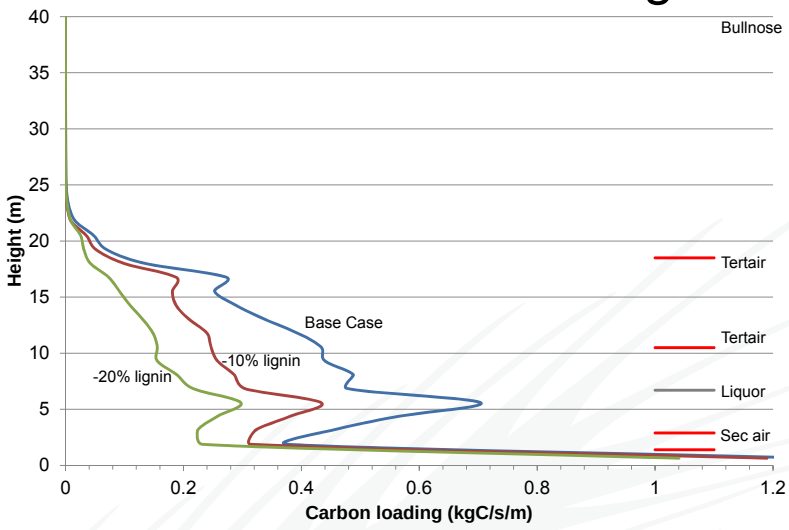
Left wall, back wall, and char bed

Carbon to walls/bed

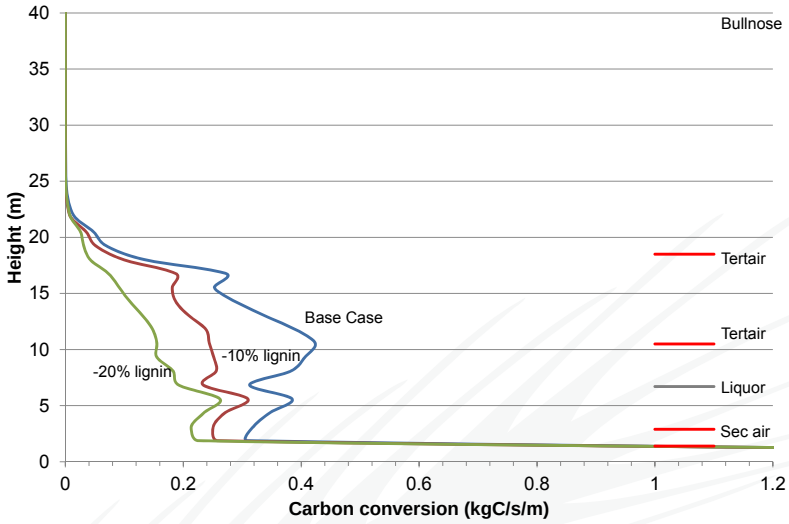


Right wall and front wall

Furnace carbon loading



Furnace carbon conversion



Fate of char carbon

(kg/s)	Base Case	10% reduced lignin	20% reduced lignin
In liquor feed	8.81	6.19	4.30
in-flight conversion	3.90	2.60	1.79
to bed/walls	4.91	3.59	2.51
conversion on bed/walls	4.70	4.37	4.10
carbon accumulation	0.21	-0.78	-1.59

Fate of char carbon

(%)	Base Case	10% reduced lignin	20% reduced lignin
In liquor feed	100.0	100.0	100.0
in-flight conversion	44.3	42.0	41.6
to bed/walls	55.7	58.0	58.4
conversion on bed/walls	53.4	70.5	95.5
carbon accumulation	2.3	-12.5	-37.1

Carbon accumulation and comb. air

	Base Case	10% reduced lignin	20% reduced lignin
carbon accumulation (kg/s)	0.21	-0.78	-1.59
Air to balance carbon accumulation (kg/s)	2.4	-8.9	-18.2

Conclusions - Runs 1-3

- Less char-C with lignin removal
- Lower furnace less loaded with char-C
- Dynamic situation of more carbon conversion than delivery
- Operational changes
  - Reduce prim/sec air (runs 4 & 5) and/or
  - Change spraying – larger droplets (runs 6 & 7)

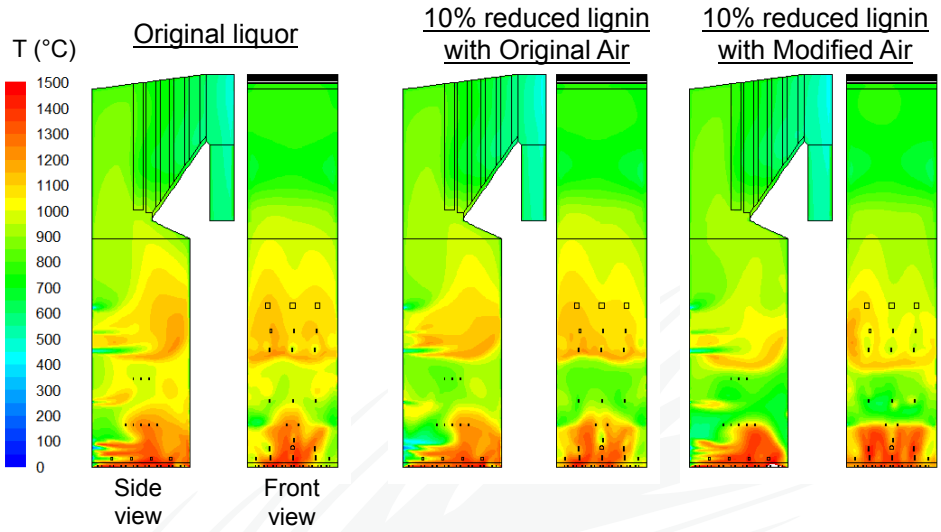
Runs 4 and 5 – Reduced air

- Primary and secondary air reduced to reflect the reduced char carbon load to the lower furnace
- CFD calculation objective:
  - Reduce carbon oxidation in lower furnace until carbon balance ≈ 0
  - By reducing prim/sec air
- Run 4: 10% lignin removed
- Run 5: 20% lignin removed

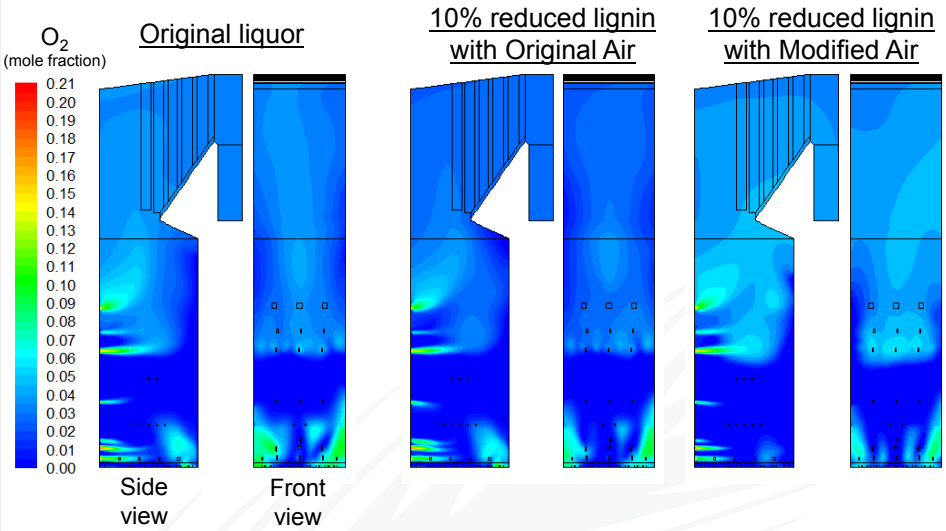
Air Distribution – Runs 4 and 5

	Run 2	Run 4		Run3	Run 5
Lignin Removed	10%	10%		20%	20%
	Original Air	Modified Air		Original Air	Modified Air
Total Air (kg/s)	256	256		232	232
Primary (kg/s)	56	44		51	35
Secondary (kg/s)	110	97		100	58
Tertiary (kg/s)	90	115		81	139
Primary (%)	22	17		22	15
Secondary (%)	43	38		43	25
Tertiary (%)	35	45		35	60

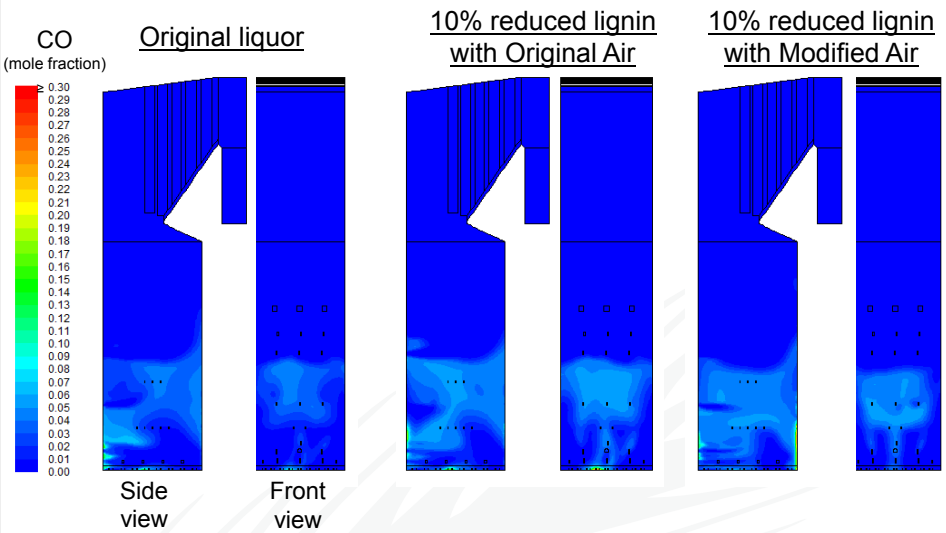
Temperature (-10% lignin)



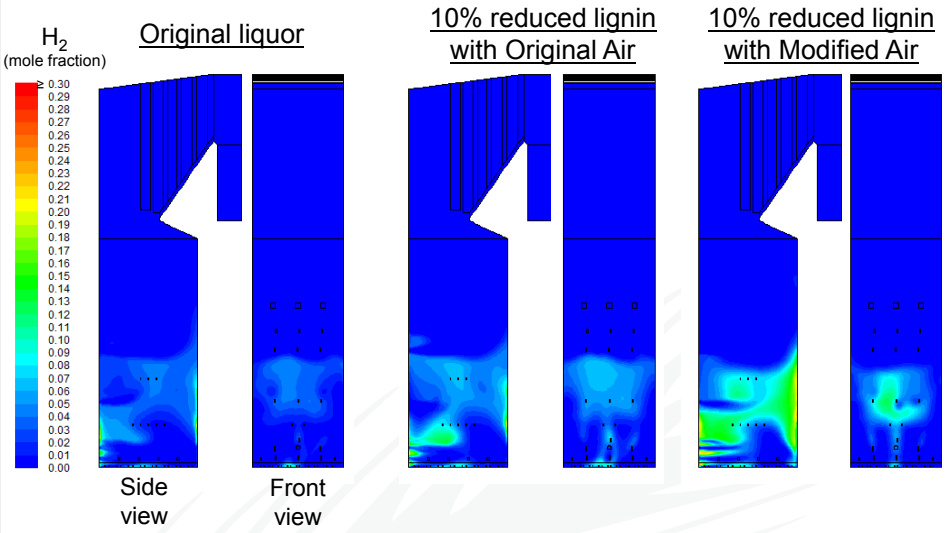
O_2 concentration (-10% lignin)



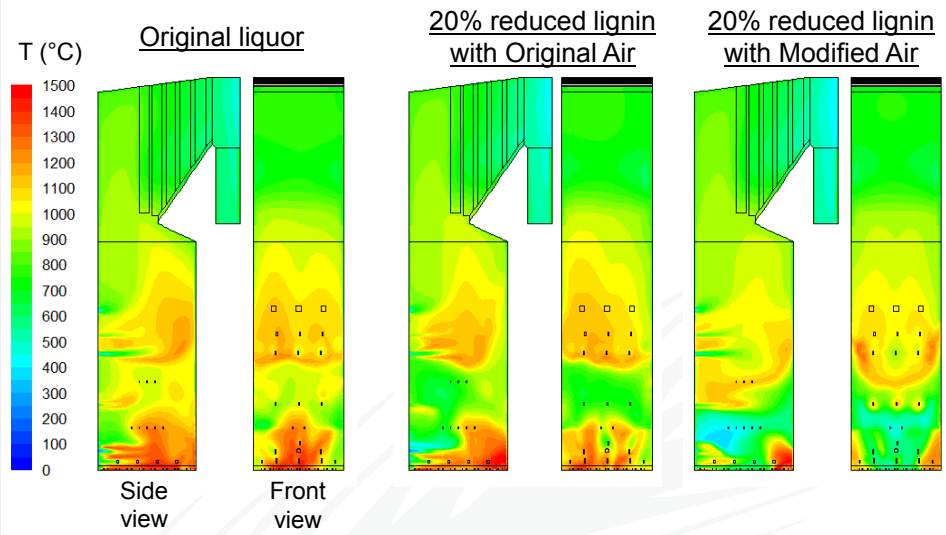
CO concentration (-10% lignin)



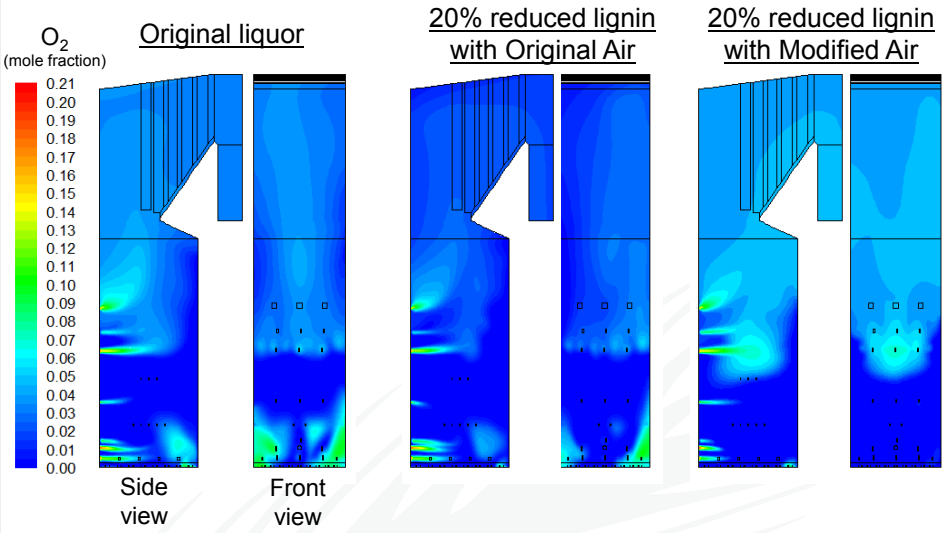
H_2 concentration (-10% lignin)



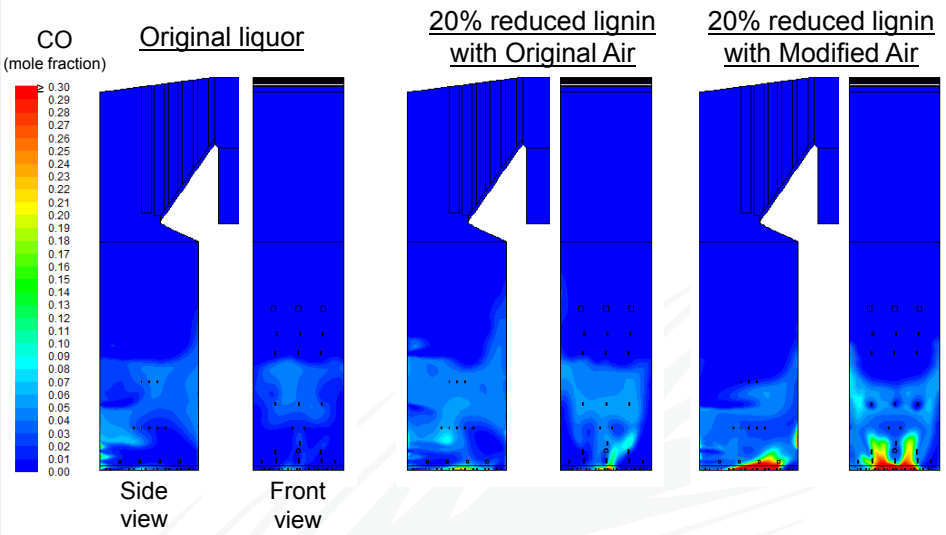
Temperature (-20% lignin)



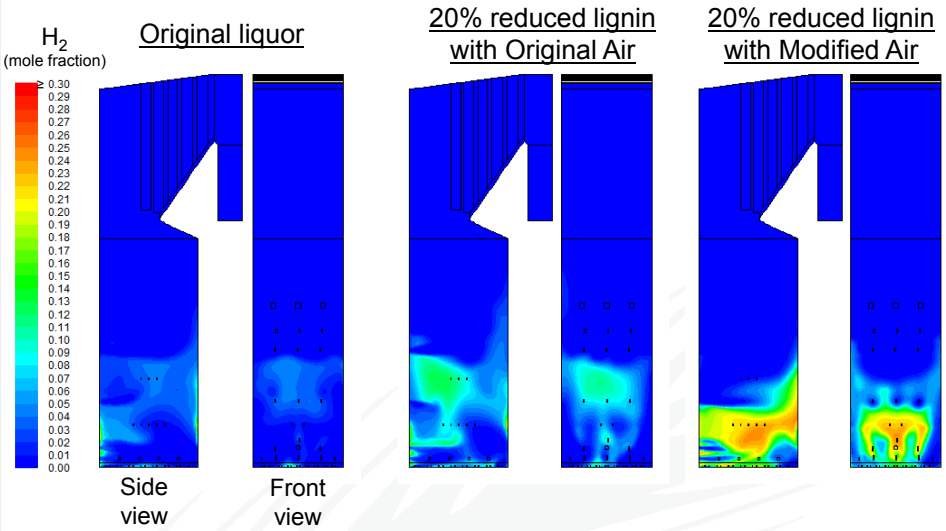
O_2 concentration (-20% lignin)



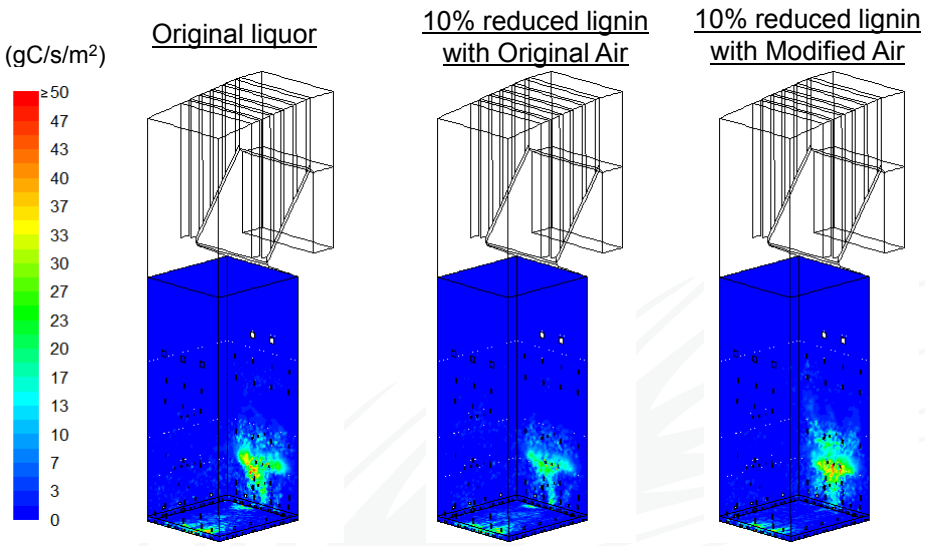
CO concentration (-20% lignin)



H_2 concentration (-20% lignin)

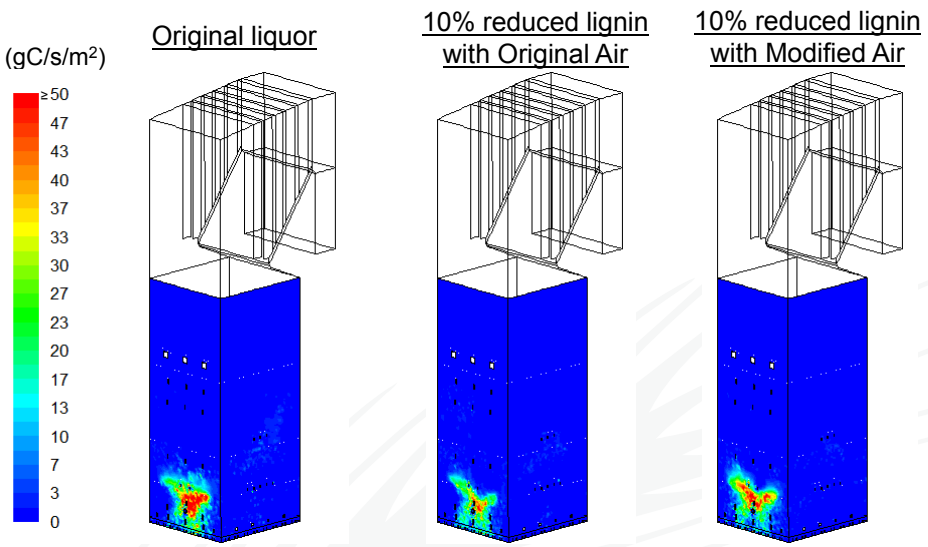


Carbon to walls/bed (-10% lignin)



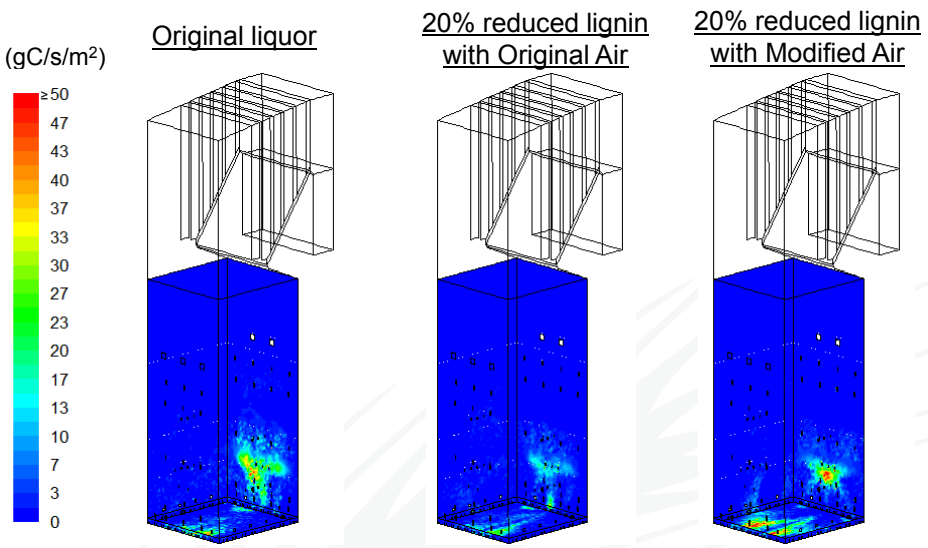
Left wall, back wall, and char bed

Carbon to walls/bed (-10% lignin)



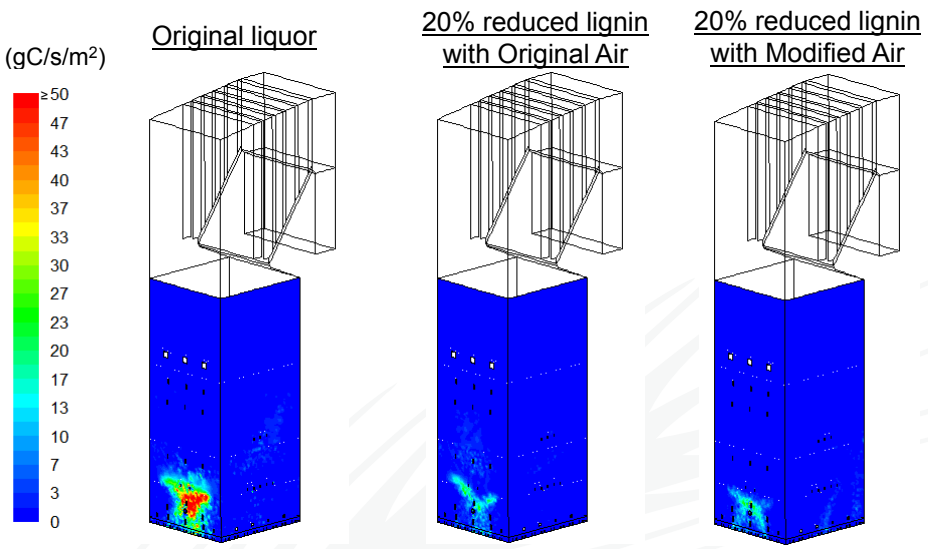
Right wall and front wall

Carbon to walls/bed (-20% lignin)



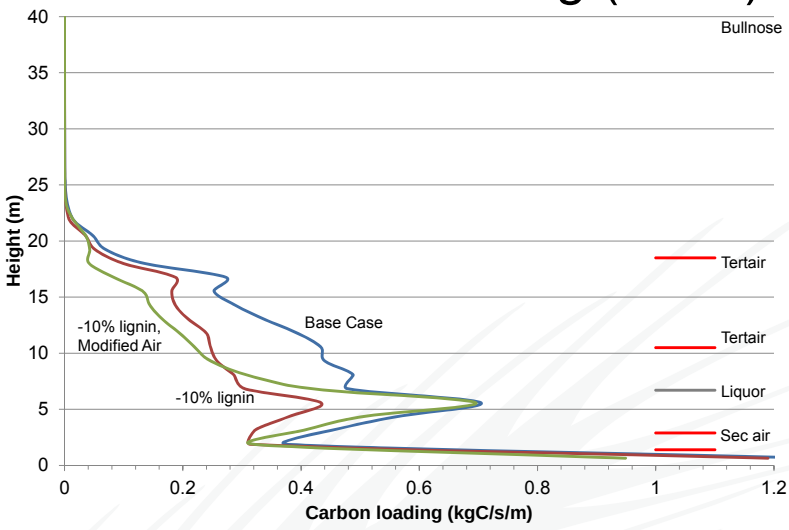
Left wall, back wall, and char bed

Carbon to walls/bed (-20% lignin)

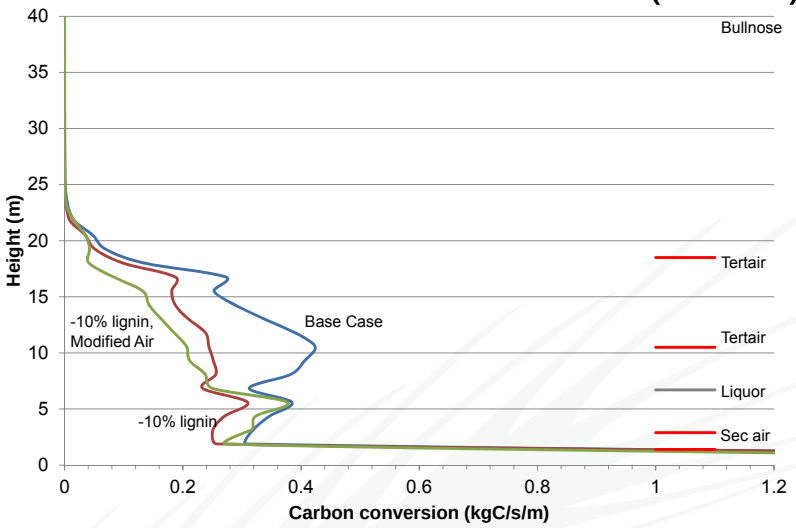


Right wall and front wall

Furnace carbon loading (-10%)



Furnace carbon conversion (-10%)



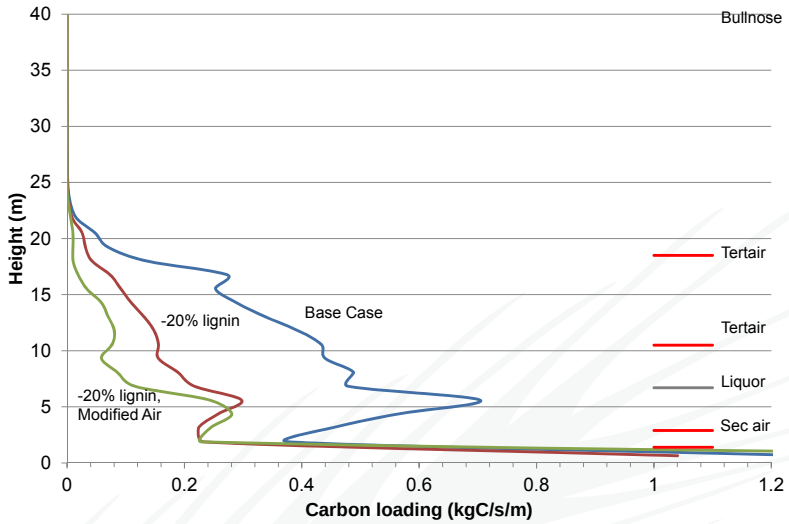
Fate of char carbon (-10%)

(kg/s)	Base Case	10% reduced lignin, Original Air	10% reduced lignin, Modified Air
In liquor feed	8.81	6.19	6.19
in-flight conversion	3.90	2.60	1.79
to bed/walls	4.91	3.59	4.40
conversion on bed/walls	4.70	4.37	4.38
carbon accumulation	0.21	-0.78	0.01

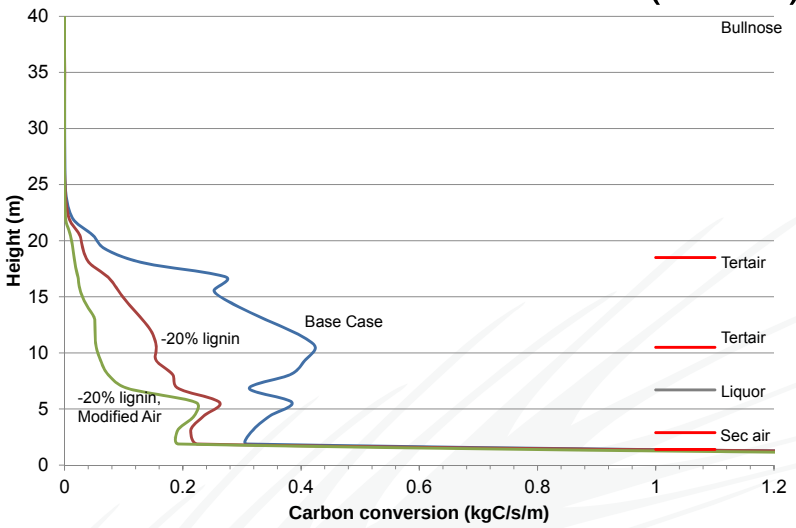
Fate of char carbon (-10%)

(%)	Base Case	10% reduced lignin, Original Air	10% reduced lignin, Modified Air
In liquor feed	100.0	100.0	100.0
in-flight conversion	44.3	42.0	28.9
to bed/walls	55.7	58.0	71.1
conversion on bed/walls	53.4	70.5	70.9
carbon accumulation	2.3	-12.5	0.2

Furnace carbon loading (-20%)



Furnace carbon conversion (-20%)



Fate of char carbon (-20%)

(kg/s)	Base Case	20% reduced lignin, Original Air	20% reduced lignin, Modified Air
In liquor feed	8.81	4.30	4.30
in-flight conversion	3.90	1.79	0.67
to bed/walls	4.91	2.51	3.63
conversion on bed/walls	4.70	4.10	3.68
carbon accumulation	0.21	-1.59	-0.05

Fate of char carbon (-20%)

(%)	Base Case	20% reduced lignin, Original Air	20% reduced lignin, Modified Air
In liquor feed	100.0	100.0	100.0
in-flight conversion	44.3	41.6	15.5
to bed/walls	55.7	58.4	84.5
conversion on bed/walls	53.4	95.5	85.7
carbon accumulation	2.3	-37.1	-1.2

Conclusions - Runs 4 and 5

- Considerable changes to lower furnace air needed to reach carbon balanced situation
  - Base Case: 22% prim / 43% sec / 35% tert
  - Run 4: 17% prim / 38% sec / 45% tert
  - Run 5: 15% prim / 25% sec / 60% tert
- Uncertain if modeled air splits could be used in reality
- Results suggest air distribution adjustment unlikely alone to be sufficient (if even possible) operational change

Conclusions - Runs 1-3

- Less char-C with lignin removal
- Lower furnace less loaded with char-C
- Dynamic situation of more carbon conversion than delivery
- Operational changes
  - Reduce prim/sec air (runs 4 & 5) and/or
  - Change spraying – larger droplets (runs 6 & 7)

Runs 6 & 7 – Larger Droplets

- Larger droplets will result in more carbon reaching the lower furnace. The droplet size distribution has been proposed to provide a carbon balance based on the original primary, secondary and tertiary air distribution
- In practice this larger particle size distribution would be achieved by reducing the firing temperature or changing the spray angle or nozzle

CFD runs 6 and 7

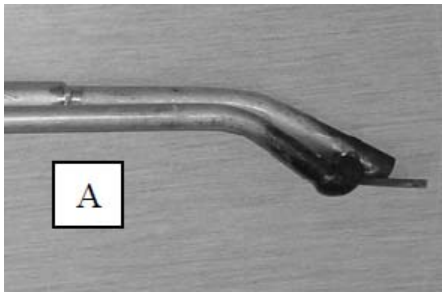
- Objective:
  - Increase char-carbon delivery to lower furnace until carbon balance ≈ 0
  - by increasing droplet size in liquor spray (lower liquor T)
- Run 6: 10% lignin removed
- Run 7: 20% lignin removed

CFD runs 6 and 7

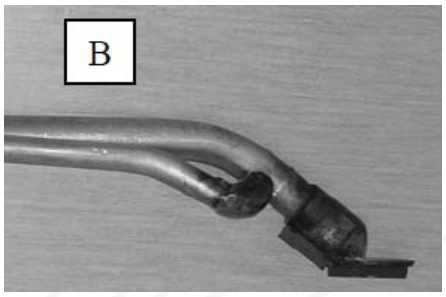
- Droplet size, liquor temperature, droplet velocity, etc – freely adjustable, independent parameters in CFD model
- For Runs 6 and 7, need to link droplet size, droplet velocity, and liquor temperature to each other in CFD model
- How are droplet size and droplet velocity connected to liquor temperature?

Spray characterization (Miikkulainen et al.)

Nozzle A



Nozzle B



	Nozzle A	Nozzle B
Nozzle pipe diameter	27 mm	28 mm
Splash plate angle	23°	36°
Nozzle exit area reduced by plate?	Partly reduced	Not reduced

Miikkulainen, P., Kankkunen, A. & Järvinen, M. 2002, "The Effect of Excess Temperature and Flashing on Black Liquor Spray Properties", *IFRF Finnish - Swedish Flame Days 2002, Vaasa, Finland, 24-25 September*

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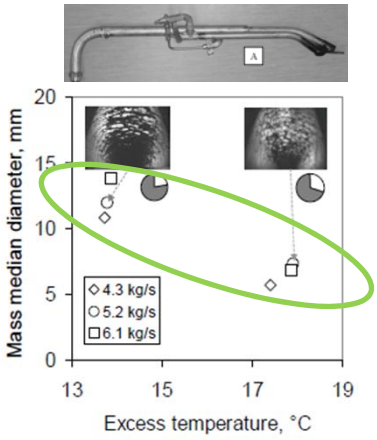
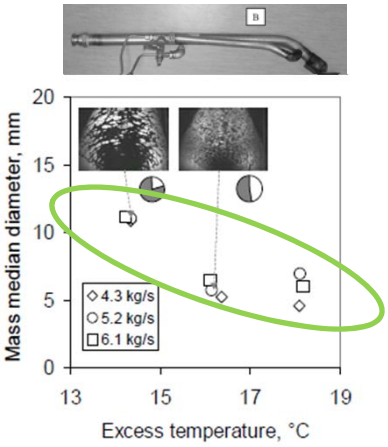
Liquor T - droplet size – dependence

Nozzle A



Nozzle B



Miikkulainen, P., Kankkunen, A. & Järvinen, M. 2002, "The Effect of Excess Temperature and Flashing on Black Liquor Spray Properties", *IFRF Finnish - Swedish Flame Days 2002, Vaasa, Finland, 24-25 September*

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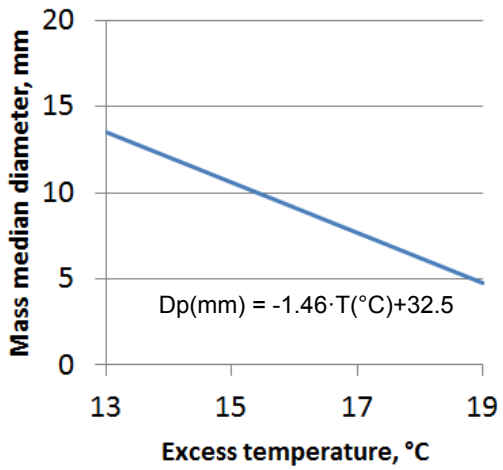
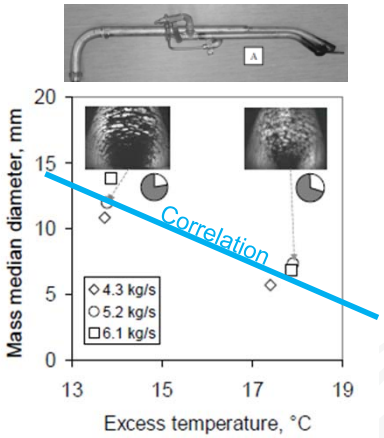
Liquor T - droplet size – dependence

Generic correlation for CFD

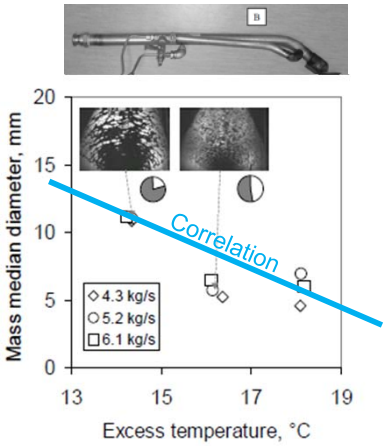


Liquor T - droplet size – dependence

Nozzle A



Nozzle B



Miikkulainen, P., Kankkunen, A. & Järvinen, M. 2002, "The Effect of Excess Temperature and Flashing on Black Liquor Spray Properties", *IFRF Finnish - Swedish Flame Days 2002, Vaasa, Finland, 24-25 September*

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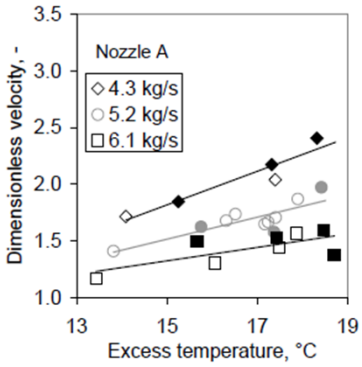
Liquor T - droplet velocity – dependence

Nozzle A



Dimensionless velocity, v(-)

$$v(-) = \frac{\text{Actual Liquor Velocity}}{\text{Liquor Velocity assuming no flashing}}$$

Miikkulainen, P., Kankkunen, A. & Järvinen, M. 2002, "The Effect of Excess Temperature and Flashing on Black Liquor Spray Properties", *IFRF Finnish - Swedish Flame Days 2002, Vaasa, Finland, 24-25 September*

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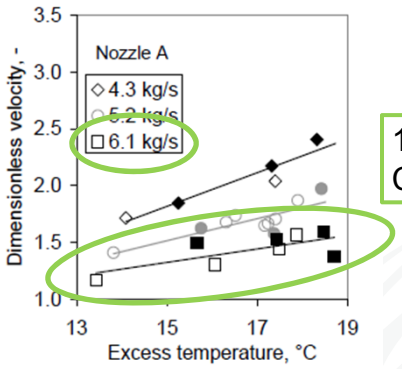
Liquor T - droplet velocity – dependence

Nozzle A



10% and 20% reduced lignin Cases, liquor mass flow ~7 kg/s

Miikkulainen, P., Kankkunen, A. & Järvinen, M. 2002, "The Effect of Excess Temperature and Flashing on Black Liquor Spray Properties", *IFRF Finnish - Swedish Flame Days 2002, Vaasa, Finland, 24-25 September*

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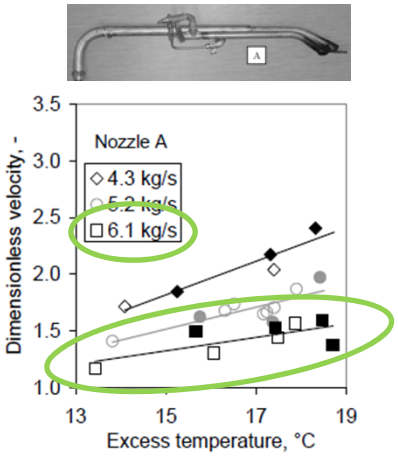
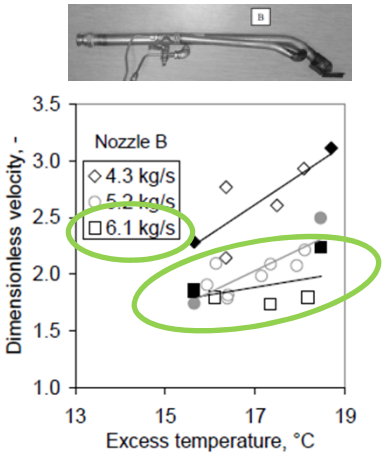
Liquor T - droplet velocity – dependence

Nozzle A



Nozzle B



10% and 20% reduced ligning
Cases, liquor mass flow ~7 kg/s

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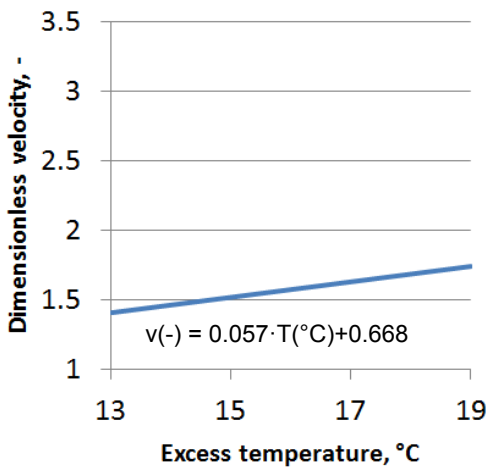
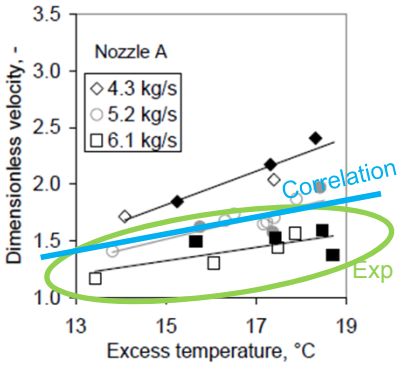
Liquor T - droplet velocity – dependence

Generic correlation for CFD

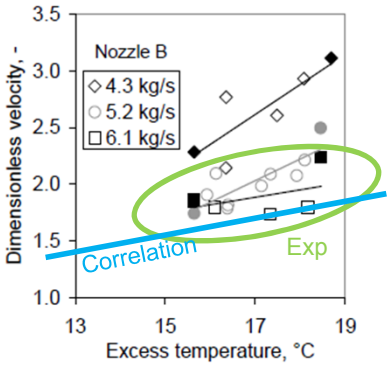


Liquor T - droplet velocity – dependence

Nozzle A



Nozzle B



Miikkulainen, P., Kankkunen, A. & Järvinen, M. 2002, "The Effect of Excess Temperature and Flashing on Black Liquor Spray Properties", *IFRF Finnish - Swedish Flame Days 2002, Vaasa, Finland, 24-25 September*

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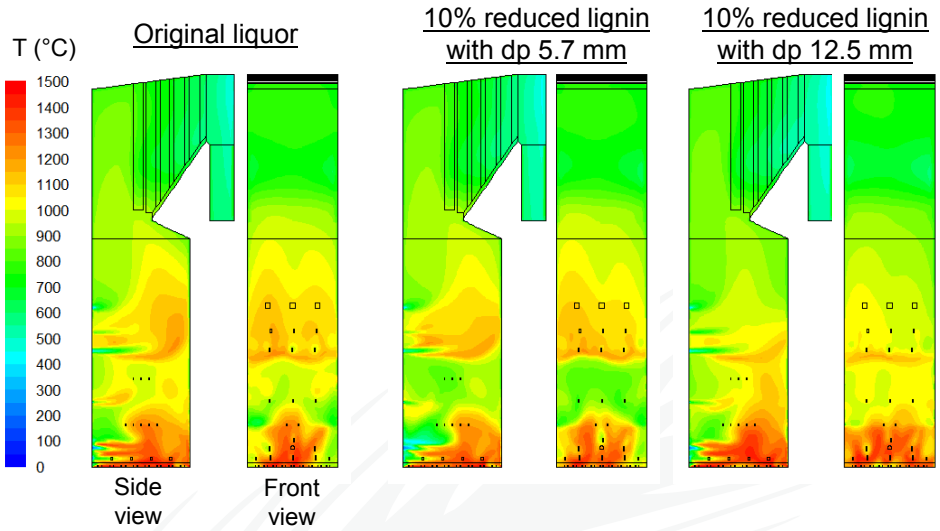
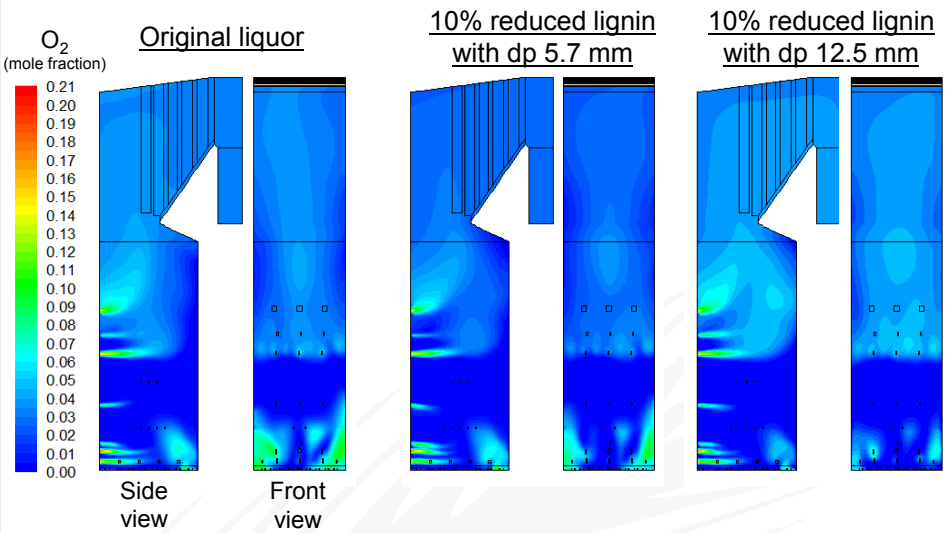
CFD runs 6 and 7 vs. Base Case

	Base Case	10% reduced lignin (Run 6)	20% reduced lignin (Run 7)
Average droplet size	5.7 mm	12.5 mm	23.0 mm
Initial droplet velocity	15.0 m/s	12.7 m/s	9.2 m/s
Excess temperature	18.4 °C	13.7 °C	6.5 °C
Liquor T changed from Base Case		-4.7 °C	-11.9 °C

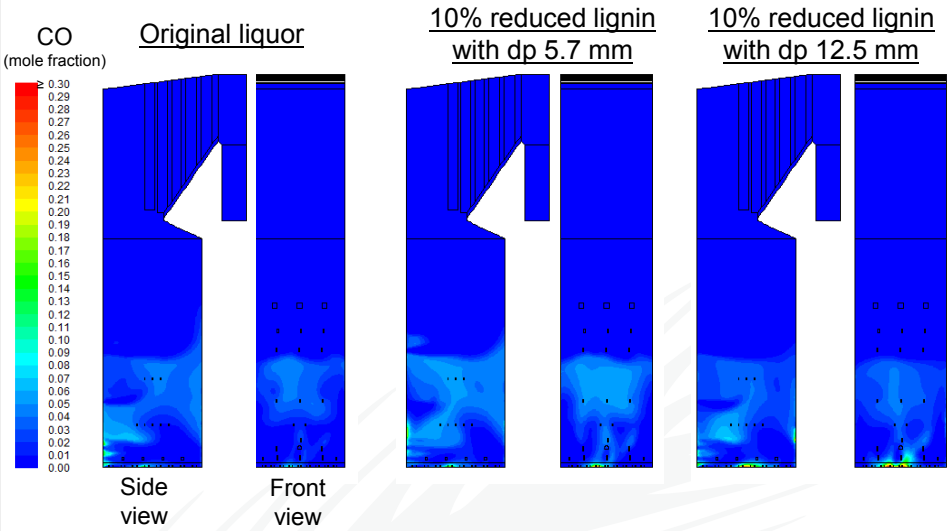
Temperature (-10% lignin)



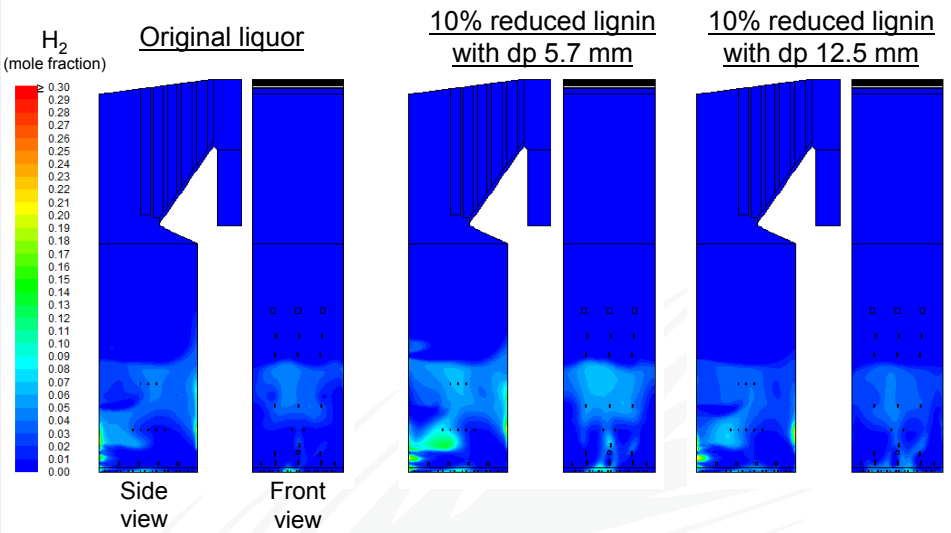
O_2 concentration (-10% lignin)



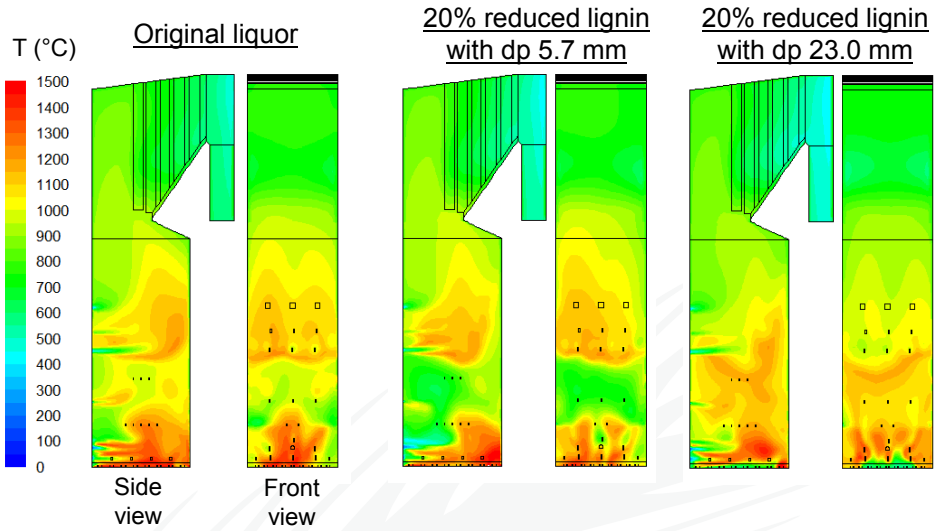
CO concentration (-10% lignin)



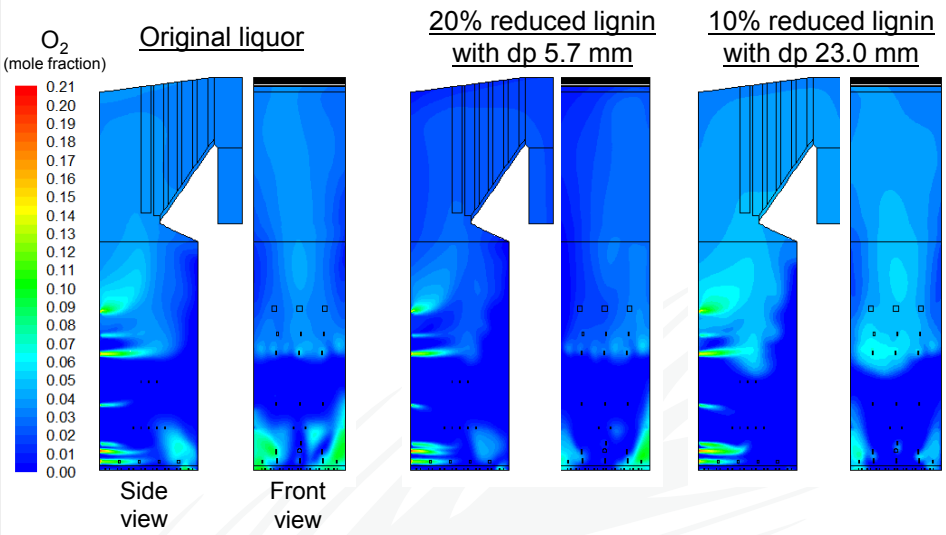
H_2 concentration (-10% lignin)



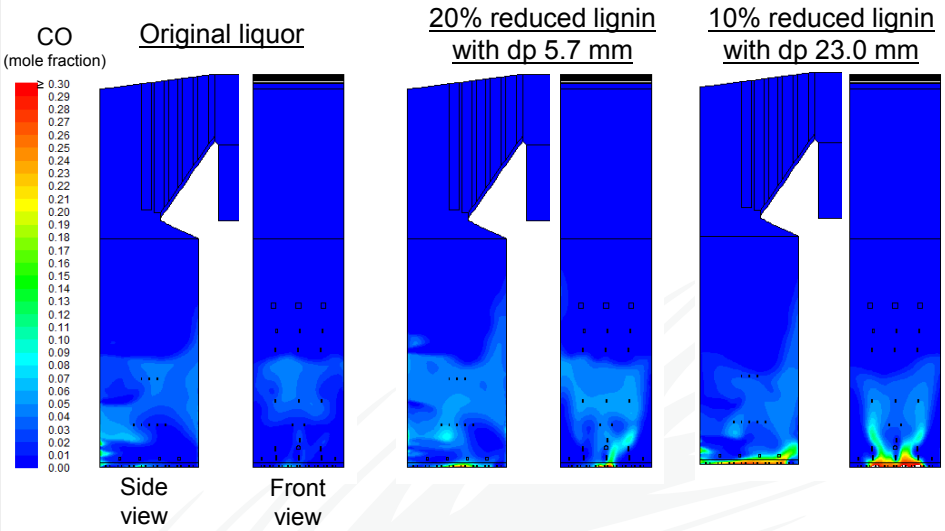
Temperature (-20% lignin)



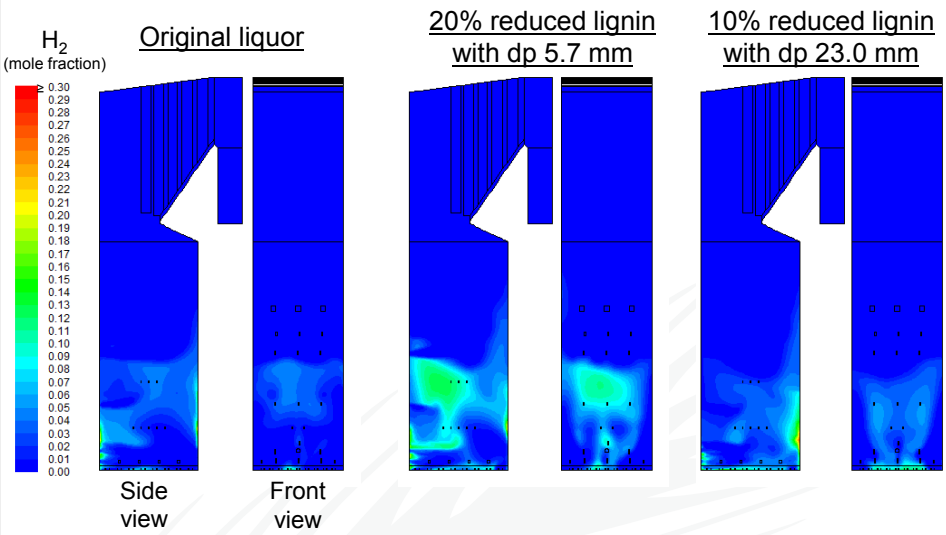
O_2 concentration (-20% lignin)



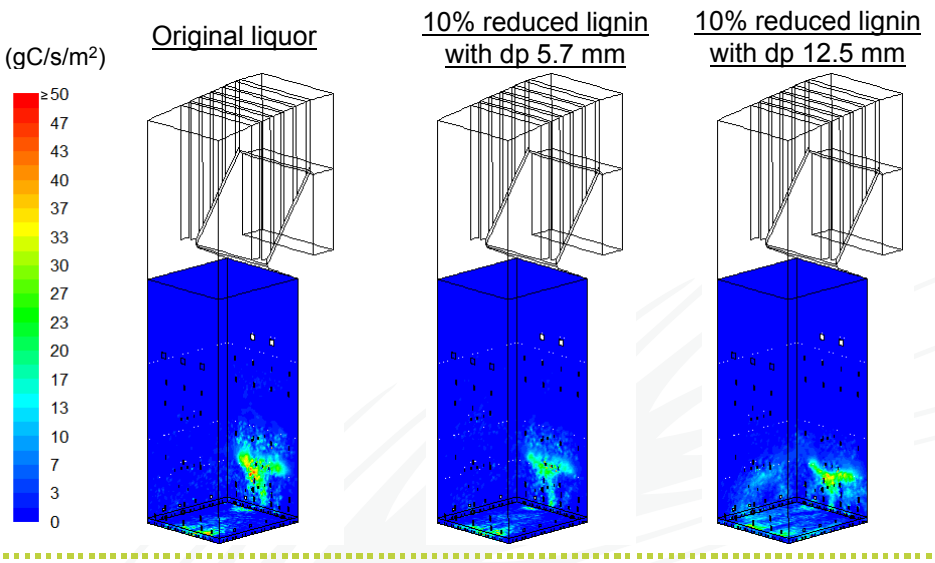
CO concentration (-20% lignin)



H_2 concentration (-20% lignin)

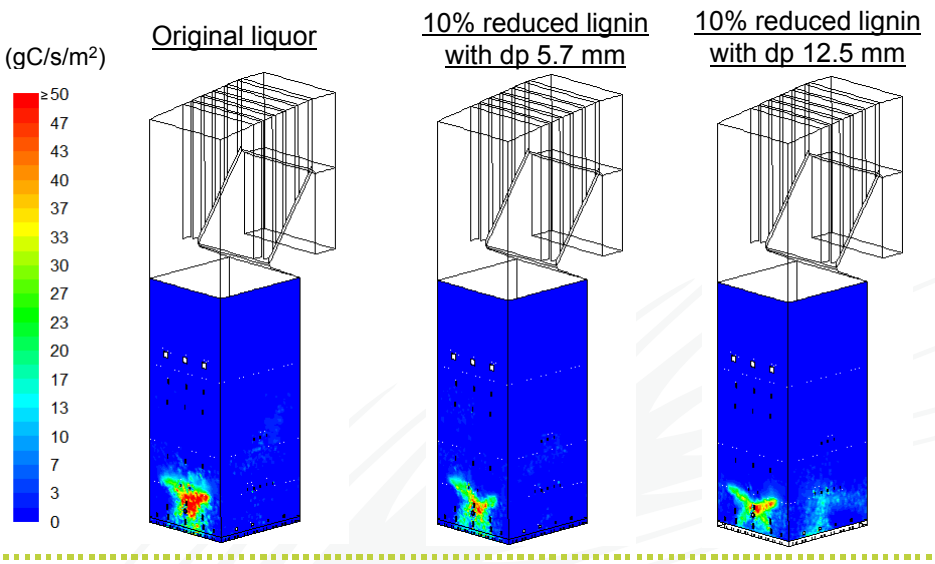


Carbon to walls/bed (-10% lignin)



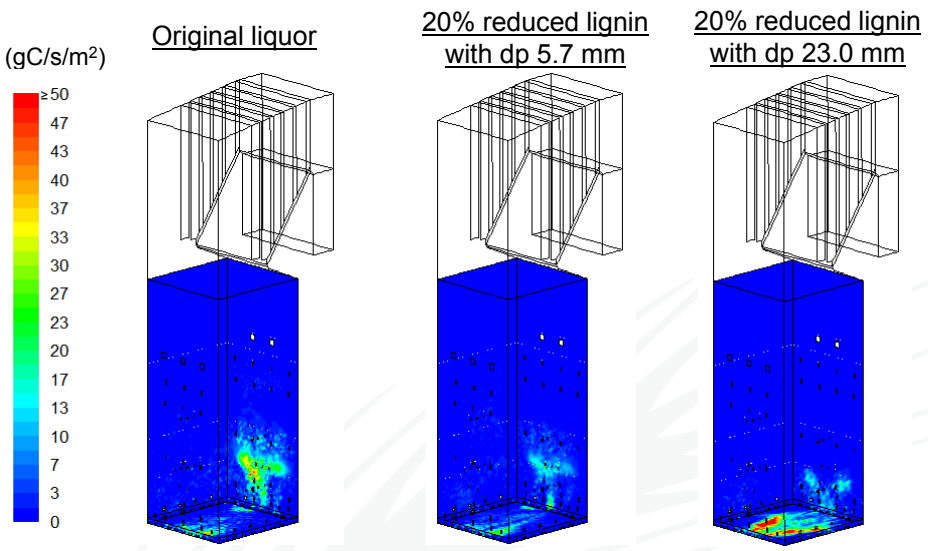
Left wall, back wall, and char bed

Carbon to walls/bed (-10% lignin)



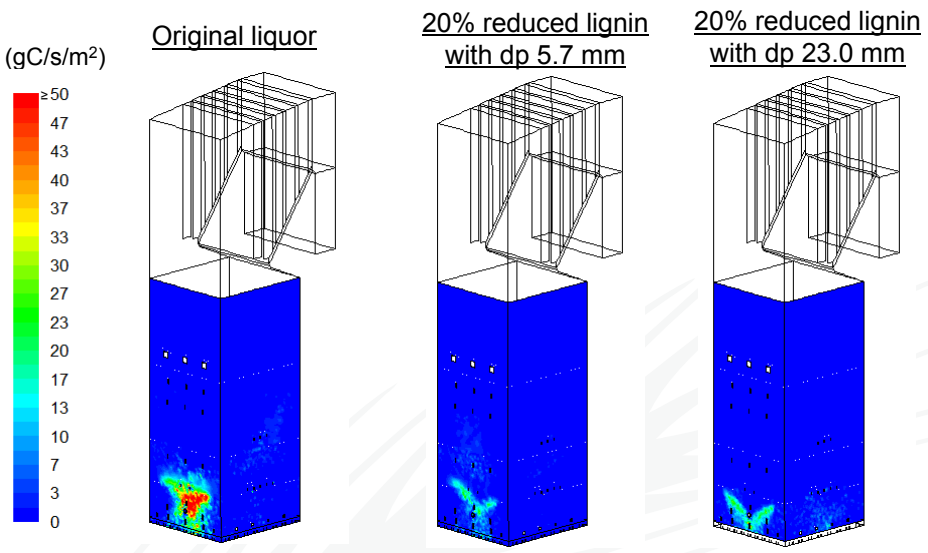
Right wall and front wall

Carbon to walls/bed (-20% lignin)



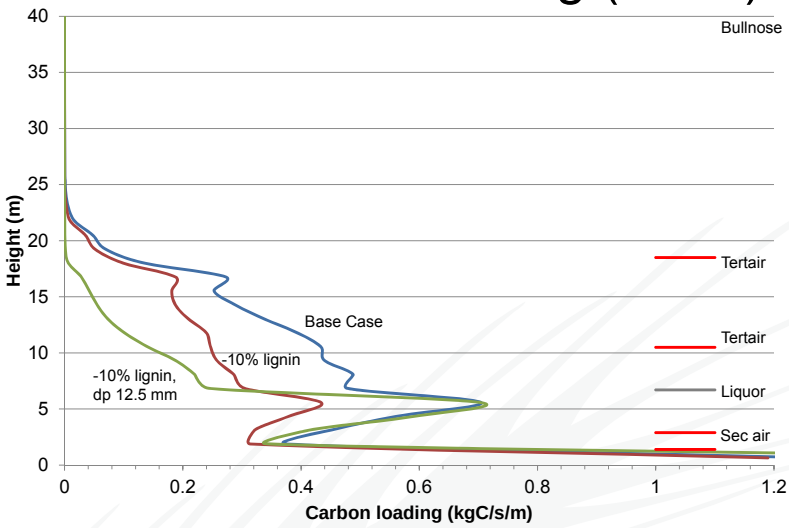
Left wall, back wall, and char bed

Carbon to walls/bed (-20% lignin)

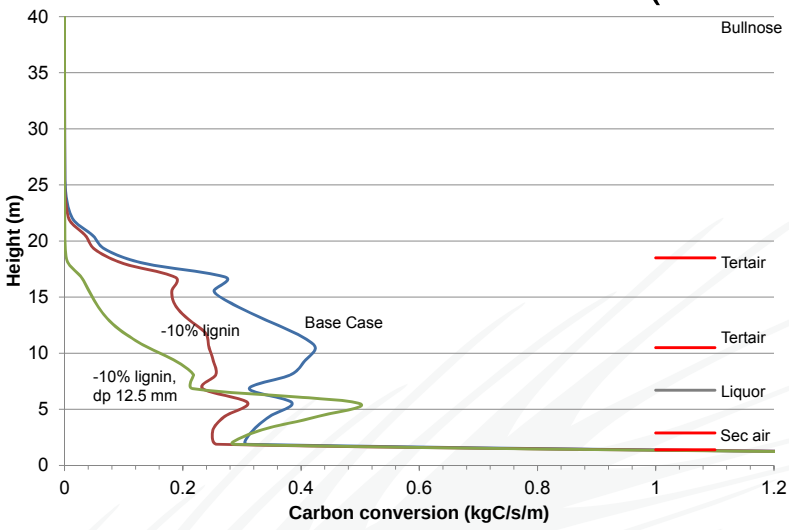


Right wall and front wall

Furnace carbon loading (-10%)



Furnace carbon conversion (-10%)



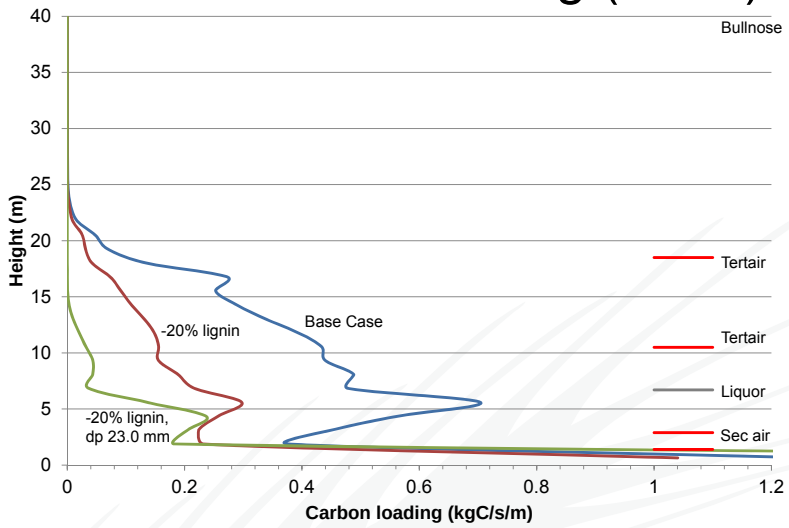
Fate of char carbon (-10%)

(kg/s)	Base Case	10% reduced lignin, dp 5.7 mm	10% reduced lignin, dp 12.5 mm
In liquor feed	8.81	6.19	6.19
in-flight conversion	3.90	2.60	1.01
to bed/walls	4.91	3.59	5.18
conversion on bed/walls	4.70	4.37	5.16
carbon accumulation	0.21	-0.78	0.02

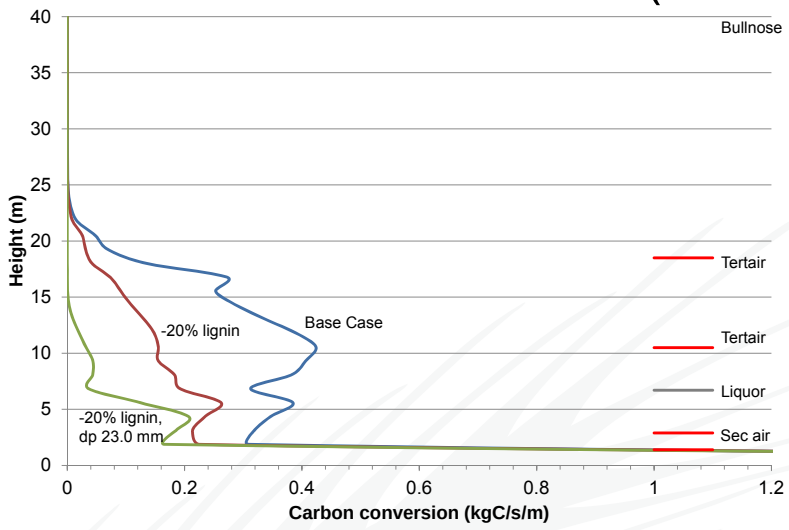
Fate of char carbon (-10%)

(%)	Base Case	10% reduced lignin, dp 5.7 mm	10% reduced lignin, dp 12.5 mm
In liquor feed	100.0	100.0	100.0
in-flight conversion	44.3	42.0	16.3
to bed/walls	55.7	58.0	83.7
conversion on bed/walls	53.4	70.5	83.4
carbon accumulation	2.3	-12.5	0.3

Furnace carbon loading (-20%)



Furnace carbon conversion (-20%)



Fate of char carbon (-20%)

(kg/s)	Base Case	20% reduced lignin, dp 5.7 mm	20% reduced lignin, dp 23.0 mm
In liquor feed	8.81	4.30	4.30
in-flight conversion	3.90	1.79	0.24
to bed/walls	4.91	2.51	4.05
conversion on bed/walls	4.70	4.10	4.02
carbon accumulation	0.21	-1.59	0.03

Fate of char carbon (-20%)

(%)	Base Case	20% reduced lignin, dp 5.7 mm	20% reduced lignin, dp 23.0 mm
In liquor feed	100.0	100.0	100.0
in-flight conversion	44.3	41.6	5.7
to bed/walls	55.7	58.4	94.3
conversion on bed/walls	53.4	95.5	93.6
carbon accumulation	2.3	-37.1	0.7

Conclusions - Runs 6 and 7

- With lignin removal and air split unchanged considerably larger droplets are needed to reach carbon balanced situation (="steady operation")
- Estimated to correspond to a decrease in liquor temperature of 4.7 °C or 11.9 °C when 10% or 20% lignin removed respectively
- Results suggest both liquor temperature and air distribution will need to be adjusted

Conclusions - Runs 1-7

- Less char-C with lignin removal
- Lower furnace less loaded with char-C
- Operational changes
  - Reduce prim/sec air **and**
  - Change spraying – larger droplets

Conclusions – condidates for additional runs

- Reduced lignin 10% and 20%, but with 100% MCR (runs so far have been 97% MCR and 94% MCR respectively)
- Spray tilt (10% and 20% reduced lignin)
- Combination of changes to spray (T or tilt) and air distribution
- Sensitivity analysis – Impact of distribution of carbon between volatiles and char & impact of swelling

SUOMEN SOODAKATTILAYHDISTYS RY
RAPORTTISARJA

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Konemestaripäivä 13.2.2014, esitelmät
Scandic Vierumäki, Stora Enso Oyj, Heinolan tehdas
(16A0913-E0147) 13.2.2014

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Soodakattilan sähkösuodintuhkan hyötykäyttömahdollisuudet,
Osahanke V: Sähkökemiallinen käsittely
Kurt Siren, Oy Sirra Ab
(16A0913-E0148) 10.3.2014

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Soodakattila-alan yhteistoiminta
Vuosikertomus 2013
(16A0913-E0149) 24.4.2014

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Pöytäkirja. Vuosikokous 24.4.2014, Radisson Blu Plaza hotelli, Helsinki
(16A0913-E0150) 24.4.2014

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(16A0913-E0151) 30.10.2014

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Jaakko Pellinen, JP-analysis
(16A0913-E0152) 20.11.2014

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Polttoperäisten päästöjen ja nano-hiukkasten
haitallisuuden määrittäminen uudella tutkimusmenetelmällä (POPE)
Itä-Suomen Yliopisto
(16A0913-E0153) 3.12.2014

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(16A0913-E0154) 29.1.2015

2/2015 Suomen Soodakattilayhdistys ry
Aktiivihiilen mitoituksen varmistus ja optimointi sekä TOC-reduktion varmistaminen
(16A0913-E0155) 29.1.2015

3/2015 Suomen Soodakattilayhdistys ry
Soodakattilan käynnistys-, pysäytys- ja häiriöjaksojen määrittely
(16A0913-E0156) 14.4.2015

4/2015 Suomen Soodakattilayhdistys ry
CFD Modeling of Reduced Lignin Black Liquor Combustion
Markus Engblom ja Nikolai DeMartini, Åbo Akademi
(16A0913-E0157) 14.4.2015