Cinar Ltd: Est. 1988

Providing Combustion and Process services for over 25 Years
Cinar is a ‘Spin-Out’ Company from IC, incorporated in 1988 to provide Technical services to Combustion and Emissions related Problems;

Cinar applies its ‘in-house’ developed models (CFD/MI-CFD) to solve industrial problems

Industrial applications:
- Boilers (power plants);
- Stationary/Aero gas turbines;
- Incinerators;
- Steel reheating/Blast furnaces;
- Glass/brick industries;
- R&D projects: EU/DTi (over 20)
- Cement and lime plants;

200 Projects
## Cinar and its Services

<table>
<thead>
<tr>
<th>Question</th>
<th>MI-CFD (includes mineral interaction &amp; multi-fuel combustion models)</th>
</tr>
</thead>
<tbody>
<tr>
<td>What is so Special in Cinar’s Approach?</td>
<td>Only CFD Part</td>
</tr>
<tr>
<td>Who else can provide the same services?</td>
<td>Realistic T &amp; CO₂</td>
</tr>
<tr>
<td>What’s the difference?</td>
<td>10-12 Weeks</td>
</tr>
<tr>
<td>How long does it take to provide a solution?</td>
<td>You'd love it!</td>
</tr>
<tr>
<td>How much does it cost?</td>
<td>Few Weeks</td>
</tr>
<tr>
<td>What’s the payback time?</td>
<td>Low Capex/free estim.</td>
</tr>
<tr>
<td>What are the typical advantages?</td>
<td>Many!!</td>
</tr>
<tr>
<td>Are there any successful applications?</td>
<td>3-D design spec.</td>
</tr>
<tr>
<td>What’s the typical output from MI-CFD?</td>
<td></td>
</tr>
</tbody>
</table>
CINAR - Associates

**Cyclone technologies**
- Preheater/calciner upgrade
- Installation and commissioning services

**Preheater/calciner upgrade**
- Installation and commissioning services

**Burner/Combustion system design**
- Low-CapEx Solutions

**Plant performance analysis via MI-CFD**

**Burner**
- Design
- Testing
- Commissioning
- Purpose-built burners

**Customised AFR design/installation**
- Emissions
- Plant trials

**Complete Solutions!**

**Fuel Strategy**
- Business planning
- AFR Market analysis
- Permitting/lobby
For LafargeHolcim, completed over 35 projects
<table>
<thead>
<tr>
<th>Date</th>
<th>Calciner type</th>
<th>Production</th>
<th>Primary Fuel</th>
<th>TSR</th>
<th>Alternative Fuels</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>Polysius RSP</td>
<td>4000 tpd</td>
<td>Petcoke</td>
<td>20%</td>
<td>SRF 1</td>
</tr>
<tr>
<td>2012</td>
<td>FLS-ILC “Low Nox”</td>
<td>3000 tpd</td>
<td>Petcoke</td>
<td>35%</td>
<td>Tyre chips, SRF 2</td>
</tr>
<tr>
<td>2013</td>
<td>FLS - ILC</td>
<td>2700 tpd</td>
<td>Petcoke</td>
<td>43%</td>
<td>SRF1, domestic waste</td>
</tr>
<tr>
<td>2013-2014</td>
<td>FLS – ILC “Low Nox”</td>
<td>4700 tpd</td>
<td>Petcoke</td>
<td>64%</td>
<td>Tyre chips, SRF 2</td>
</tr>
<tr>
<td>2013-2014</td>
<td>FLS – ILC “Low Nox”</td>
<td>3000 tpd</td>
<td>Petcoke</td>
<td>84%</td>
<td>Tyre chips, SRF 2, rice husk, sawdust briquette</td>
</tr>
<tr>
<td>2014</td>
<td>FLS – ILC</td>
<td>2600 tpd</td>
<td>Petcoke</td>
<td>55%</td>
<td>Tyre chips, SRF 1, contaminated soil</td>
</tr>
<tr>
<td>2014</td>
<td>FLS – ILC</td>
<td>2950 tpd</td>
<td>Petcoke</td>
<td>34%</td>
<td>Tyre chips, SRF 2</td>
</tr>
<tr>
<td>2015-2016</td>
<td>Polysius</td>
<td>2800 tpd</td>
<td>Petcoke</td>
<td>9%</td>
<td>Tyre chips, SRF 2</td>
</tr>
<tr>
<td>2015-2016</td>
<td>Sinoma</td>
<td>4100 tpd</td>
<td>Petcoke</td>
<td>50%</td>
<td>Tyre chips, SRF 2</td>
</tr>
</tbody>
</table>
Cinar Workshops (MI-CFD)

- Holcim, (USA), Europe (Eastern), Indonesia
- Lafarge (North America),
- GCC (North America),
- Essroc (North America),
- Fives-Pillard (Europe & China),
- IEEE/PCA (USA) & Cinar workshops (I, II and III),
- Heidelberg, Italcementi, Cimpor, BMH (Europe),
- Cherat and Vicram Cements (Pakistan & India), SGC (Thailand)
- Votorantim (Brazil)
- TCC (Japan)
- Lafarge-Holcim, (China)
The Simulation Tool: MI-CFD

- Multi-fuel firing capability (coal, oil, gas, AF’s) – tracking all fuels as they burn;
- Combustion is Directly coupled with Calcination and clinker formation chemistry – (Hence CO₂ release from combustion and calcination are taken into account plus temperature drop due to calcination – both are essential in predicting the ‘hot-spots’, CO, NOx, burnout and calcination levels).

Applied and tested on over 200 kilns and calciners
Lhoist Projects

- 2001: Rotary kiln off center gas burner (patent)
- 2008-2009: Dugny ASK various fuels
- 2009-2010: MLD RCE temperature profile. NOx reduction
- 2010: MTZ PFRK temperature/gas profile
- 2010: Terrasson PFRK NOx reduction (patent)
- 2010: Gorazdze PFRK Lean Gas (lower CV NG)
  - FLD PFRK NG Vs oil
- 2011: PFRK 600 tpd flexible template
- 2013: Jemelle ASK kiln & lower burners. Flameless combustion
- 2014: Jemelle ASK upper multichannel burner (patent to be filed)
  - HSI oil in PFRK. Evaluation of Maerz (patent)
  - O’Neal K2 preheater cassette
- 2015: Limeira NG firing PFRK reducing conditions
- 2016: St. Gen. kiln burner evaluation (in progress)
Annular-Shaft-Kiln (RAC)

Upper burners

Lower burners
100% Lignite Substitution in a Lime Kiln

67% Lignite – 33% NG

\[ T_{\text{exit}} = 1190 \, ^\circ\text{C} \]

100% Lignite

\[ T_{\text{exit}} = 1002 \, ^\circ\text{C} \]

\[ T_{\text{exit}} = 1220 \, ^\circ\text{C} \]

New burner design

\[ 57 \, \text{m/s} \]

\[ 34 \, \text{m/s} \]
Burner Design Modifications

Old Burner: 71% Lignite Burnout

New Burner: 95% Lignite Burnout

100% Lignite

1M€ Savings/year
From one kiln
payback: 4 weeks
Kiln Burner (Rings and Balls)

Balls/rings? Mineralogy issue or its the burner or the calciner? – MI-CFD can help!
Analysis of Kiln Base Case Results – 70%NG, 30%Tallow

The burner is placed 1 metre away from the kiln nose-ring

Flame lift-off distance: 0.5 m

Exit Temp. = 1077 °C

A single bright flame with hotter region several meters away from the burner tip.
Calciner Flame (Invisible Flame)
Calciner Flame (Localised Hot-Spots)

No visible single flame but localised hot-spots.
Fuel Streamlines in Oxygen: (Maximum oxygen 2.3%)

Oxygen concentrations along fuel streamlines in a 6-s calciner

Black lines represent fuel streamlines

$O_2$ [% vol.]

- 2.30
- 2.04
- 1.79
- 1.53
- 1.28
- 1.02
- 0.77
- 0.51
- 0.26
- 0.00
Calciner are more Fuel-Flexible but!!

- It is assumed that meal particles are fully dispersed and fuels fully burn!

- It is difficult to visualise (invisible flame) and correct it

(so calciner is taken as black box, RT is taken from the volume of calciner and the flow of the gases going through it);

The Most Common Problem:
Insufficient Mixing!
Kiln gases and TA Mixing
IRZ and ERZ (Kiln/Calciner)

Throat/Venturi helps reducing flow stratification

TA/Riser duct momentum ratio: 45/55
Kiln and TA flow Mixing: Velocity Vectors
Riser Burner:
Flow rate: 1.5 kg/s; \( V = 60 \text{ m/s} \)

Burner Velocity = 150 m/s

Riser flow: 32 kg/s; \( V = 35 \text{ m/s} \)

Riser Velocity = 12 m/s

MR = 1:12

MR = 1:2

Half momentum mixing approach:
(relocating burners/JAMS !)
Calciner Geometries and the Residence time (s)

Calciners are fired with ≈ 60% of the fuel
Typical Flow/Process Problems

- Flame Impingement,
- Flow stratification,
- Hot-spots,
- Volatile cycles (heat losses),
- Build-ups (plugging),
- Inefficient combustion issues,
- Emissions (CO, NOx, SO2, VOCs, Hg….)
- Clinker quality, i.e., (unreacted species, i.e., free lime)
What ‘Typically’ a Customer will get?

• A burner/combustion system design (for lower emissions, less deposits, stable kiln operation………;

• A simple low-cost implementation (by plant and/or via Cinar associates);

• Free process analysis from plant data and estimate of benefits and payback time;

• On what MI-CFD model is based upon?
An introduction to CFD and MI-CFD
Process and Combustion Interactions

• Turbulence (mixing, excess air/ignition source, i.e., IRZ), radiation (confinement), calcination, combustion (in suspension - residence time):

• Single-phase/two-phase combustion (gas/oil/coal) - characterisation, combustion/emission data collection facilities;

• Mathematical Models to simulate combustion, flow, calcination – in order to save experimental costs;

• Multi-fuel combustion model and validation for a number of other waste fuels, i.e., RDF, ASR, SRF, SS, WW, MBM, MSW, tyre chips, whole tyres, diaper cubes.

• Generally applied mathematical tools: next slide
Empirical and Simplified Models?

• Empirical/Simplified Models relate inputs to outputs using experimental data or heat and mass balances.

• No detailed process/flame information.

Wall losses
-5 MW

Exit gas
-5 MW

Radiation loss
-1 MW

Material
-1 MW

Combustion
+26 MW

Radiation loss
-3 MW

Secondary air
+4 MW
Difficulty with scaling criteria, information is only related to mixing and is of qualitative nature
ASSUMPTIONS:
1. Each slab fully stirred.
2. Longitudinal heat release distribution known.
3. Net mass flow rates known at slab interfaces.

Information limited to radiation heat transfer
CFD is Based on Physical Laws

**NEWTON:** \( F = ma \)

**FOURIER:** \( Q_{\text{conduction}} = k \frac{(T_1 - T_2)}{L} \)

**NUSELT:** \( Q_{\text{convection}} = h \left( T_{\text{fluid}} - T_{\text{surface}} \right) \)

**MAXWELL:** \( Q_{\text{radiation}} \sim \varepsilon T^4 \)

**ARHENIUS:** \( R_{\text{chemistry}} \sim Y_{\text{fuel}} Y_{\text{oxygen}} \exp \left( -\frac{E}{RT} \right) \)
Form of the Generalized Governing Equation

- Turbulence is characterized by a wide spectrum of scales. The smallest of which are very small (few μm) and cannot be resolved by even the biggest computers.

- So models are required to link the effects of turbulence to solve for time-averaged variables.

\[
\frac{\partial}{\partial x_j} \left\{ \overline{\rho \tilde{U}_j \tilde{\phi}} + \overline{\rho u_j'' \phi} \right\} = \frac{\partial}{\partial x_j} \left\{ \Gamma \frac{\partial \tilde{\phi}}{\partial x_j} \right\} + \overline{S_\phi}
\]

- This can only be solved by numerical means using a modern computer.
Computational Fluid Dynamics (CFD)

- Developed with the advent of modern computers, first model CFD model from Imperial College (teach code).

- So, it began to take off in the 1970’s for flow simulations.

- First applications in the aerospace and gas turbine industries, followed by furnaces.

- But for cement industry, still not enough information to calculate representative oxygen and temperatures fields, required for trace species, i.e., NO, CO
Development of MI-CFD

- Process interaction failings of ‘conventional’ CFD are overcome by incorporating the calcination and clinkering reactions;

- MI-CFD has been applied to plant components, for reliable trend predictions.

- MI-CFD enables one to ‘see’ and optimise a process, without excessive cost and risk!
Calcination & clinkering Models

• Raw materials: CaCO₃, MgCO₃, SiO₂, Al₂O₃, Fe₂O₃, H₂O, others considered inert:

  \[
  \text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2 \quad \Delta H \quad \text{(SRM)}
  \]

• Species considered in the clinker model:
  CaO, 2CaO.SiO₂ (C₂S), 3CaO.SiO₂ (C₃S),
  3CaO.Al₂O₃ (C₃A),
  4CaO.Al₂O₃. Fe₂O₃ (C₄AF)

• CaCO₃ → CaO + CO₂
• CaO + C₂S → C₃S
• 2CaO + SiO₂ → C₂S
• 3CaO + Al₂O₃ → C₃A
• 4CaO + Al₂O₃ + Fe₂O₃ → C₄AF
MULTI-FUEL FIRING

2-D projection of a 3-D mixture fraction space for solid fuel combustion

\[ \alpha_3 = \left(1 - \frac{f_3}{f_3^{st}}\right) \]

\[ f_1(f_3)^{st} = f_1^{st} \alpha_3 \]

\[ f_2(f_3)^{st} = f_2^{st} \alpha_3 \]

\[ R_{(f_1,f_2)}^{st} = f_1 + \frac{f_2}{f_2^{st}} = 1 - \frac{f_3}{f_3^{st}} \]

\[ B(f_1,f_2) = f_1 + f_2 = 1 - \frac{f_3}{f_3^{st}} \]
Post-Processing for Trace Species

• Proven global reactions are used for the CO and NOx (nitrogenous species).

![Diagram showing the process of post-processing for trace species]

- Fuel N → HCN/NH3
- HCN/NH3 + O₂ → NO
- NO + CHi → N₂
- N₂ + O₂ → Thermal NOx
- Products
Main Features of MI-CFD

- Multi-fuel capability (coal, oil, gas, AF’s)
- Calcination and clinker formation chemistry.
- Coupling between combustion and meal models.
- Accurate account of thermal radiation.
- 3D MI-CFD software with unstructured meshes.
- GUI mesh generation.
- NOx emissions, including calciner ‘reburn’ and SNCR.
- CO, SO2/SO3 formation/partitioning models.
- Turbulence models (K-ε, Reynolds Stress, etc.).
- Other validated physical and chemical models, i.e., slagging (build-up), fouling, toxic metals, VOCs, HCl.

How good these Models are?
4-Stage Calciner

Stage 3 Meal Upper
Data Ports
Calciner Burners
Tertiary Air Burner
Tertiary Air
Bypass
Kiln Gases

CO₂
O₂

Temperature and gas distribution in the calciner stages.
## Plant Data Comparison with MI-CFD (Oxygen)

### S-1.1

<table>
<thead>
<tr>
<th>Radial Distance (mm)</th>
<th>Oxygen (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>11.5</td>
</tr>
<tr>
<td>400</td>
<td>12.1</td>
</tr>
<tr>
<td>600</td>
<td>11.9</td>
</tr>
</tbody>
</table>

### S-1.2

<table>
<thead>
<tr>
<th>Radial Distance (mm)</th>
<th>Oxygen (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>14.8</td>
</tr>
<tr>
<td>400</td>
<td>15.3</td>
</tr>
<tr>
<td>600</td>
<td>14.9</td>
</tr>
</tbody>
</table>

### S-1.3

<table>
<thead>
<tr>
<th>Radial Distance (mm)</th>
<th>Oxygen (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>10.1</td>
</tr>
<tr>
<td>400</td>
<td>10.1</td>
</tr>
<tr>
<td>600</td>
<td>9.5</td>
</tr>
</tbody>
</table>
### Plant Data Comparison with MI-CFD (Oxygen)

#### S-2.2

<table>
<thead>
<tr>
<th>Radial distance (mm)</th>
<th>Oxygen (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>2.3</td>
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<tr>
<td>400</td>
<td>2.2</td>
</tr>
<tr>
<td>600</td>
<td>1.9</td>
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</tbody>
</table>

#### S-2.3

<table>
<thead>
<tr>
<th>Radial distance (mm)</th>
<th>Oxygen (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>1.8</td>
</tr>
<tr>
<td>400</td>
<td>1.6</td>
</tr>
<tr>
<td>600</td>
<td>1.7</td>
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#### S-2.1

<table>
<thead>
<tr>
<th>Radial distance (mm)</th>
<th>Oxygen (%)</th>
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</thead>
<tbody>
<tr>
<td>200</td>
<td>8.8</td>
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<tr>
<td>400</td>
<td>8.1</td>
</tr>
<tr>
<td>600</td>
<td>9.1</td>
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</table>

#### S-2.4

<table>
<thead>
<tr>
<th>Oxygen (%)</th>
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<tbody>
<tr>
<td>200</td>
</tr>
<tr>
<td>400</td>
</tr>
<tr>
<td>600</td>
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</tbody>
</table>
Plant Data Comparison with MI-CFD (Oxygen)

### S-3.2

<table>
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<tr>
<th>Radial distance (mm)</th>
<th>Oxygen (%)</th>
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<tbody>
<tr>
<td>200</td>
<td>0.9</td>
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<tr>
<td>400</td>
<td>1.0</td>
</tr>
<tr>
<td>600</td>
<td>0.9</td>
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</table>

### S-3.3

<table>
<thead>
<tr>
<th>Radial distance (mm)</th>
<th>Oxygen (%)</th>
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<tbody>
<tr>
<td>200</td>
<td>1.0</td>
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<tr>
<td>400</td>
<td>1.1</td>
</tr>
<tr>
<td>600</td>
<td>0.9</td>
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</table>

### S-3.4

<table>
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<tr>
<th>Radial distance (mm)</th>
<th>Oxygen (%)</th>
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<tbody>
<tr>
<td>200</td>
<td>0.5</td>
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<tr>
<td>400</td>
<td>0.5</td>
</tr>
<tr>
<td>600</td>
<td>0.1</td>
</tr>
</tbody>
</table>
Boundary and inlet conditions
The Problem – the Solution

• After identifying an improvement potential, a proposal is submitted to plant with expected benefits of the project and payback duration;

• Cinar’s guarantee is payback in a matter of weeks;

• After agreement with plant, a PO is issued and project starts;

• First a Base Case is simulated – that is the current operating condition;

• Then the solution finding simulations (What-Ifs) are carried out in agreement with plant;

• The next slides show the required information for the MI-CFD model.
Geometrical Details and boundary Conditions

• MI-CFD simulations will require detailed kiln, kiln-hood, preheater/precalciner drawings showing all the inlets, the kiln backend, details of splash box, and kiln hearth regions, locations of burners, hot-meal entry location(s), tertiary air duct(s) dimensions, and the outlet to the cyclone region.

• CAD drawings or photocopies of existing printouts
Geometrical Details and boundary Conditions

• NG/oil chemical composition (proximate and ultimate analysis), particle/droplet size distribution, calciner burner feed rates;

• Hot meal particle size distribution, feed rate at each injection location and hot meal analyses (i.e., LOI) at the calciner entry locations and at the exit of the calciner;

• Kiln inlet/backend hot meal expected composition (LOI) and feed rate as well as the composition of the combustion gases (O$_2$,CO,CO$_2$), their temperature and the kiln burner fuel and air flow rates and respective temperatures.
**Cooler Geometry and Inlets**

- **TA Outlet**: 34006 Nm³/h
- **Kiln Outlet**
- **False Air**: 6073 Nm³/h
- **Rest of the Air Inlet**: 21671 Nm³/h
- **IKN Fans Inlet**: 24611 Nm³/h
Geometry and Dimensions
### Simulation Data – Base Case

<table>
<thead>
<tr>
<th>Kiln Gases</th>
<th>kg/s</th>
<th>tph</th>
</tr>
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<tbody>
<tr>
<td>Flow Rate</td>
<td>19.033</td>
<td>68.52</td>
</tr>
<tr>
<td>Temperature</td>
<td>1050</td>
<td>1323</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Kiln Gases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kiln Gases (CO2)</td>
</tr>
<tr>
<td>Kiln Gases (H2O)</td>
</tr>
<tr>
<td>Kiln Gases (N2)</td>
</tr>
<tr>
<td>Kiln Gases (O2)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Flow Rate (total)</td>
</tr>
<tr>
<td>Burner 1</td>
</tr>
<tr>
<td>Burner 2</td>
</tr>
</tbody>
</table>

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<td>Fuel Flow Rate (total)</td>
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</tr>
<tr>
<td>Burner 2</td>
</tr>
<tr>
<td>Burner 3</td>
</tr>
<tr>
<td>Burner 4</td>
</tr>
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<table>
<thead>
<tr>
<th>Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Flow Rate (total)</td>
</tr>
<tr>
<td>Burner 1</td>
</tr>
<tr>
<td>Burner 2</td>
</tr>
<tr>
<td>Burner 3</td>
</tr>
<tr>
<td>Burner 4</td>
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<table>
<thead>
<tr>
<th>Tertiary Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow Rate</td>
</tr>
<tr>
<td>Temperature</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stage 4 Meal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow rate</td>
</tr>
<tr>
<td>Temperature</td>
</tr>
<tr>
<td>LOI (Adjusted acc. to C5)</td>
</tr>
</tbody>
</table>

880 kcal/kg
Simulation Data—Base Case

Fuel Data:

<table>
<thead>
<tr>
<th>Natural Gas Composition (Mass %)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>67.8</td>
</tr>
<tr>
<td>H</td>
<td>20.1</td>
</tr>
<tr>
<td>N</td>
<td>0.09</td>
</tr>
<tr>
<td>O</td>
<td>12.01</td>
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Gas Calorific Value

<table>
<thead>
<tr>
<th></th>
<th>36.3</th>
<th>MJ/Nm³</th>
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<tbody>
<tr>
<td>Oil Calorific Value</td>
<td>41.84</td>
<td>MJ/kg</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>O2 %</th>
<th>Kiln Back End</th>
<th>2.36</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Calciner Exit</td>
<td>0.56</td>
</tr>
</tbody>
</table>

Stage 4 Meal PSD

Oil DSD