Mild Combustion of non-conventional and liquid fuels

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Combustion processes are essential for power generation, thus the development of a combustion technology able to accomplish improvement of efficiency with reduction of pollutants emissions, as NOx and soot, is a main concern.

To improve the thermal efficiency of combustion processes, in the ’80 lots of studies were focused on Heat Exchange and Heat Recovery problems.
Excess enthalpy combustion\(^1\)
Heat-recirculating combustion: the exhausts can be used to preheat the reactants upstream the flame region\(^2\)

\(^1\) Lloyd, Weinberg, *Nature*, 251, 1974
PRELIMINARY ISSUES

Advantages
- Thermal efficiency is increased
- Reduced fuel consumption
- Possibility to burn low-calorific fuels

Drawbacks
- Very high peak temperatures
- High NOx emissions (thermal-NOx)
- Critical design of the burner
NOx CONTROL STRATEGIES

Flame control
- Temperature
- Stoichiometry
- Species–dilution and scavenging

Post-flame control
Post-flame NOx reduction by
- Reburning
- Non-catalytic selective reduction
- Catalytic selective reduction (SCR)

NOx-control strategies by burner design:
- Staging
- Swirling
- Recirculation

These techniques effectively control:
- Flame core stoichiometry
- Peak flame temperature

**RECIRCULATION vs FLAMMABILITY**

- Exhaust gas recirculation
- Oxygen enrichment
- Flammable mixture (26°C)
- LFL
- UFL
- FP
- AIT
- Auto Ignition

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DILUTION, PREHEATING, HIGH-MOMENTUM JETS

Traditional flame

Mild

Milani, Saponaro, *La Termotecnica*, 1, 2000

Derudi et al., *6th HiTACG Symposium*, 2005
ADVANCED LOW-NOx TECHNOLOGY
REGENERATIVE BURNERS - 2

Cortesia NFK

Burner tile
Exhaust gas
Secondary fuel
Primary fuel
Ceramic Honeycomb

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SELF-RECUPERATIVE BURNERS

FLOX burner, WS GmbH
ONE TECHNOLOGY, MANY NAMES

• Heat-recirculating combustion
• Preheated air combustion (PAC)
• Diluted Combustion
• Noiseless combustion
• High temperature air combustion (HiTAC)
• Flameless oxidation
• MILD combustion
  (Moderate or Intense Low oxygen Dilution)
WHY FLAMELESS?

Natural Gas
48MWth

“TEA” swirl burner
(ANSALDO)

Fuel
internal recirculation
MILD COMBUSTION - DEFINITION


\[ T_{\text{inlet}} > T_{\text{SI}} \text{ and } \Delta T < T_{\text{SI}} \text{ [K]} \]

Cavaliere, de Joannon, Prog. Energy Combust. Sci., 30, 2004
TYPICAL EXPERIMENTAL TRENDS

Krishnamurthy et al., *Proceedings of the Combustion Institute*, 32, 2009

MILD

Laboratory-scale burner is constituted by three main sections:
- feeding and pre-heating
- burner
- sampling and measurements

Lab-scale burner advantages:
- low-cost
- low-time
- high flexibility
LAB-SCALE BURNER: DILUTION RATIO

Industrial burner:

\[ k_v = \frac{\frac{i_{VA}}{M_e}}{M_a + M_f} \]

- \( M_e \): recycled exhaust gases stream
- \( M_a \): primary air inlet stream
- \( M_f \): fuel inlet stream

Lab-scale burner:

\[ k_v = \frac{R - SA}{1 + SA} + \frac{IA \cdot (1 + R)}{(1 + FA) \cdot (1 + SA)} \]

- \( SA \): 2\(^{\text{ary}}/1\(^{\text{ary}}\) air volumetric ratio
- \( IA \): inert/1\(^{\text{ary}}\) air volumetric ratio
- \( FA \): fuel/air ratio
- \( R \): recycle factor
DILUTION RATIO - $k_v$

SN: 25% of air external to the nozzle

$\kappa_v = \frac{\int_A \rho_E v_E dA}{m_F}$

SN: 80% of air external to the nozzle

Dilution ratio induced by the jets as a function of the dimensionless distance from the air nozzle
H$_2$-enriched fuels are interesting:
  - ↓ greenhouse gases
  - from solid fuels (e.g. coal/biomasses gasification)
  - byproducts of industrial processes (e.g. coke oven gas)

BUT… H$_2$ shows properties that make conventional burners unsuited:
  - alternative technologies (MILD)
  - need of research (little work on H$_2$ enriched fuels…)
RESULTS: \( \text{CH}_4/\text{H}_2 \)

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Measured T [K]</th>
<th>Predicted T [K]</th>
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<tbody>
<tr>
<td></td>
<td>1279</td>
<td>1273</td>
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<td></td>
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<td>1368</td>
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<td></td>
<td>1363</td>
<td>1375</td>
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</tbody>
</table>

\( Y_{\text{OH}} \) 5.0E-4

\( Y_{\text{CH}_2\text{O}} \) 9.3E-5
RESULTS: CH$_4$/H$_2$

Temperature predicted with EDC and DRM-19
Contributions of different formation routes to the total NO emissions (dry basis) with CH₄/H₂ mixture for different dilution ratios, kv

NNH intermediate mechanism:

\[ \text{N}_2 + \text{H} \leftrightarrow \text{NNH} \]

\[ \text{NNH} + \text{O} \leftrightarrow \text{NH} + \text{NO} \]

TOWARD A MILD COMBUSTION OF LIQUID FUELS

- Retrofit a lab-scale burner developed for mild combustion of gases in order to use liquid fuels
  - Different nozzles configuration
  - Atomizer for the direct liquid fuel feeding

- Definition of an experimental procedure for tests with liquid fuels (n-octane, n-dodecane, …)

- Evaluate main characteristic parameters for mild combustion of liquids → requirements for real-size burners design

- Preliminary definition of operating maps for pure (n-octane) and practical (kerosene) fuels
LAB-SCALE MILD BURNER LAYOUT

Exhausted gases outlet

Upper oven for heat maintenance

Thermocouple

Refractory insulation

Secondary air inlet

Liquid Fuel inlet

Gaseous Fuel inlet

Quartz-wool insulation

Preheating oven

Primary air + inert inlet

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LIQUID FUEL ATOMIZATION

A pneumatic atomizer (supported by a nitrogen stream), water-cooled to avoid fuel pyrolysis, was developed to create a short fuel jet.

The liquid fuel is sprayed directly into the burner.
The burner cannot be fired directly with a liquid fuel, so the fuel feed is varied once stable mild combustion conditions are achieved with a gaseous fuel (CH$_4$, C$_2$H$_6$).

\[
K_v = \frac{(M_{a1} + M_f + M_i) \cdot R - M_{a2}}{M_{a1} + M_{a2} + M_f}
\]

K$_v$ can be modulated in a wide range.
MIXED ZONE: ROAD TO MILD

Thermal gradients smoothing

A – Flame Combustion

B – Transition

C – Clean mild combustion

NO < 30 ppm
CO < 50 ppm
GAS TO LIQUID TRANSITION

**Single nozzle (SN)**

**Dual nozzle (DN)**

**HYBRID FUEL FEED:** GAS and LIQUID

**PURE METHANE OR ETHANE**

**PURE LIQUID FUEL**
n-OCTANE COMBUSTION

\( K_V = 8.75 \), air excess = 14\%, air preheated @ 950°C

Temperature increase due to the different thermal input

Low thermal gradient

Stable Mild clean regime during and after the gas to liquid fuel transition

NO < 30 ppm and no CO emissions during the transition
TEMPERATURE PROFILES

$K_V = 8.75$, air excess = 14%, air preheated @ 1100°C

$K_V = 5.6$

Preheated air nozzle

$K_V = 2.7$

Exhausts exit
MILD CLEAN REGION: n-OCTANE

![Graph showing temperature (T) versus Kv for different temperatures (1005°C and 840°C).]
Typical composition of a kerosene

<table>
<thead>
<tr>
<th>Surrogate component</th>
<th>Content (mol %)</th>
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<tbody>
<tr>
<td>n-octane</td>
<td>ref 9: 15</td>
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<tr>
<td>n-decane</td>
<td>ref 10: 32.6</td>
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<tr>
<td>n-dodecane</td>
<td>ref 11: 3.5</td>
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<tr>
<td>n-tetradecane</td>
<td>ref 12: 26</td>
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<tr>
<td>n-hexadecane</td>
<td>ref 13: 34.7</td>
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<td>isoctane</td>
<td>ref 14: 30</td>
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<td>isooctane</td>
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<tr>
<td>methylcyclohexane</td>
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<tr>
<td>cyclooctane</td>
<td>ref 16: 20</td>
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<tr>
<td>decaline</td>
<td>ref 17: 20</td>
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<tr>
<td>xylene</td>
<td>ref 18: 16.7</td>
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<tr>
<td>butyl benzene</td>
<td>ref 19: 16.7</td>
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<tr>
<td>tetramethylbenzene</td>
<td>ref 20: 16.7</td>
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<tr>
<td>α-methylxanthenene</td>
<td>ref 21: 16.7</td>
</tr>
<tr>
<td>tetralin</td>
<td>ref 22: 16.7</td>
</tr>
</tbody>
</table>

INFLUENCE OF REFERENCE COMPONENTS

Branched hydrocarbons

Cyclic hydrocarbons

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Kerosene contains not only linear chain and branched molecules, but also alkyl-benzenes and other cyclic compounds.

**GC-MS Analysis**

**Main fraction: C\textsubscript{10} - C\textsubscript{13} hydrocarbons**
OPTIMAL AIR EXCESS

Lower CO emissions found for lower air preheating temperatures (it is increased the reactants residence time into the combustion chamber)

No CO emissions for air excess larger than 20%

CH₄ to KEROSENE TRANSITION

NO < 30 ppm and CO < 1 ppm during the transition

SOₓ emissions (max 2 ppm)

Kᵥ = 9, air excess=20%, air preheated @ 1100°C
MILD CLEAN REGION: KEROSENE

$K_v = 1.7$

$T \ [ ^\circ C ]$

$K_v$

$1060^\circ C$

$850^\circ C$
CONCLUSIONS

• Successful retrofit of a mild combustion burner designed for gaseous fuels to operate with liquid fuels.

• These tests evidenced that it is possible to change, also during a run, the fuel feeding strategy without affecting the mild sustainability.

• Separated nozzles can help to realize mild combustion at lower Kv with respect to the SN layout, thus foreseeing the possibility to obtain mild combustion of liquid wastes and/or high reactive fuels (at moderate/high air temperatures and velocities) at low dilution ratios.
Mild combustion of liquid wastes

Coal mild combustion

Biomass mild combustion

Fig. 4. NO_x-emissions over burner excess air ratio for bluminous coal, data key in Table 1, open symbols, RWTH; filled symbols, USTUTT.

Stadler et al., Proceedings of the Combustion Institute, 32, 2009

1. Test facility at RWTH Aachen University.
OXY-fuel mild combustion

High-pressure mild combustion

“OXY-coal” mild combustion