Advancements in Atmospheric Combustion

Combustion technology at Berkeley Labs and working with the National Lab System

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American Society of Gas Engineers

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Agenda

Lawrence Berkeley National Lab

Working with the National Lab System

Low Swirl Burner

Grid Burner
Combustion Research at LBNL

- Chemistry (Chemical Science Division)
  - Chemical measurements of low pressure flames using soft X-ray probes
  - Chemical mechanisms for flame modeling
- Premixed Turbulent Flames (Computation Research Division and Energy Storage & Distributed Resources Division)
  - Direct numerical simulations
  - Fundamental studies of flame/turbulence interactions
- Technology Developments (Energy Storage and Distributed Resources Division)
  - Ultra-low emission fuel-flexible gas turbines and industrial boilers
  - Small HCCI engines
  - Ultra-clean home appliances
  - Bio-Fuel fingerprinting
Combustion Lab Research Team

- Dr. Peter Therkenelsen, Research Scientist
- Dr. Robert K. Cheng, Senior Scientist
- Dr. Vi Rapp, Research Scientist
- Darren Sholes, Research Associate
- Gary Hubbard, Computer System Engineer
- Dr. Okjoo Park, Postdoctoral Fellow
- Alex Frank, Ph.D. Candidate

- Collaborators:
  - John Bell & Marc Day (LBNL, Computation Research Div.)
  - Vince McDonell (Univ. of California, Irvine)
  - Shigeru Tachibana (Japan Aerospace Exploration Agency)
  - Tim Lieuwen (Georgia Institute of Technology)
  - Sy Ali (Clean Energy Consulting)

- Sponsors:
  - DOE, Fossil Energy, Advanced Turbine Program
  - California Energy Commission
  - New York State Energy Research Agency
LBNL Combustion Laboratory

• Historic focus on
  — Fundamental turbulent fluid dynamics studies
  — Laser diagnostics
  — Experimental and computational work
  — Funded by DOE Basic Energy Science, DOE Fossil Energy and NASA

• Current focus on
  — Concept and early development for advanced combustion systems
  — Fuel flexibility and carbon neutral fuels (biogas, landfill gas, liquid biofuel)
  — Rapid and wide turndown (fast thermal load following)
  — Small scale system (< 1MW)
Bridging Science-Technology Gap

LBNL combustion technologies (low-swirl burner and grid burner) evolved from laboratory research tool to ultra-clean combustion technologies

- Developed for basic studies of flame/turbulence interactions
- Scientific underpinnings facilitate adaptation to real world systems
  - Simple and scalable designs
  - Stable ultra-low NO\textsubscript{x} lean premixed flames
  - Fuel-flexible,
  - High turndown
LSB evolved from laboratory tool to an ultra-clean combustion technology

- Developed for basic studies of flame/turbulence interactions
  - supports stable ultra-low NO\textsubscript{x} lean premixed flames
- Scientific underpinnings facilitate adaptation to 1kW to 200 MW systems
  - residential furnaces & water heaters
  - commercial & industrial heaters
  - gas turbines operating on natural gas, digester gas, syngases & H\textsubscript{2}
  - petroleum refining process heaters
- Enabling technology for next-generation advanced combustion systems
  - Biogas microturbines (CEC project)
  - Combined heat and power
  - High efficiency combined cycle systems
Low Swirl Burner Schematic

- Combustor Spill Plate
- Open Center Channel
- 16 Swirl Blades (37°)
- Sensor Port
- Center Channel Screen

Dimensions:
- 6.8 cm
- 2.8 cm
- 1.9 cm
- 2.2 cm
Experimental Approach to Burner Development
Features of the LSB Flowfield

Axial velocity at the leading edge of the flame brush defines the local turbulent displacement flame speed,

Flame brush position invariant with $U_0$ and phi

Intense turbulence confines to the outer shear layer and corner recirculation zone
High Swirl vs. Low Swirl

High swirl injector uses a central recirculation zone (CRZ) to stabilize flames.

Low swirl injector stabilizes flames along the shear layers as the central divergence zone (CDZ) expands.

High Swirl

(a) Reactants

Low Swirl

(b) Reactants
Application Benefits of the LSB

- Simple design
- Fuel flexible (fixed burner)
  - Natural gas
  - Propane
  - Acetylene
  - Vaporized kerosene
  - Biogas
  - Hydrogen
- Ultra low NO\textsubscript{x} emissions
- Lower cost
- Durable
## Development and Commercialization Status of the LSB

<table>
<thead>
<tr>
<th>Applications</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial oven and process heaters</td>
<td>Commercialized for 300,000 Btu/hr to 90 MMBtu/hr</td>
</tr>
<tr>
<td></td>
<td>Over 1,000,000 hours field run time</td>
</tr>
<tr>
<td>Residential and commercial water heaters</td>
<td>Developed and lab tested</td>
</tr>
<tr>
<td>Residential and commercial furnaces</td>
<td>Developed and lab tested</td>
</tr>
<tr>
<td>Industrial boilers</td>
<td>Lab tested and field demonstrated</td>
</tr>
<tr>
<td>Industrial steam boilers</td>
<td>Seeking development partner</td>
</tr>
<tr>
<td>Industrial process fluid heaters</td>
<td>Developed and lab tested</td>
</tr>
<tr>
<td>Microturbines (&lt; 200 KW)</td>
<td>Field demonstrated with natural gas and bio gas</td>
</tr>
<tr>
<td>Mid-Size gas turbines (&lt; 10 MW)</td>
<td>Developed and engine tested</td>
</tr>
<tr>
<td>Utility size gas turbines (&gt; 100 MW)</td>
<td>Rig tested</td>
</tr>
</tbody>
</table>
MAXON Offers Two Lines of LSB Based Products

- “Achieved industry best emissions without sacrificing cost or performance”
  - 4-7 ppm NO\text{\textsubscript{x}} (@3\%O\textsubscript{2}) guaranteed
- M-PAKT burners (0.5 – 3.5 MMBtu/hr) since 2003
  - Natural gas, propane and butane
  - 10:1 turndown without pilot assistance
  - Hundred of units installed
  - Improve product quality (paint curing & food processing)
  - 1\textsuperscript{st} unit operating continuously since 2002
- OPTIMA SLS gas/liquid dual-fuel burners (12 - 90 MMBtu/hr) since 2006
  - 8”, 10”, 12”, 16” & 22” burner diameters
  - Enhanced 13:1 turndown
  - Backup liquid fuel firing
LSB Development for Gas Turbines

- Retrofits for 7MW natural gas engine
- Microturbine field demonstrations on natural gas and biogas
- Feasibility study for 200 MW natural gas engines
- Liquid fueled gas turbine
- Conceptual study for high efficiency 3MW combined cycle generator
- Reduced scale LSI for high-hydrogen gas turbines

*Projects involve proprietary information. Publication of data is restricted.
LSB Retrofit for Solar Turbine’s 7.7 MW Taurus 70 Engine

- US DOE-EERE Goals
  - < 5 ppm NOₓ (@ 15% O₂)
  - Transition to back-up fuels
  - Durable for at least 8000 hours
  - Cost effective
  - No negative impacts on performance

- Developed “drop-in” LSI retrofit
  - built from existing parts
  - No special requirements for materials and control
  - Exceptional in engine performance (< 5 ppm NOₓ)
  - Potential for efficiency improvement

- 2007 R&D100 award winner
Objective

- Overcome the economic and environmental barriers to biogas utilization via a cost-effective and ultra-low emissions industrial system with real time biogas/natural gas/propane fuel switching capability

Approach

- Combine low-swirl burner technology from LBNL with the fuel sensor technology from University of California, Irvine to a boiler at the Chiquita Water Reclamation Plant (CWRP) in Orange County California

Status

- Real-time duel-switching demonstrated in laboratory experiments
- Fuel sensor prototype demonstrated at CWRP

Ultra-sonic fuel sensor developed at U.C. Irvine will detect fuel composition for controlling the LSB to maintain efficiency and ultra-low emissions
• Package LSB engineered for fuel-switching with a fuel sensor, fuel-delivering circuit, and feedback control processor
CDRP Demonstration Facility

ADG tank

Irvine

Laguna Beach

Dana Point
LSB Baseline Performance on Biogas
LSB Operational History and Design Challenge for GENSETS

- Historic LSB operation conducted outside GENSETS design target
  - More turbulent flow regimes
  - Larger scales
- GENSETS design target to test
  - Limits of turbulent flow field development
  - Divergent flow field flame stabilization principle
Optimized GENSETS swirlers were designed and fabricated utilizing 3D printed technology. Final design meets and exceeds all GENSETS targets.

- Parametric study used to optimize swirler diameter, number of vanes, center plate geometry, as well as quarl geometry while achieving target flame stability, lean blow off, and pressure drop.

- Optimal design utilizes 14 mm diameter swirler with center plate consisting of 34 strategically placed holes.

- Targets an operating point with a bulk exit velocity of 9 m/s at an equivalence ratio of 0.65 for a power output of 3.33 kW (30% efficiency of surrounding components).
LSB GENSETS Burner Development

GENSETS LSB shows a highly-stable, short, and symmetrical flame with no flashback and a low lean blow off limit at simulated GENSETS conditions

- LSB development examined flame at various conditions to ensure optimal flame shape is achieved
- Flame shows no signs of flashback at any condition and has a lean blow off of 0.58 at target bulk exit velocity.
- Flame within enclosure (simulated combustor wall) is symmetric, compact, and stable

GENSETS LSB at $\phi = 0.75$, 9 m/s (rich for photographs)
GENSETS LSB meets targets at GENSETS conditions, showing the ultra-low emissions capability of the LSB

- GENSETS LSB NO\textsubscript{x}, CO, & THC emissions were measured at a fixed fueling rate (constant power output of 3.33 kW) while the varying burner bulk exit velocity and \( \phi \)

- Emissions are far below target for all equivalence ratios below 0.8, showing a wide band of potential operating points

- THC emissions were unmeasurably low

- CO\textsubscript{2} emissions level is 1450 lb/MW-hr based on the 30% efficiency target
  - SOPO goal of 1500 lb/MW-hr
California Energy Commission Solicitation:

- Develop combustion or post-combustion control technology(ies)
- Residential or commercial natural gas-fired devices
- Reduce $\text{NO}_x$ emissions to levels significantly below current South Coast Air Quality Management District emissions standards
- Technologies must not result in increased natural gas use
State of the art counter top burners emit ~ 90 ppm NO\textsubscript{x} and ovens 70 - 85 ppm NO\textsubscript{x}

**Forced draft ring-stabilizer technology** reduced furnace emissions below 15 ppm NO\textsubscript{x}

Lowest ring-stabilizer NO\textsubscript{x} emissions: 2.1 ppm
Lean premixed flame has only one reaction zone where all the fuel is consumed.

— Result: low flame temperature
  • Flame temperature is the dominant driver of NO\textsubscript{x} formation.

— Result: excess air weakens the flame
  • Aerodynamics and mechanical approach develop to maintaining a stable ultra-lean premixed flames.

• Testing at LBNL for NASA’s microgravity program proved Ring-Stabilizer viable for low NO\textsubscript{x} operation.
Reducing Ring-Stabilizer Port Size

- Manufacturing limitation = Gap = 0.60”
- Minimum port diameter 0.375”
  - Selected to minimize flashback potential
Experimental Setup
Grid Burner Geometry Relationship

- Forced Draft Test Results – Crossover Ignition
- Various distances between ports
- Ignition at one end of burner plate
- Self igniting until port distance too large
Natural Draft Development

- Operation of Natural-Draft Grid Burner
- Natural draft operation of small-scale Grid Burner is achievable with little modification to venturi fueling system.
Grid Burner Design
Grid Burner NOx Emissions

![Graph showing Grid Burner NOx Emissions with equivalence ratio on the x-axis and NOx @ 3% O2 on the y-axis. Different symbols represent different burners and conditions.]

- GB1 Enclosed
- GB1 Open
- GB2 Enclosed
- GB2 Open
- LSB
- Commercial burner
Grid Burner CO Emissions

![Graph showing CO emissions at 3% O2 against equivalence ratio for different burners: GB1 Enclosed, GB1 Open, GB2 Enclosed, GB2 Open, and LSB.](image)
Grid Burner Tech-to-Market Study

Benefits:
- Significantly improved heating efficiency
- Spatially-uniform heat output
- Enables innovative burner designs and configurations
- Dramatic NO\textsubscript{x} and CO emissions reductions
- Market testing indicates strong consumer desire

Advanced Product Concepts

Field of Flames
- Ignited pattern matches cookware
- Cookware placed anywhere on entire cooktop surface

Technology:
- Fully premixed air/fuel
- Natural draft
- Satellite ports stabilize flame

Conventional Burner

<table>
<thead>
<tr>
<th></th>
<th>Grid Burner</th>
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</thead>
<tbody>
<tr>
<td>Flame Pattern</td>
<td></td>
</tr>
<tr>
<td>Boil time</td>
<td>25% lower</td>
</tr>
<tr>
<td>Efficiency</td>
<td>33% higher</td>
</tr>
<tr>
<td>Uniform Heating</td>
<td>Yes</td>
</tr>
<tr>
<td>Match Flame Pattern to Pot Size</td>
<td>Yes</td>
</tr>
<tr>
<td>Low NO\textsubscript{x}</td>
<td>Yes 90% lower</td>
</tr>
<tr>
<td>Innovative and Flexible Aesthetic Design</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Heat cookware fast, uniformly, and efficiently with a captivating grid of low-NO\textsubscript{x} flames

Our customers are high-end cooktop manufacturers
The core of whose product is a undifferentiated burner technology

We solve this problem by delivering a distinct burner and surface that also alleviates critical end user functionality pains
- cleanable
- high BTUs, high turn-down
- 25\% lower boil time
- match flame area to pot size
- uniform heating
Nondisclosure Agreement (NDA)

<table>
<thead>
<tr>
<th>Definition</th>
<th>Protocols Proprietary information exchanged between parties (1, 2, or more ways)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protection of Generated Information</td>
<td>None</td>
</tr>
<tr>
<td>Rights in IP</td>
<td>None</td>
</tr>
<tr>
<td>Industry Resource Commitment</td>
<td>None</td>
</tr>
<tr>
<td>Lab Resource Commitment</td>
<td>None</td>
</tr>
<tr>
<td>Difficulty to Execute</td>
<td>Simple</td>
</tr>
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</table>

- This is an agreement that proprietary information provided by one party to another will be protected from further disclosure.
- It is frequently used to cover initial interactions between the laboratory and a potential industrial partner.
- An agreement normally protects information from public disclosure for 3 years.
# Cooperative R&D Agreement (CRADA)

<table>
<thead>
<tr>
<th><strong>Definition</strong></th>
<th>Enables industry to collaborate with the laboratory for the purpose of joint research and development.</th>
</tr>
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<tbody>
<tr>
<td>Protection of Generated Information</td>
<td>Commercially valuable but un-patentable information may be protected for 5 years.</td>
</tr>
<tr>
<td>Rights in IP</td>
<td>Rights to IP are negotiated separately. Industry partner receives first right to negotiate a license for new lab IP generated under the CRADA.</td>
</tr>
<tr>
<td>Industry Resource Commitment</td>
<td>Cost is shared through contributions of personnel, equipment, services, facilities, and funds by both the lab and industry partner.</td>
</tr>
<tr>
<td>Lab Resource Commitment</td>
<td>If funds available, lab shares in costs. If no funds available, industry partner responsible for full cost.</td>
</tr>
<tr>
<td>Difficulty to Execute</td>
<td>Simple - Medium</td>
</tr>
</tbody>
</table>

- Laboratory can not pay out funds to the industry partner.
- U.S. gov’t retains nonexclusive, nontransferable, irrevocable, paid-up license on IP generated under the CRADA.
## Nonfederal Work for Others (WFO)

<table>
<thead>
<tr>
<th>Definition</th>
<th>Enables industry to have the lab perform specific scope of work.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protection of Generated Information</td>
<td>Proprietary treatment of data available.</td>
</tr>
<tr>
<td>Rights in IP</td>
<td>Rights to lab inventions generated under WFO may be available depending upon contract.</td>
</tr>
<tr>
<td>Industry Resource Commitment</td>
<td>Industry covers all lab costs.</td>
</tr>
<tr>
<td>Lab Resource Commitment</td>
<td>Personnel, equipment, and facilities are used at the expense of the sponsor.</td>
</tr>
<tr>
<td>Difficulty to Execute</td>
<td>Medium - Difficult</td>
</tr>
</tbody>
</table>
| • Specific reimbursable work to be performed at the lab  
• Work must use a unique capability of the lab as to not compete with the private sector |
## User Facility Agreement (UFA)

<table>
<thead>
<tr>
<th>Definition</th>
<th>Permits industry users to conduct research using the labs unique experimental research equipment and facilities.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protection of Generated Information</td>
<td>Information is given proprietary or non-proprietary treatment depending upon the agreement.</td>
</tr>
<tr>
<td>Rights in IP</td>
<td>Industry user retains rights to inventions.</td>
</tr>
<tr>
<td>Industry Resource Commitment</td>
<td>Industry covers all costs associated with using the facility if the agreement is proprietary, shared cost if non-proprietary.</td>
</tr>
<tr>
<td>Lab Resource Commitment</td>
<td>Use of facilities is subject to availability.</td>
</tr>
<tr>
<td>Difficulty to Execute</td>
<td>Simple - Medium</td>
</tr>
</tbody>
</table>

- Laboratories have multiple unique experimental facilities and laboratories for use by domestic and foreign entities.
- Industry partner conducts the activity that occurs in the framework of the UFA.