Pulsed Microwave Coupling to Flames, Plasma Filaments and Development of New Diagnostics

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Research Thrusts

- Flame Speed Enhancement at atmospheric and higher pressures with microwave coupling
- Ignition enhancement by microwave coupling
  - Extension of the lean ignition limit
  - Authoritative, reliable ignition
    - Scramjets/ramjets
    - Pulse detonation engines
    - Spark ignition engines
- Laser and microwave sustained laser filaments
- Discharge dynamics and contraction
- Mixing enhancement with laser designated filamentary discharges
- New diagnostics for combustion
Collaborations

• Sergey Leonov (Russian Academy of Sciences)
  • Filament enhanced ignition and mixing
• Albina Tropina (Kharkov National Automobile and Highway University, Ukraine)
  • Modeling of filamentary plasma ignition processes
  • Modeling nonequilibrium effects on combustion
• Svetlana Starikovskiaya (Ecole Polytechnique, France)
  • Plasma streamer dynamics
• Christophe Laux (Ecole Centrale, Paris)
  • Nitrogen second positive emission for temperature
• Dr. M.Mokrov (Institute for Problems in Mechanics, RAS) and Dr. G.M.Milikh (University of Maryland)
  • Modeling of contraction
• Yiguang Ju
  • Radar REMPI in flames
• OSU
  • Plasma sheaths
Pulsed Microwave Coupling to Flames
Flame Speed Enhancement
Pulse Rep Rate Dependence

- Potential source of understanding for characteristic times of the MW interaction
- Significant power absorption approaching 1000 Hz repetition rate
- Flame passage time
  - $v_{\text{flame}} < 50 \text{ cm/s}$, $\delta_L \sim 0.5 \text{ mm}$
  - $t \sim 1 \text{ms} \rightarrow 1000 \text{ Hz}$
- What is the mechanism for flame speed enhancement?
MW-driven plasma luminosity

- $\varphi = 0.77$
- Good localization near reaction zone
- Short MW pulse -> no drift in deposition location at low rep rate
Filtered Rayleigh scattering for Temperature Imaging

MW pulse generator

DG-535

Oscilloscope

I₂ Cell

Nd:YAG
Spectra-Physics
GCR-170

Plasmas for Combustion
FS+MW Ignition
MW Enhancement
FRS sensitivity

Absolute Temperature

Relative Temperature Error

Plasmas for Combustion  FS+MW Ignition  MW Enhancement
FRS Thermometry Calibration

- Research Technologies RD1x1 Hencken Burner
- With line scattering can obtain Rayleigh signal-to-background > 20:1
- Normalize flame Rayleigh scattering to that of $N_2$ co-flow
- Accuracy and precision better than 5%

H$_2$/Air Hencken Burner Measurements with averaged FRS

![Plot of adiabatic flame temperature against $\phi$](chart.png)
Single pulse temperature jump

- Deposition localized near flame front/reaction zone
- 25 mJ, 1 us pulse gives 200 K rise
- 50 mJ, 2 us pulse gives 350 K rise
- Low $T_{ad}$ results from drift in FRS laser frequency
- Relative temperature error < 10%
Downstream sampling

- Transit time is on the order of seconds - small tube carries products along flame centerline
- Post-flame, cooled gases result in frozen NO concentrations and constant temperature across equivalence ratio sampling
- Long (>> 100 ms) effective residence time due to stagnation along centerline
NO detection by Radar REMPI

- NO detection via a 1+1 REMPI process
  \[
  A^2\Sigma^+ (v' = 0) \rightarrow X^2\Pi (v'' = 0)
  \]

- MW Enhancement
  - FS+MW Ignition
  - Plasmas for Combustion

Mechanical and Aerospace Engineering
Applied Physics Group

Plasmas for Combustion  FS+MW Ignition  MW Enhancement
Comparison of NO rise with absorbed power

- Combustion power of stoichiometric flame: ~800 W
- Total deposition less than 20 W
- Ratio of temperature enhanced flame of 200 and 400 K (roughly corresponding to FRS temperature data for these flames) is consistent with observed increase
MW Enhancement
Summary

- Effective flame speed increase (~10-20%)
- Single microwave pulse energy deposition in stationary flame fronts
  - > 100 K Temperature rise (~50% microwave energy deposition)
- Good localization at low repetition rate
- Relative NO concentration increases consistent with super-adiabatic temperatures
Filamentary Plasmas
Double Laser Pulse ionization and Heating in atmospheric pressure air

Remote Power Delivery for Plasma Assisted Combustion
Guiding microwave

Hybrid schemes:
fs laser + microwave
fs laser + ns laser
1D model

\[
\frac{\partial[n_s]}{\partial t} + \frac{1}{r} \frac{\partial(r[\Gamma_s])}{\partial r} = [G_s] - [L_s]
\]

Where \( n_s \) are: \( \text{N}^2+; \text{O}^2+; \text{O}^2-; \text{N}^4+; \text{O}^4+; e, \text{O}, \text{N}, \text{NO}^+, \text{N}^+, \text{O}^+, \text{O}^-; \text{NO}, \text{O}_3; \)

\( G_s \): generation; \( L_s \): losses

+ Poisson equation for the radial field
+ Equations for electron and vibrational temperatures
+ 1D gas dynamic equation for neutral gas + equation of state

• The rates of electron losses, recombination and attachment, are functions of \( T_e \):
  \( T_e \downarrow \Rightarrow \) rates of losses \( \uparrow \Rightarrow n_e \downarrow \)

• Photodetachment:
  \( \hbar \omega_L + \text{O}_2^- \rightarrow \text{O} + e; \ \hbar \omega_L \geq \varepsilon_a \approx 0.5 \text{ eV} \)

• Thermal detachment
Time dependence of the temperatures and densities for various carbon dioxide laser intensities

Shneider, Zeitikov, Miles, Physics Plasmas, 18 (2011)
Dynamic Contraction of the Positive Column of a Glow Discharge in Molecular Gas Flow

M. Schneider in collaboration with Dr. M. Mokrov (Institute for Problems in Mechanics, RAS and Dr. G. M. Milikh (University of Maryland)

The objectives of this work is to develop a self-consistent theoretical model which will allow us to
1. Predict the critical conditions for contraction (ionization-thermal instability)
2. Conduct qualitative and quantitative study of the spatial and temporal evolution of current contraction in molecular gas flows.
3. Parametric study of contraction
4. Study of possibility of generation of multiple hot channels in fast non-equilibrium weakly-ionized gas flows

Gas discharge in a large volume laser with close-cycle convective cooling; p=50 Torr; u=230 m/s; CO2:N2:He=1:6:12
N.A. Generalov et al, 1977

Electron density
(in n_e = 1.2x10^10 cm^-3)

Translational temperature
(in T_0 = 300 K)

N2; p=100 Torr; u=100 m/s

Hysteresis regime of contraction: a uniform “cold” glow discharge can be forced to contraction in a designated time and place

Contraction front propagation velocity ~10-100 m/s as

The model can be applied to analyze the critical conditions and simulate transient processes in medium pressure flow-stabilized gas discharges in powerful lasers, plasma-chemical reactors, and plasma assisted combustors

M. N. Schneider, M. S. Mokrov, G. M. Milikh, PHYSICS OF PLASMAS 19, 033512 (2012)
FS laser filament HV breakdown localization: S. Leonov and A. Dogariu
control of high-voltage breakdown position and initiation time

No FS laser guiding
FS laser guiding

HV long discharge initiation exactly on the boundary between fuel jet and air flow

➢ The first stage of the spark breakdown is the multiple streamers propagation from the “hot” electrode toward the grounded one.
➢ The second stage is the real selection of the discharge path among the multiple channels with non-zero conductivity.

Theory:
1. FS laser filament plasma
2. HV-breakdown development in pre-ionized channel at different time delays
3. After-spark evolution: with turbulent generation and decaying
4. Ignition conditions in air-fuel mixture

Experiment in collaboration with
Dr. S. Leonov (High Temperature Institute, RAS)

Theory in collaboration: with Dr. N. Popov and Dr. A. Tropina

Scheme of experiment
2012 Y Tests and Analysis: S. Leonov

- Consideration of physical mechanisms of instability development;

- Measurements of mixing efficiency by Probe Discharge Fluorescence;

- Detail description of jets’ generation pattern;

- Study of effect of specific localization of filamentary discharge;

- Discharge geometry adjustment to meet more practical schemes of mixing.
New Diagnostics
Femtosecond Laser Electronic Excitation Tagging FLEET
Nitrogen Atom Recombination

800 nm = 1.55 eV

Second Positive band (prompt)

First Positive band (delayed)
Spectra

Prompt – Second positive band in air

Delayed – “Pink afterglow” First positive band in air
FLEET in Combusting Environments

Single shot

Hencken Burner

10 shot average

Long time exposure for flame visualization
Tagging at high temperature

- Tagging in stoichiometric methane/air flame
- \( T_{ad} \sim 2200 \text{ K} \)
- Low flow velocity: 2 us delay with 1 us ICCD gate
Temperature Measurement

- The shape of the second positive spectrum (C to B) allows temperature to be calculated.

- The shape of the rotational tail can be fit to calculated spectra to give the rotational temperature.

- Alternatively, the ratio between the second positive and first negative systems can be used to find the gas temperature.
Nitrogen Second Positive Spectral Variation with Temperature
Fitting for Temperature

Fitting gives 485K for air - heated by laser
Temperature Measurement across a hot air blower output

- Temperature profiles can be measured, since images capture displacement on one axis and spectrum on the other.
- Profile measurements based on ratio between systems show good agreement with thermocouple measurements.
- Temperatures calculated based on rotational spectra are slightly warmer than measured, perhaps due to slight laser heating of focal region.
Temperature Profiles by Hyperspectral imaging

Spectra over 4mm of filament
Species Identification

![Graph showing species identification through a spectrum with peaks at 700 nm, 750 nm, 800 nm, and 850 nm, with annotations for O atom and fs laser scattering.]
Spectra of argon/air emission

Spectra are taken in the same configuration as the images.

Regions of mixing are apparent from spectra.

A filter with long wavelength (>700 nm) transmission sees only argon.
FLEET Characteristics

- No seeding required
- Operates in air and nitrogen and other gas mixtures containing nitrogen
- Instantaneous profiles
- No intrusive probe required
- High resolution (better than 40 microns)
- Simplicity (one laser and one camera)
- Grids and crosses give vorticity and shear stresses
- Operation at pressures as low as 1 Torr to > 1 atm
- Operation at temperatures from condensation to combustion (<100K to > 2000K)
- Operation with combustion products (water vapor, etc)
- May provide temperature profiles
- May provide species profiles
- May provide density profiles
Calibrated NO detection in flames
R. Miles, M. Shneider and Tat Loon Chng

- Amplitude of Radar REMPI signal is directly proportional to the electron number (concentration) of the target species.
  - Subsequent signal decay is due to various electron loss processes such as diffusion, recombination and attachment.
  - These processes can be as fast as on the order of tens of ns
- Signal decay time should be >> response time of the microwave detection system (~ 1 ns) to avoid attenuation of the signal amplitude.
  - Critical for accurate absolute concentration measurements.
- Experimenting with atomic buffer gases is a possible approach to mitigating this problem.
- Also of fundamental interest for combustion environments where a multitude of gases may exist.
- For a fixed target species (Xe) partial pressure, the use of a noble gas buffer such as Ar results in a significantly longer decay time compared to N₂.
  - Consistent with a longer equilibration time between the electron temperature and gas temperature.
Current and Future Work
Miles group and international collaborators

- Coupling of short pulsed microwaves to flames using 500 kW source
  - External – no cavity
  - Single reflector – “optical” cavity
- Development of calibrated Radar REMPI for measurements of species in flames
  - Use of noble gases for calibration
- Development of instantaneous temperature measurement methods
  - Femtosecond multiphoton laser induced fluorescence
  - Filtered Rayleigh and Raman
- Modeling and experimental work on efficient methods for controlled ignition using laser guided patterns
- Modeling and experimental work on enhanced mixing with filament guided energy addition