Fundamental Mechanisms,
Predictive Modeling,
and Novel Aerospace Applications
of Plasma Assisted Combustion

AFOSR
MURI Review Meeting

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Main Tasks

• High Temperature
• High Pressure
• High Speed
• High Voltage
• High Power
Rapid Compression Machine:
P = 10-70 atm, T = 650-1200 K
Scheme of the RCM

- Driving chamber
- Speed control chamber
- Combustion chamber
- Oil reservoir
- Piston
- Lock chamber
- Fast active valve
- Oil
- N\textsubscript{2}

Solenoid:
- P=30 bar of N\textsubscript{2}
- P=1 bar
Gas Dynamic Limitations

![Graph showing pressure over time for different conditions.]

- Green line: 13mm, 958 K, 19.77 bar
- Pink line: 9mm, 967 K, 20.87 bar
Gas Discharge Limitations

ICCD images of the discharge at 1 atm dry air. Negative polarity of the high-voltage electrode, 22 kV, 25 ns duration, $f = 40$ Hz [Kosarev et al, 2009].

Mixture $\text{C}_2\text{H}_6:\text{O}_2=2:7$ at 1 bar and ambient initial temperature was successfully ignited in $\sim 100$ ms in relatively large volume [Sagulenko et al, 2009].
SDBD Development at High Pressures

1 atm, 10 kV

3 atm, 30 kV
DBD Discharges: 20 kV, 10 kHz
ICCD gate 50 ns

Side view: \( T_0 = 300 \text{ K}, \phi = 0.0 \), pulse\#10

Front view: \( T_0 = 300 \text{ K}, \phi = 0.0 \)

Side view: \( T_0 = 500 \text{ K}, \phi = 0.3 \)

Front view: \( T_0 = 500 \text{ K}, \phi = 0.3 \)

<table>
<thead>
<tr>
<th>Pressure (torr)</th>
<th>( \text{H}_2)-air</th>
<th>( \text{C}_2\text{H}_4)-air</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td><img src="image1" alt="Images" /></td>
<td><img src="image2" alt="Images" /></td>
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<tr>
<td>300</td>
<td><img src="image3" alt="Images" /></td>
<td><img src="image4" alt="Images" /></td>
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<tr>
<td>500</td>
<td><img src="image5" alt="Images" /></td>
<td><img src="image6" alt="Images" /></td>
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Pulse

<table>
<thead>
<tr>
<th>P = 10</th>
<th>50</th>
<th>200 Torr</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td><img src="image7" alt="Images" /></td>
<td><img src="image8" alt="Images" /></td>
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<tr>
<td>10</td>
<td><img src="image9" alt="Images" /></td>
<td><img src="image10" alt="Images" /></td>
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<tr>
<td>100</td>
<td><img src="image11" alt="Images" /></td>
<td><img src="image12" alt="Images" /></td>
</tr>
</tbody>
</table>
DBD Discharges: 20 kV, 10kHz
ICCD gate 50 ns. P = 20 Torr

Air

Contraction stage
Gasdynamic expansion stage

\[ \tau_{\text{inst}} \sim \frac{\tau_T}{\gamma_i} \sim 0.1 \quad \gamma_i = \frac{d \ln(n_i)}{d \ln(E/N)} \]
\[ \tau_T \sim \frac{\gamma}{(\gamma - 1)} \frac{p}{\langle W \rangle} \text{ - typical heating time} \]
\[ \tau_{\text{inst}} \sim 10^{-4} - 10^{-2} \text{ s} \]

Energy distribution profiles. Dynamic discharge contraction and gasdynamic expansion stages are clearly seen.

Nitrogen

Contraction stage
Gasdynamic expansion stage
Kinetic Analysis.
Konnov’s Chemical Mechanism, $T_0 = 500$K, $P = 50$ Torr $C_2H_6$-Air. $E/n = 300$ Td, Different discharge energy.

Even 25% inhomogeneity will lead to order of magnitude difference in ignition delay – and completely compromise the kinetic analysis.
Kinetic Error Analysis

Air

- Median = 43250
- Maximum = 54500
- Energy Error = 26%
- Ignition Error ~ 5 times

C₂H₄-Air

- Median = 24250
- Maximum = 51250
- Energy Error = 111%
- Ignition Error ~ 20 times

H₂-Air

- Median = 41250
- Maximum = 61000
- Energy Error = 48%
- Ignition Error ~ 10 times

Inhomogeneous

Homogeneous?

Ignition of a stoichiometric hydrogen-air mixture modeling. OSU, 2009
Plasma-Assisted Ignition at High Pressures

CH\textsubscript{4} + O $\Rightarrow$ CH\textsubscript{3} + OH

CH\textsubscript{3} + OH $\Rightarrow$ CH\textsubscript{2}O + H\textsubscript{2}

CH\textsubscript{3} + O\textsubscript{2} $\Rightarrow$ CH\textsubscript{2}O + OH

CH\textsubscript{3} + O\textsubscript{2} + M $\Rightarrow$ CH\textsubscript{3}O\textsubscript{2} + M

Ignition delay time for modified mixtures, f=1.0, EGR=30%. Discharge 20ms before compression stroke

T\textsubscript{2} = 794 K, P\textsubscript{2} = 32 bar

T\textsubscript{2} = 672 K, P\textsubscript{2} = 20 bar.
Kinetics of Ignition Development

Stage 1. Discharge in Methane-Air mixture at temperature $\sim 330$ K, 1 atm. Production of metastable components.

Stage 2. Fast adiabatic compression to a temperature of 800-950 K. Metastable components decomposition and ignition development.

<table>
<thead>
<tr>
<th></th>
<th>CH$_2$O</th>
<th>CO</th>
<th>CH$_3$OH</th>
<th>CH$_3$O$_2$H</th>
<th>H$_2$O$_2$</th>
<th>Delay Time</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>540 ppm</td>
<td>170 ppm</td>
<td>260 ppm</td>
<td>21 ppm</td>
<td>49 ppm</td>
<td>0.33</td>
<td></td>
<td></td>
</tr>
<tr>
<td>540 ppm</td>
<td>170 ppm</td>
<td>260 ppm</td>
<td>21 ppm</td>
<td>49 ppm</td>
<td>0.51</td>
<td>910</td>
<td></td>
</tr>
<tr>
<td>170 ppm</td>
<td>260 ppm</td>
<td>21 ppm</td>
<td>49 ppm</td>
<td>0.89</td>
<td>0.60</td>
<td>19,050</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.47</td>
<td>10,820</td>
<td></td>
</tr>
</tbody>
</table>
Non-diffusive hybrid scheme for simulation of filamentary discharges

**FLUID MODEL**

The balance equation within hydrodynamic (drift-diffusion) approximation for required species and Poisson’s equation for electric potential:

\[
\frac{\partial n_s}{\partial t} + \text{div} \vec{j}_s = Q_s \\
\vec{j}_s = \vec{W}_s n_s - D_s \nabla n_s \\
\vec{W}_s = \mu_s \vec{E} \\
\Delta \varphi = -\frac{1}{\varepsilon \varepsilon_0} \sum q_s n_s \\
\vec{E} = -\nabla \varphi
\]

Secondary processes of electron production: photoionization in N₂-O₂, ion-electron emission, photoemission.

**HYBRID MODEL**

Non-fluid regions:

\[N_s = n_s \times \Delta V \leq 1\]

**1. DISCRETE FLUXES**

Original flux \( j_x \) and number \( \Delta N \) of transported over interface \( A_x \) species:

\[j_x = W_x n_s - D \frac{\partial n_s}{\partial x} \Rightarrow \Delta N = |j_x| A_x \Delta t\]

\[\Delta N = \Delta N^{int} + \Delta N^{rem},\]

where \( \Delta N^{int} \in \mathbb{Z} \) and \( \Delta N^{rem} < 1 \)
AVALANCHE TO STREAMER TRANSITION IN UNIFORM ELECTRIC FIELD
(air, 1 bar, 300 K, 1 cm, various voltages)
AVALANCHE TO STREAMER TRANSITION IN UNIFORM ELECTRIC FIELD
(air, 1 bar, 300 K, 1 cm, various E/n)
PS High-Pressure Discharge

Air, 1 atm

$E/n = 200 \text{ Td}: \quad \tau_{\text{max}}(\rho_0) \sim 10 \text{ ns}$

$E/n = 300 \text{ Td}: \quad \tau_{\text{max}}(\rho_0) \sim 2 \text{ ns}$

$\rho_1 \sim 21 \rho_0 (P_1 = 70 \text{ atm})$

$\tau_{\text{max}}(200 \text{ Td}) \sim 500 \text{ ps}$

$\tau_{\text{max}}(300 \text{ Td}) \sim 100 \text{ ps}$

FPG 200-01PB pulse generator
Voltage up to 200 kV
Pulse duration 350 ps
Rise time 120-140 ps
Voltage rise rate $2 \times 10^{15} \text{ V/s}$

Water, 1 g/cm$^3$

Voltage on electrodes, kV

Time, ns
MURI Deliverables: Diffusion, Mixing, Transport and High-Speed Combustion

- **Flames** (Ju, Sutton)
- **Cavity Flow Ignition** (Adamovich)
- **Shock Tunnel** (Starikovskiy)

![Graph showing MURI Deliverables: Diffusion, Mixing, Transport and High-Speed Combustion](image)
Discharge Formation and Flame Stabilization in High Speed Flow – Plasma Shock Tunnel

Combustion-Driven Shock Tube

Vacuum Chamber 1x0.5x0.5 m³
Discharge Formation and Flame Stabilization in High Speed Flow – Plasma Shock Tunnel

Combustion-Driven Shock Tube

Nozzle

Pulser

100 kV, 1 MHz
12 ns, 1000 p/b

1 MHz, 50 kV, 1 ms

1 MHz, 100 kV, 1 ms

Graphs showing relationships between initial pressure and temperature.
MURI Deliverables: Kinetic Data Generation

- Shock Tube (Starikovskiy)
- RCM (Starikovskiy)
- Flames (Ju, Sutton)
- Flow Reactors (Yetter, Adamovich)
- Streamer (Adamovich)
- JSR (Ju)
- MW+laser (Miles)
Plasma Shock Tube

PAC Kinetics at High T, Low P
Plasma Shock Tube

FID 120/60

MDR12 + R6357

431 nm CH

306 nm OH

MDR12 + R6357

TDS-3054

TDS-2014

TDS-2014

BNC-575

Tek-370

HV PS

HV PS

SW 1

NSpulse

SW 2

SW 3

Ignition

Time, ms

Channels 1-4

Sh1

Sh2

Sh3

306 nm
Pulse Current Dynamics – Cable

$C_2H_6:O_2:N_2:Ar = 2:7:28:63$

$P_5 = 1.0 \text{ atm}$
$T_5 = 1610 \text{ K}$
$\rho_5 = 0.273 \text{ kg/m}^3$

$P_5 = 3.3 \text{ atm}$
$T_5 = 1360 \text{ K}$
$\rho_5 = 1.06 \text{ kg/m}^3$
Pulse Current Dynamics – Shock Tube

\[ \text{C}_2\text{H}_6: \text{O}_2: \text{N}_2: \text{Ar} = 2:7:28:63 \]

Ethane. Hayashi 1987

Oxygen. Ionin 2007

Argon. Tachibana 1989

N\textsubscript{2}. Phelps 1994

\[ \frac{\partial (nf)}{\partial t} + \textbf{v} \nabla (nf) + \frac{Ze}{m} \left\{ \textbf{E} + \frac{1}{c} [\textbf{v} \times \textbf{H}] \right\} \nabla_v (nf) = S(nf) \]

\[ f(v, \theta) = \sum_{l=0}^{\infty} f_l(v) P_l(\cos \theta) \approx f_0(v) + f_1(v) \cos \theta \quad \frac{\nu_e}{\nu_m} \ll 1 \]
Discharge Energy Comparison

$C_2H_6:O_2:N_2:Ar = 2:7:28:63$
Discharge Dynamics
Ignition Delay Time

$C_2H_6:O_2:N_2:Ar = 2:7:28:63$

Combustion model: Konnov (2005)
Ignition Delay Time

$\text{C}_2\text{H}_6: \text{O}_2: \text{N}_2: \text{Ar} = 2:7:28:63$

Combustion model: Konnov (2005)
Measured Ignition Delay Time in Stoichiometric

$C_2H_6:O_2:Ar$ and $C_2H_2:O_2:Ar$ Mixtures

Kosarev et al. (2009)

$C_2H_6:O_2:Ar$

Current work
Peak Reduced Electric Field and Field at the Instant of Peak Current

$C_2H_2:O_2:Ar = 17:83:900$  
($\phi = 0.5$)
Total Specific Deposited Discharge Energy and Energy Deposited in First Pulse

\[
\begin{align*}
\text{C}_2\text{H}_2 : \text{O}_2 : \text{Ar} &= 17 : 83 : 900 \\
(\varphi = 0.5)
\end{align*}
\]
Ignition delay time in $\text{C}_2\text{H}_2:\text{O}_2:\text{Ar}$ mixtures

solid symbols: measurements

hollow symbols: calculations with kinetic scheme by Wang et al. (2007)
Evolution in time of calculated mole fractions for main components

Stoichiometric $C_2H_2:O_2:Ar$ mixture

**Autoignition**

at 1115 K and 0.91 atm

**Ignition after discharge** at 1130 K and 0.91 atm
Sensitivity analysis for autoignition and ignition by discharge

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Auto</th>
<th>FIW</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{C}_4\text{H}_2 + \text{OH} = \text{H}_2\text{C}_4\text{O} + \text{H}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{C}_4\text{H}_2 + \text{H} = \text{iC}_4\text{H}_3$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{C}_2\text{H}_3 + \text{O}_2 = \text{HCO} + \text{CH}_2\text{O}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{C}_2\text{H}_3 + \text{O}_2 = \text{CH}_2\text{CHO} + \text{O}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{C}_2\text{H}_2 + \text{O} = \text{HCCO} + \text{H}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{C}_2\text{H}_3 (+\text{M}) = \text{C}_2\text{H}_2 + \text{H} (+\text{M})$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{HCCO} + \text{H} = \text{CH}_2^* + \text{CO}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{C}_2\text{H} + \text{O}_2 = \text{HCO} + \text{CO}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{HCO} + \text{O}_2 = \text{CO} + \text{HO}_2$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{H} + \text{O}_2 = \text{O} + \text{OH}$</td>
<td></td>
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</tbody>
</table>

Autoignition 1115 K and 0.91 atm
Ignition by discharge 1130 K and 0.91 atm

Stoichiometric $\text{C}_2\text{H}_2 : \text{O}_2 : \text{Ar}$ mixture
Ignition Delay Time, $\phi = 0.5$

$C_2H_5OH:O_2:Ar(90\%)$

---

Graph showing discharge current versus time with various data points and labels for experimental and calculated values.
Ignition Delay Time, $\phi = 1.0$

$C_2H_5OH:O_2:Ar(90\%)$

Ignition times, $\mu$s versus $1000/T_5$.
Plasma Shock Tube Experiments Summary

\[ \text{C}_2\text{H}_2: \text{O}_2: \text{Ar}(90\%) \]
Combustion model: Wang et al. (2007)

\[ \text{C}_2\text{H}_5\text{OH}: \text{O}_2: \text{Ar}(90\%) \]

\[ \text{C}_2\text{H}_6: \text{Air}: \text{Ar}(63\%) \]
Combustion model: Konnov (2005)

\[ \text{C}_2\text{H}_6: \text{Air}: \text{Ar}(63\%) \]
Combustion model: Konnov (2005)
Ignition Delay Time Decrease at 0.1 eV/mol

\[ \tau_p = \tau_a \exp\left(-\frac{E_p}{E_0}\right) \]

\( C_2H_5OH:O_2:Ar(90\%) \)
Plasma Ignition Sensitivity

$0.1 \text{ eV/mol}$

Plasma assisted ignition efficiency

$Q = 0.1 \text{ eV/mol}$

- $\text{H}_2$:Air
- $\text{CH}_4$:O$_2$:Ar
- $\text{CH}_4$:Air:Ar
- $\text{C}_2\text{H}_2$:O$_2$:Ar
- $\text{C}_2\text{H}_5\text{OH}$:O$_2$:Ar
- $\text{C}_2\text{H}_6$:O$_2$:Ar
- $\text{C}_2\text{H}_6$:Air:Ar
- $\text{C}_3\text{H}_8$:O$_2$:Ar
- $\text{C}_4\text{H}_{10}$:O$_2$:Ar
- $\text{C}_5\text{H}_{12}$:O$_2$:Ar

Sensitivity

$\tau_{\text{auto}} / \tau_{\text{plasma}}$

$1000/T, \text{ K}^{-1}$

$\tau_{\text{a}} / \tau_{\text{p}} \sim 8$

$\varepsilon \sim 0.0125 \text{ eV/mol}$

$\tau_{\text{a}} / \tau_{0.01} \sim 5$ (- 40%)

$\tau_{\text{a}} / \tau_{0.10} \sim 2 \times 10^7$
PAC Kinetics $H_2$ Model Development

Plasma model:
- Plasma assisted combustion models for hydrogen oxidation understood for conditions of low energy loading per molecule. It means low ionization degree – we can neglect e-e collisions and EEDF Maxwellization due to this process.
- We have complete set of cross-sections for rotational, vibrational and electronic excitation, dissociation, dissociative ionization, ionization. These cross-sections were verified both for two-term approximation of Boltzmann equation (local EEDF) and could be modified for non-local case of extremely strong electric fields (differential cross-sections are also available).

Afterglow Model:
- **Because of fast relaxation we assume** $T_{tr} = T_{rot}$ **for ground state.**
- We have recombination rates for ion-electron collisions, ion-ion recombination (in some cases the products are unknown). Rates of complex ions formation/decomposition are unknown for elevated temperatures – but these ions control the plasma recombination rate.
- Quenching rates of major states are available, in some cases products are unknown. Specifically we do not know the products of reactions $N_2^* + H_2 \rightarrow ...$

Chemical Model:
- We have complete state-to-state model of chemical reactions including vibrationally-nonequilibrium conditions for $H_2$-air system since 2001.
- We have verified this model for 300 K (low-P reactor), 300-800 K (1 atm streamer) and 800-1500 K (0.5 atm, reflected shock wave).

Unsolved problems:
- Because of huge number of reactions some pathways are still questionable. We need to investigate in more details the products of electron-ion and ion-ion recombination, products of electronic states dissociative quenching (focus on electronically-excited products formation).
- Reaction rate coefficients of electronically and vibrationally excited species should be verified in some cases.
- We need additional analysis of the role of complex ions in recombination and chemistry at low-$T$ conditions.
Plasma Assisted Combustion: Translational Nonequilibrium

\[ \text{N}_2 : \text{O}_2 : \text{H}_2 = 4:1:2 \]
Mechanism of Fast Heating in Air Plasma

Aleksandrov & Starikovskiy, 2010

- B $n_e = 10^{14}$, $p=20$ Tor
- C $n_e = 10^{15}$, $p=20$ Tor
- D $n_e = 10^{14}$, $p=1$ atm
- E $n_e = 10^{15}$, $p=1$ atm

E/N, Td

Pancheshnyi (2009)

Popov (2011)

Popov (2001)
Potential Energy Curves of Molecular Hydrogen

\[ H_2(b^3\Sigma_u), \ 8.9 \text{ eV} \]
\[ \sigma_{\text{max}} = 0.33 \text{ Å}^2 (17 \text{ eV}) \]

\[ H_2(a^3\Sigma_g), \ 11.8 \text{ eV} \]
\[ \sigma_{\text{max}} = 0.12 \text{ Å}^2 (15 \text{ eV}) \]

\[ H_2(B^1\Sigma_u), \ 11.3 \text{ eV} \]
\[ \sigma_{\text{max}} = 0.48 \text{ Å}^2 (40 \text{ eV}) \]

\[ H_2(C^1\Pi_u), \ 12.4 \text{ eV} \]
\[ \sigma_{\text{max}} = 0.40 \text{ Å}^2 (40 \text{ eV}) \]
Potential Energy Curves of Molecular Oxygen

**Potential Energy Curves: O₂(A³Σ_u⁺)**, 4.5 eV
- \( \sigma_{\text{max}} = 0.18 \text{ Å}^2 \) (6.6 eV)

**Potential Energy Curves: O₂(³Π_g)**, 5.6 eV
- \( \sigma_{\text{max}} = 0.16 \text{ Å}^2 \) (12 eV)

**Potential Energy Curves: O₂(B³Σ_u⁻)**, 8.4 eV
- \( \sigma_{\text{max}} = 1.0 \text{ Å}^2 \) (9.4 eV)
Potential Energy Curves of Molecular Nitrogen

\[
\begin{align*}
\text{N}_2(A^3\Sigma_u^+), & \quad 6.2 \text{ eV} \\
\sigma_{\text{max}} & = 0.08 \text{ Å}^2 (10 \text{ eV}) \\
\text{N}_2(B^3\Pi_g), & \quad 7.35 \text{ eV} \\
\sigma_{\text{max}} & = 0.20 \text{ Å}^2 (12 \text{ eV}) \\
\text{N}_2(C^3\Pi_u), & \quad 11.03 \text{ eV} \\
\sigma_{\text{max}} & = 0.98 \text{ Å}^2 (14 \text{ eV})
\end{align*}
\]
Major Channels of Hot Atoms Production

\[ \text{N}_2 + e = \text{N}_2(C^3\Pi_u) + e; \quad k = f(E/n) \]

\[ \text{N}_2(C^3\Pi_u) + \text{H}_2 = \text{N}_2 + 2\text{H}(^1\text{S}) + 6.55 \text{ eV}; \quad k = 3.2 \times 10^{-10} \text{ cm}^3/\text{s} \]

\[ \text{N}_2(C^3\Pi_u) + \text{O}_2 = \text{N}_2 + 2\text{O}(^3\text{P},^1\text{D}) + 3.9 \text{ eV}; \quad k = 2.7 \times 10^{-10} \text{ cm}^3/\text{s} \]

\[ \text{O}_2 + e = e + 2\text{O}(^3\text{P},^1\text{D}) + 1.3 \text{ eV}; \quad k = f(E/n) \]

\[ \text{H}_2 + e = e + 2\text{H}(^1\text{S}) + 4.4 \text{ eV}; \quad k = f(E/n) \]
Chain Initiation/Branching Reactions

\[ H + O_2 = O + OH \]
\[ k = 1.6 \times 10^{-10} \times \exp(-7470/T) \text{ cm}^3/\text{s} \]
\[ k(300) = 2.5 \times 10^{-21} \text{ cm}^3/\text{s} \]
\[ k(\text{hot}) = 1.6 \times 10^{-10} \text{ cm}^3/\text{s} \]

\[ H + O_2 + M = HO_2 + M \]
\[ k(300, 1 \text{ atm}) = 1.6 \times 10^{-12} \text{ cm}^3/\text{s} \]
\[ T_{\text{crit}} \sim T_{\text{autoignition}} \]

\[ O + H_2 = H + OH \]
\[ k = 8.5 \times 10^{-20} \times T^{2.67} \times \exp(-3160/T) \text{ cm}^3/\text{s} \]
\[ k(300) = 9.3 \times 10^{-18} \text{ cm}^3/\text{s} \]
\[ k(\text{hot}) = 1.5 \times 10^{-10} \text{ cm}^3/\text{s} \]
\[ k^{(1D)} = 1.1 \times 10^{-10} \text{ cm}^3/\text{s} \]

\[ O + O_2 + M = O_3 + M \]
\[ k(300, 1 \text{ atm}) = 2.2 \times 10^{-14} \text{ cm}^3/\text{s} \]
\[ T_{\text{crit}} \sim 650K \]

\[ H(\text{hot}) + (N_2,H_2) = H + (N_2,H_2) \]
\[ k \sim 2m/M k_{gk} \sim 1.6 \times 10^{-10} \text{ cm}^3/\text{s} \]

\[ O(\text{hot}) + (N_2,O_2) = O + (N_2,O_2) \]
\[ k \sim 2m/M k_{gk} \sim 1.3 \times 10^{-10} \text{ cm}^3/\text{s} \]

\[ H(\text{hot}) + O_2 = H + O + O \]
\[ \]

\[ H(\text{hot}) + H_2 = H + H + H \]

\[ O^{(1D)} + (M) = O + (M) \]
\[ k = 2.6 \times 10^{-11} \text{ cm}^3/\text{s} \ (M = O_2) \]
\[ k = 1.3 \times 10^{-11} \text{ cm}^3/\text{s} \ (M = N_2) \]
\[ k = 5.2 \times 10^{-11} \text{ cm}^3/\text{s} \ (M = H_2) \]
Radicals Production Increase in Cold $\text{H}_2$-Air Mixture Due to Hot Atoms Formation
SUMMARY - 1

Experimental Facilities

   \( P = 10-70 \text{ atm}, \ U = 120 \text{ kV} \)
   1 GW in 60 ns

1. Plasma Shock Tunnel. \( M = 3-5, \ U = 100 \text{ kV} \)
   0.5 MW during 1 ms

1. Plasma Shock Tube. \( T = 800 - 2000 \text{ K}, \ U = 120 \text{ kV} \)
SUMMARY - 2

Major Results

Two new mechanisms of PAC proposed:

1) Influence of Vibrational Excitation on Low-Temperature Kinetics

\[
\begin{align*}
N_2 + e &= N_2(C^3) + e \\
N_2(C^3) + O_2 &= N_2 + O + O \\
O_2 + e &= O + O + e \\
N_2 + e &= N_2(v) + e \\
N_2(v) + HO_2 &= N_2 + HO_2(v) \\
HO_2(v) &= O_2 + H
\end{align*}
\]

Synergetic Effect of High and Low Electric Fields

2) Radicals Production Increase Due to Hot Atoms Formation

\[
\begin{align*}
N_2(C^3\Pi_u) + H_2 &= N_2 + 2H(^1S) + 6.55 \text{ eV} \\
N_2(C^3\Pi_u) + O_2 &= N_2 + 2O(^3P,^1D) + 3.9 \text{ eV} \\
O_2 + e &= e + 2O(^3P,^1D) + 1.3 \text{ eV} \\
H_2 + e &= e + 2H(^1S) + 4.4 \text{ eV}
\end{align*}
\]
Major Results
Plasma Ignition Efficiency for Different Fuels Analyzed
Future Plans

1) Role of Translational and Vibrational Nonequilibrium Analysis of non-Boltzmann, non-Maxwell regimes of reactions

2) Reference Experiments Database for PAC
   High-pressure regimes (RCM)
   Low-pressure regimes (STube)
   High-speed conditions (STunnel)

3) “Best Fuel for PAC”
Major International Collaborations and International Projects

Nickolay Aleksandrov (MIPT, Russia)
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PROJECTS:
PARTNER UNIVERSITY FUND “Physics and Chemistry of Plasma-Assisted Combustion” (Princeton-LPP)