Mathematical Modeling of Plasma Assisted Combustion

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INTRODUCTION

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LASER + DIRECT CURRENT DISCHARGE

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FUTURE WORK
Motivation

Applications requiring well-defined, well-controlled energy deposition

Flow control (optimal location for deposition of momentum, energy addition to trigger or suppress instabilities, reduce drag)

Tailored energy addition: new opportunities for combustion process control, tailored heat release; reaction progress control

Modification of temperature/density field to modify global performance

Authoritative, reliable ignition, ignition at the high speed flow

Different discharges influence on the combustion process

EXTENSION OF FLAMMABILITY LIMITS (OPERATION LIMITS)

LOCATION AND TIMING of IGNITION CAN BE CONTROLLED

VOLUMETRIC IGNITION

MORE EFFICIENT FUEL USAGE

STABILIZATION and FLAME HOLDING

POLLUTION REDUCTION THROUGH ULTRA-LEAN COMBUSTION
PLASMA ASSISTED COMBUSTION

Pulsed high-voltage nanosecond discharge in different modes [1,2]

Microwave discharge [3]

High-power filamentary DC discharge [4]

Dielectric barrier discharge [5]

Combined laser-microwave discharge [6]

Mechanisms

- thermal
- nonthermal


3. Esakov, L.P. Grachev, K.V. Khodataev, V.A. Vinogradov, D.M. Van Wie, 

4. A.V. Leonov, D.A. Yarantsev, A.P. Napartovich, I.V. Kochetov, 

5. D.E. Asphis, D.R. Thurman, 

Subcritical Microwave Applications

Volumetric subcritical discharge

Laminar flame speed enhancement


Stockman, et al., Combustion and Flame, 156 (2009).

- Extension of flammability limits (operation limits)
- Stabilization and flame-holding
- Enhancement for short residence time applications (scramjets)
Nanosecond Pulsed Discharge

Fast and efficient flame ignition:
flame sustainability due to periodic ignition at the plasma repetition rate

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Plasma assisted combustion
in the terms of continuum mechanics

Thermodynamic system is a small volume element of a medium interacting with an electromagnetic field by ponderomotive force.

Internal energy of the element is the energy of the intramolecular, heat motion and polarization energy

\[ \rho T ds = \rho du + \rho (p + p') d \frac{1}{\rho} - \overline{EdP} - \rho \sum_{k=1}^{n} \mu_k dY_k - \rho \sum_{v=1}^{v_{\text{max}}} \sum_{k=1}^{n} A_k^v dY_k^v \]

Combustion processes of the multi-component mixture in the electromagnetic field

\[
\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} = -\mathbf{E} u \nabla p + \frac{1}{\rho \operatorname{Re}} \left( \nabla \left( 2 \eta \mathbf{v}_{ik} + \frac{1}{3} \text{div} \mathbf{v} \delta_{ik} \right) \right) + \frac{1}{\rho} \left( G_q \mathbf{E} + A_l \cdot \mathbf{j} \times \mathbf{B} - G_d E^2 \nabla \varepsilon + G_d \nabla \left[ E^2 \rho \left( \frac{\partial \varepsilon}{\partial \rho} \right) \right] \right)
\]

(1)

\[
\frac{\partial n_i}{\partial t} + (\mathbf{v} \cdot \nabla) n_i = \frac{\beta}{\rho \cdot Sc_e \cdot \operatorname{Re}} \text{div} (\rho \mathbf{D}_i \nabla n_i) - (-1)^{i-1} \frac{\beta}{\rho \operatorname{Re}_\gamma} \text{div} \left( \mathbf{D}_i n_i \rho \mathbf{E} \right) + \sum_{j=1}^{N} Da_j \phi_j (\theta) \cdot \mathbf{W} (Y_i, n_i, n_e)
\]

(2)

\[
\frac{\partial n_e}{\partial t} + (\mathbf{v} \cdot \nabla) n_e = \frac{1}{\rho \cdot Sc_e \cdot \operatorname{Re}} \text{div} (\rho \mathbf{D}_e \nabla n_e + \rho k_T \frac{\nabla \theta}{\theta + \theta_0}) + \frac{1}{\rho \operatorname{Re}_\gamma} \text{div} \left( n_e \rho \mathbf{D}_e \mathbf{E} \right) + Da_e \phi_e (\theta) \cdot \mathbf{W} (Y_i, n_i, n_e)
\]

(3)

\[
\frac{\partial Y_i}{\partial t} + (\mathbf{v} \cdot \nabla Y_i) = \frac{1}{\rho \cdot Sc_i \cdot \operatorname{Re}} \text{div} (\rho \mathbf{D}_i \nabla Y_i) + \sum_{j=1}^{n} Da_j \phi_j (\theta) \cdot \mathbf{W} (Y_i, n_i, n_e) \quad i = 1, n
\]

(4)

\[
p = \rho(\theta + \theta_0) \sum_{i=1}^{n} \frac{Y_i}{m_i}
\]

(5)
Combustion processes of the multi-component mixture in the electromagnetic field

\[ \rho \frac{\partial H}{\partial t} + \rho (\vec{v} \cdot \nabla) H = (\text{Pr} \cdot \text{Re})^{-1} \text{div}(\vec{\lambda} \nabla \theta) + \frac{1}{\text{Re}} \text{div} \left( \rho \sum_{i=1}^{n} \left( \frac{1}{\text{Sc}_i} h_i \vec{D}_i \nabla Y_i \right) \right) + \]

\[ + I_d \sigma E^2 + I_d \sigma \vec{v} \times \vec{B} + I_w \varepsilon E^2 + \sum_{j=1}^{r} \rho^2 D_a j \varphi_j (\theta) \cdot h_j \cdot \vec{W}(Y_j, n_j, n_e) + Br \cdot \nabla \cdot \tau_{ik} \vec{u} \]

\[ \text{div}(\varepsilon \vec{E}) = \xi \left( \sum_{i=1}^{N} n_i - n_e \right) \]

\[ \vec{j} = \text{Re}_m (\sigma \vec{E} + \sigma \vec{v} \times \vec{B}) \]

\[ \text{div} \vec{B} = 0 \quad \text{rot} \vec{H} = \frac{1}{c} \frac{\partial \vec{D}}{\partial t} + \frac{4\pi \vec{j}}{c} \]

\[ \frac{1}{c} \frac{\partial \vec{B}}{\partial t} = -\text{rot} \vec{E} \]

Nondimensional parameters of the system

\[ G_q = \frac{e n_0 E_0 d_0}{\rho_0 \nu_0^2}, \quad I_w = \frac{\varepsilon_0 E_0^2 d_0}{8\pi \rho_0 \nu_0 (H_i - H_0)}, \quad G_d = \frac{E_0^2 \varepsilon_0}{8\pi \rho_0 \nu_0^2}, \quad \alpha_j = \frac{RT_i}{U_j}, \quad \text{Re}_m = \frac{\sigma_0 d_0 \mu \nu_0}{c}, \quad \text{Sc}_i = \frac{\eta_0}{\rho_0 \text{D}_i} \]

\[ I_d = \frac{\sigma_0 E_0^2 d_0}{\rho_0 \nu_0 (H_i - H_0)}, \quad \xi = \frac{4\pi e n_0 d_0}{\varepsilon_0 E_0}, \quad \text{Re} = \frac{\rho_0 \nu_0 d_0}{\eta_0}, \quad \beta = \frac{D_i 0}{D_e 0}, \quad \text{Pr} = \frac{\eta (H_i - H_0)}{\lambda (T_i - T_0)}, \quad \theta_0 = \frac{T_0}{T_i - T_0}, \quad I_d = \frac{\sigma_0 E_0^2 d_0}{\rho_0 \nu_0 (H_i - H_0)} \]

\[ A_l = \frac{j_0 B_0 d_0}{\rho_0 \nu_0^2}, \quad \text{Sc}_e = \frac{\eta_0}{\rho_0 \text{D}_e}, \quad \text{Re}_e = \frac{E_0 e D_e}{\nu_0 k_B (T_i - T_0)}, \quad \varphi_j(\theta) = \exp \left( -\frac{\theta - 1}{\alpha_j \theta_i} \right), \quad \text{Da}_j = k_j \exp \left( -\frac{1}{\alpha_j} \right), \quad \theta_i = \frac{T_i}{T_i - T_0} \]
Combustion processes of the multi-component mixture in the electromagnetic field

\[
\frac{\partial}{\partial t} (n_e \theta_e) + \frac{\partial}{\partial x_i} \left( \frac{5}{2} v_i n_e \theta_e \right) = (\text{Re} \cdot \text{Pr}_e)^{-1} \nabla \lambda_e \cdot \nabla \theta_e + G_{de} \vec{j} \cdot E - G_{Te} \nu_{\epsilon\phi\phi}(\theta_e - \zeta_e \theta) - Q_{e-V} - G_e Q_e
\] (9)

\[
c_p^* \rho \left( \frac{\partial \theta}{\partial t} + \vec{v} \cdot \nabla \theta \right) = (\text{Pr} \cdot \text{Re})^{-1} \nabla \lambda^* \cdot \nabla \theta + G_T \nu_{\epsilon\phi\phi} (\zeta_e^{-1} \theta_e - \theta) + G_{VT} \rho \frac{\varepsilon_v(\theta_v) - \varepsilon_0(\theta)}{\tau_{VT}} +
\]

\[
+ \frac{1}{\text{Re}} \text{div} \left( \rho \sum_{i=1}^{n} \left( \frac{1}{Sc_i} h_i \vec{D}_i \nabla Y_i \right) \right) + \sum_{j=1}^{r} \rho^2 \text{Da}_j \phi_j (\theta, \theta_e, \theta_V) \cdot h_j \cdot \vec{W}(Y_j, n_j, n_e)
\]

\[
\frac{d\varepsilon_v}{dt} = (Sc_\epsilon \cdot \text{Re})^{-1} \nabla \cdot \rho D_h \nabla \varepsilon_v - G_{VT \varepsilon} \rho \frac{\varepsilon_v(\theta_v) - \varepsilon_0(\theta)}{\tau_{VT}} + Q_{e-V}
\] (11)

\[Q_{e-V} = \alpha_V G_{de} \vec{j} \cdot E\]
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FUTURE WORK
Main nondimensional parameters

\[
G_d = \frac{E_0^2 \varepsilon_0}{8 \pi \rho_0 \nu_0^2} \quad G_q = \frac{en_0 E_0 d_0}{\rho_0 \nu_0^2} \quad Al = \frac{j_0 B_0 d_0}{\rho_0 \nu_0^2} \quad \xi_V = \frac{T_V - T_0}{T_0}
\]

\[
\varphi_j(\theta) = \exp\left(-\frac{\theta - 1}{\alpha_j \theta_\theta}\right) \quad \xi_e = \frac{T_e^0 - T_0}{T_e^0} = \frac{\pi m \ell_e^2 e^2 E^2}{24 m_e k_B T_e^2} \quad \text{Re}_m = \frac{\sigma_0 d_0 \mu \nu_0}{c}
\]

Limiting cases

1) \[Al \cdot \text{Re}_m << 1 \quad G_q > 1, G_d > 1 \quad \xi_V = 1 \quad \varphi_j = \varphi_j(\theta) \]

Flame in the electric field

2) \[Al \cdot \text{Re}_m > 1 \quad G_q << 1, G_d << 1 \quad \xi_e = 1 \quad \xi_V = 1 \]

Combustion processes assisted by a plasma in the local thermodynamic equilibrium state (combustion processes assisted by high current DC discharges)
### Limiting Cases

3) \( Al \cdot Re_m > 1 \quad \xi_e \gg 1 \)

\[ G_q \ll 1, G_d \ll 1 \quad \xi_V = 1 \]

\[ \varphi_j = \varphi_j (\theta, \theta_e) \]

Combustion processes assisted by nonequilibrium plasma
(two-temperature approach)
(combustion processes assisted by the DC discharge at low currents)

4) \( Al \cdot Re_m \ll 1 \quad \xi_e \gg 1 \quad Re_m \ll 1 \)

\[ G_q \ll 1, G_d \ll 1 \quad \xi_V > 1 \]

\[ \varphi_j = \varphi_j (\theta, \theta_e, \theta_V) \]

Combustion processes assisted by nonequilibrium plasma with internal degrees of freedom
(three-temperature approach)
(combustion processes assisted by the nanosecond pulsed discharge)

Only for laminar combustion assisted by plasma
## EVALUATION

<table>
<thead>
<tr>
<th>Nanosecond pulsed discharge</th>
<th>$\xi_V = \frac{T_V - T_0}{T_0}$</th>
<th>$\xi_e = \frac{T_e^0 - T_0}{T_e^0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>methane-air, $\Phi = 0.65$</td>
<td>0.6</td>
<td>?</td>
</tr>
<tr>
<td>methane-air, $\Phi = 2.2$</td>
<td>0.3</td>
<td>?</td>
</tr>
</tbody>
</table>

| air (NP discharge)          | 2.3                             | ?                                 |
| air (NRP glow)              | 0.9                             | ?                                 |
| air (NRP filamentary)       | 1.5-3.4                         | 6.5-8.1                           |
| air (transversal arc discharge) | 2.6                         | 17                                |

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Combustion processes assisted by nonequilibrium plasma with internal degrees of freedom

4) \[ Al \cdot Re_m << 1 \quad \xi_e >> 1 \quad Re_m << 1 \quad G_q << 1, G_d << 1 \quad \xi_V > 1 \quad \phi_j = \phi_j(\theta, \theta_e, \theta_V) \]

**Main physical mechanisms**

1) Ignition delay time change caused by the generation of electronically and vibrationally excited molecules,
2) Laminar flame speed enhancement;
3) Additional impulse transfer which can cause the small-scale turbulence generation in the discharge zone;
4) Influence of energy saved in the vibrational degrees of freedom on the minimum ignition energy and combustion process;
5) Change of the ignition kinetic mechanism;
6) Change of the transfer properties of a medium.
FORMULATION OF THE PROBLEM

Plasma composition

Excited particles

\[ \text{O}_2(a^1\Delta_g), \text{O}_2(b^1\Sigma^+_g), \text{N}(^2D), \text{O}(^1D), \text{N}(^2P), \text{N}(^4S), \text{O}(^3P) \]

\[ \text{N}_2(A^3\Sigma^+_u), \text{N}_2(B^3\Pi_g), \text{N}_2(a'^1\Sigma^-_u), \text{N}_2(C^3\Pi_u), \text{N}_2(X'^1\Sigma^+_g, \nu) \]

Positive ions

\[ \text{N}_4^+, \text{N}_2^+, \text{NO}^+, \text{N}^+, \text{O}_4^+, \text{NON}_2^+, \text{N}_3^+, \text{N}_2\text{O}^+, \text{NO}_2^+, \text{O}_2^+, \text{O}^+ \]

Negative ions and electrons

\[ \text{O}_2^-, \text{O}^-, \text{NO}^-, \text{O}_3^-, \text{NO}_3^-, \text{O}_4^-, \text{NO}_2^-, \text{N}_2\text{O}^-, e^- \]

Total number of species for the fuel-air plasma

C2 mechanism – 119: neutrals(81), charged and excited particles(32),
NO mechanism (8)

GRI 3.0 mechanism -89: neutrals (53), charged and excited particles (32),
NO mechanism (4)
FORMULATION OF THE PROBLEM: Main reactions

- Excitation of electronic states, destruction and ionization of neutrals by electron impact
- Associative ionization
- Recombination of electrons and positive ions
- Electron attachment and detachment processes
- Reactions with participation of ground electronic states particles
- Reactions with participation of electronically excited particles
- Positive and negative ions reactions
- Recombination of positive and negative ions
- Reaction with participation of vibrationally excited particles
- Quenching of O(\(^{1}\)D), O(\(^{3}\)P), N(\(^{2}\)P), N(\(^{2}\)D), O(\(^{3}\)P) on neutrals
- Combustion reactions for neutral species

Specific heat correction due to the vibrational excitation

\[ c_{pm} = \frac{1}{N} \sum_{i} c_{pi} n_{ip} \]

\[ c_{pm}' = c_{pm} - \frac{n_{N_2}}{\rho} \frac{d\varepsilon_V(T)}{dT} \]

Rate constants of ionization, dissociation and dissociative attachment increase (effect of non-zero vibrational temperature \( T_V \)) [1]

\[ F = \exp \left( \frac{Cz}{(E/n)^2} \right) \]

\[ C = 6.5 \times 10^3 T d^2 \]

\[ z = \exp (-E_{N_2} / kT_V) \]

Formation enthalpy correction for the components in the excited states

\[ H_j^*(T) = H_j(T) + \varepsilon_{jm} \cdot R_0 \]

Energy of the excitation level

IGNITION DELAY TIME ANALYSIS (P=1 atm)
nanosecond pulsed discharge

Input of the vibrational excitation:
Ignition delay time decrease - 20%
Heat capacity change—0.1-0.5 %

Main ions $\text{O}_4^+, \text{O}_2^+, \text{O}^-, \text{NO}^+$

Fig.1. O atoms concentration dependence on time (methane-air mixture).

Fig.2. The ignition delay time dependence on the reduced electric field value.

Minimum ignition energy

Fig. 1. Minimum ignition energy and internal energy as a function of the pulse width.

Fig. 2. Minimum ignition energy as a function of the plasma region radius.

Fig. 3. Minimum ignition energy as a function of E/N.

Electron impact rate constants dependence on the fuel content in the mixture

Fig. 1. Normalized rate constants dependence on the reduced electric field value
a) methane-air mixture, b) ethane-air mixture.

$P=1\text{ atm}$
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FUTURE WORK
Laser+microwave discharges

Remote Power Delivery for Plasma Assisted Combustion

Guiding microwave

Hybrid schemes: fs laser + microwave [1,2]

Fig. 2 The ignition delay time dependence on the equivalence ratio (methane-air mixture microwave pulse duration is 2 μs)

Fig. 3. The ignition delay time dependence on the microwave energy input time: lean mixture (φ = 0.5)

Influence of energy saved in the vibrational degrees of freedom on the flame normal velocity

\[
\rho u = \sqrt{\frac{2Q}{H_b - H_0}} \int_0^1 \frac{\lambda}{c_p} W(z) dz
\]

\[
T_a = T^s T_V^{1-s}
\]

\[
W(z) = \exp\left(-\frac{E_a}{RT_b}\right) \exp\left(\frac{E(T_b - T_0)T_V^{1-s}}{RT_b^2}\left(Z^s - \frac{T_b}{(T_b - T_0)T_V^{s-1}}\right)\right)
\]

\[
s = 1 \quad \text{Zel’dovich solution [1].}
\]

\[
\int_{z_0}^{z_1} \frac{\lambda}{c_p} W(z) dz = \frac{\lambda_b}{c_p} k_0 \rho b^n a_0^n e^{-E/RT_b} \cdot \int_{z_0}^{z_1} (1 - z)^n \exp(\theta(s)(z^s - B(s))) dz
\]

Fig. 1. Dependence of parameter \(\Psi\) on the non-dimesional vibrational temperature.

Influence of energy saved in the vibrational degrees of freedom on the flame normal velocity

Fig. 1. The normal flame velocity dependence on the non-dimensional vibrational temperature (methane-air mixture)

\[ \Phi = 0.7 \]

Evaluation of the vibrational temperature range - \( T_V \approx 3100 \, ^\circ K \), \( \zeta_V \approx 0.56 \).

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FUTURE WORK
LASER + DIRECT CURRENT DISCHARGE (P=1 atm, T=300 K)

\[ n_{O_2^+} = 1.02 \cdot 10^{23} \text{ m}^{-3}, n_{N_2^+} = 4.08 \cdot 10^{20} \text{ m}^{-3}, n_e = 1.024 \cdot 10^{23} \text{ m}^{-3} \]

Remote Power Delivery for Plasma Assisted Combustion

Guiding microwave

Hybrid schemes:

fs laser + Direct Current discharge

Fig. 1. The temporal evolution of excited species of nitrogen.

Fig. 2. Temporal evolution of excited components on the filament axis and on the boundary of the filament (at t=50 ns the DC discharge energy input starts).
Ignition by the combined discharges

LASER PULSE TAILORED BY THE DIRECT CURRENT DISCHARGE

Fig. 1. Temporal evolution of charged species on the filament axis.

Fig. 2. Temporal evolution of methyl and hydrogen on the filament axis.
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FUTURE WORK
Influence of electromagnetic field pulsations on the combustion processes

Influence of turbulent pulsations of neutral and charged components on plasma parameters

Additional mechanism of the plasma ionization equilibrium disturbance when the initial plasma state is an equilibrium state.
Analysis of turbulent pulsations influence

Pulsations of the electron component are controlled by the pulsations of the electron generation source:

$$R_e = \nu_i n_e - \nu_a n_e - k_{ei} n_e n_+ + k^* n_- n^*$$

plasma quasineutrality

$$n'_e + n'_- = n'_+, \quad n'^* = n' = 0$$

$$\tilde{R}_e = \nu_i \tilde{n}_e + \beta_e \tilde{T}_e \tilde{n}_e - \nu_a \tilde{n}_e - \beta_a \tilde{T}_e \tilde{n}_e - \alpha_{ei} \tilde{n}_+ \tilde{n}_+ - \beta_{ei} \tilde{n}_+ \tilde{T}_e \tilde{n}_+ - \beta_{ei} \tilde{n}_- \tilde{T}_e \tilde{n}_+ - \alpha_{ei} n_e n_+ -$$

$$- \beta_{ei} \tilde{T}_e \tilde{n}_+ n_+ + k^* \tilde{n}^* \tilde{n}_-$$

Turbulent pulsations of electron component have a local isotropic structure [1]

$$\tilde{R}_e = (\nu_i - \nu_a) \tilde{n}_e + (\beta_e - \beta_a) \tilde{T}_e \tilde{n}_e \tilde{T}_e = \alpha_{ei} \tilde{n}_+ \tilde{n}_+ - \beta_{ei} \tilde{n}_+ \tilde{T}_e \tilde{n}_+ - \beta_{ei} \tilde{n}_- \tilde{T}_e \tilde{n}_+ - \alpha_{ei} n_e n_+ + \alpha^* \tilde{n}^* \tilde{n}_-$$

$$\beta_a = \frac{d\nu_a}{dT_e}, \quad \beta_e = \frac{d\nu_i}{dT_e}, \quad \beta_{ei} = \frac{d\alpha_{ei}}{dT_e}, \quad n'_e, n'_+, T'_e \rightarrow n^0_e, n^0_+, T^0_e$$

Influence of turbulent pulsations of charged components on plasma parameters

\[ T_e \cong 1 \text{ eV} \]

\[ T_e \geq 2 \text{ eV} \]

\[ T_e \cong 1.9 \text{ eV} \]

\( \frac{T_e^0}{T_e} = 5\% \)

Fig.1. Dependence of \( R_e \) on the pulsation level of the electron temperature.
Dependence on pressure

Fig. 1. The electron temperature dependence on pressure (transitional mode of the discharge)

Fig. 2. The electron temperature pulsations level dependence on pressure (transitional mode of the discharge)

One of the reasons of the discharge energy increase at the high intensity of turbulent pulsations?
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FOURIER ANALYSIS OF THE TURBULENT SPECTRA

\[ v_l = \sum_k v_l(k, t) \cdot e^{i\mathbf{k} \cdot \mathbf{x}} \]

\[ p = \sum_k p(k, t) \cdot e^{i\mathbf{k} \cdot \mathbf{x}} \]

Incompressible fluid \quad Non-solenoidal external force

\[ \frac{\partial v_l(k, t)}{\partial t} = -i \cdot P_{lm} \cdot k_j \sum_q v_j(q, t) \cdot v_m(k - q, t) - k^2 \cdot \nu \cdot v_l(q, t) + F_l(k, t) + \alpha \cdot v_l(k, t) \]

\[ P_{lm} = \delta_{lm} - k_1 k_m k^{-2} \]

\[ F_j^{\text{Lorentz}} = F_j^1 + F_j^2 = \sum_k F_j(k, t) \cdot e^{i\mathbf{k} \cdot \mathbf{x}} + \alpha \sum_k v_j(k, t) \cdot e^{i\mathbf{k} \cdot \mathbf{x}} \]

CASCADE PROCESS

Fig. 1. The turbulent spectra at $t=2.5$. Solenoidal external force at different harmonics.

Fig. 2. Influence of the non-solenoidality of the external force on the turbulent spectra.
CONTINUITY EQUATION

\[ \frac{\partial \rho(\mathbf{k}, t)}{\partial t} + 2i k_i \sum_q \rho(q, t) v_i(k - q, t) = 0 \]

\[ \sum_q \frac{\partial v_j(k, t)}{\partial t} \cdot \rho(k - q, t) + i \cdot k_n \sum_q v_n(q, t) \cdot v_j(k - q, t) \cdot \rho(k - q, t) = \]

\[ = -ik_j \cdot \mathbf{p}(\mathbf{k}, t) - k^2 \cdot v \cdot v_j(q, t) + F_i(k, t) + \alpha \cdot v_j(k, t) \]

\[ \sum_q \frac{\partial T(q, t)}{\partial t} \cdot \rho(k - q, t) + i \cdot k_n \sum_q v_n(q, t) \cdot T(k - q, t) \cdot \rho(k - q, t) = \]

\[ = \frac{\lambda k^2}{c_V} \cdot T(k, t) + F(k, t) \]
FUTURE WORK

1. Compressibility effects on the turbulent cascade process with external force.
2. Influence of turbulence generated by the combined discharges on the chemical reaction rates.
3. Study of the swirling combustion assisted by plasma.
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