Experimental and numerical investigations of flame pattern formations in a radial microchannel

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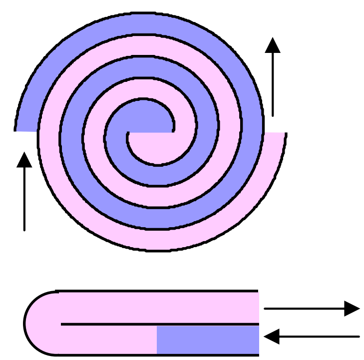
Micro combustion

Investigation of near-limit flame

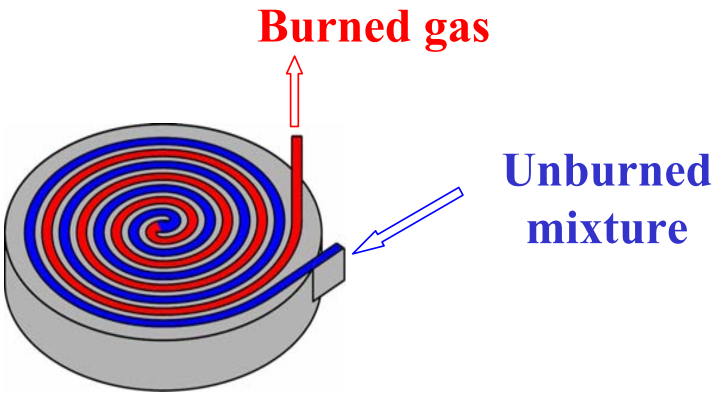
Lean burn

application to microsystems

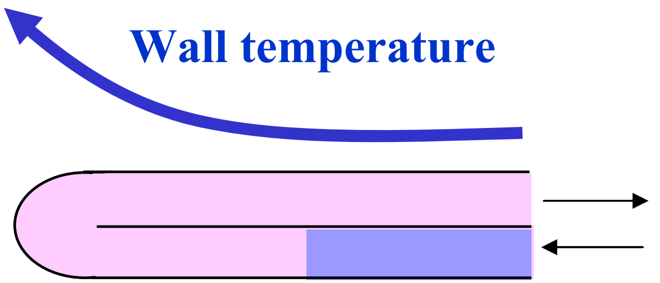
Heat regeneration



Heat regeneration



"Swiss-roll" micro-combustor



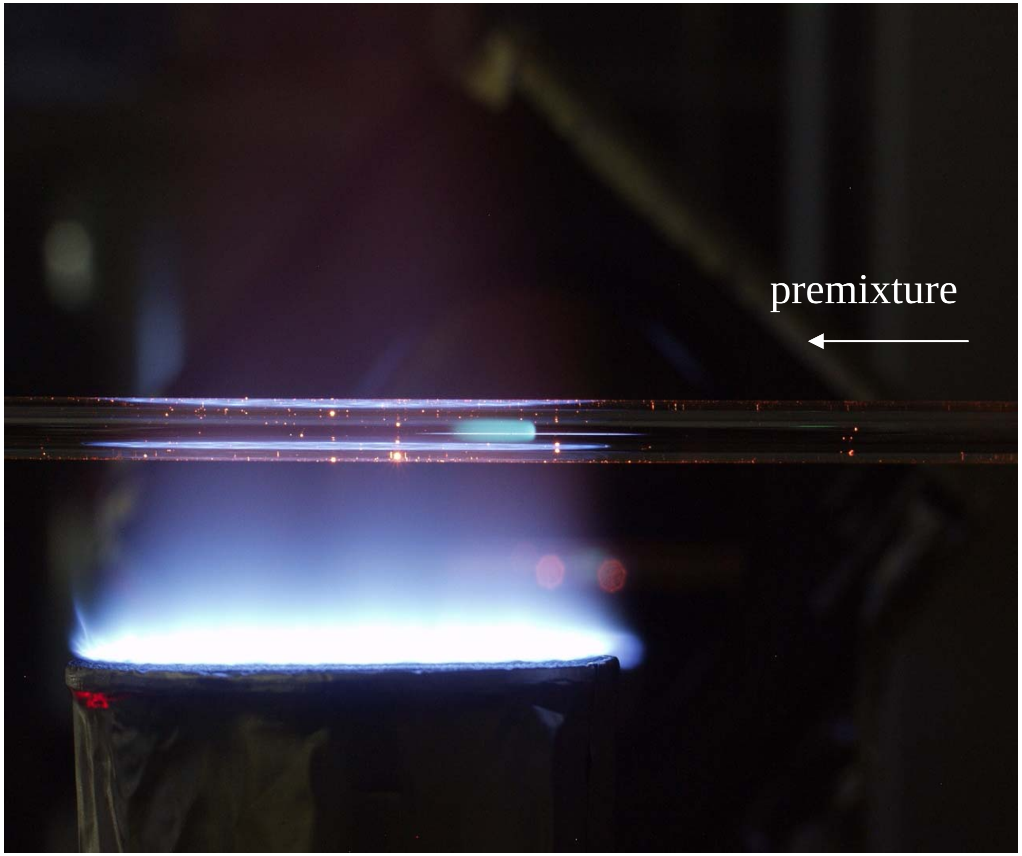
Advanced fundamental problem:
Flame propagation in small channel with temperature gradient in the wall

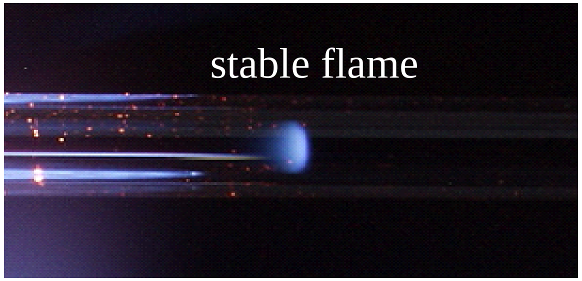
Previous study

Simplest configuration – straight quartz tube with wall temperature gradient

tube diameter < critical diameter

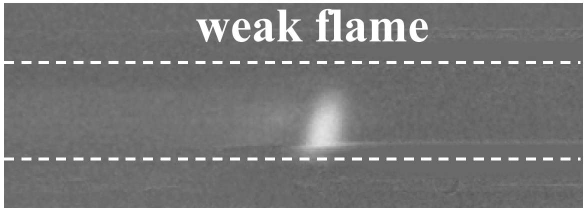
FREI - Flames with Repetitive Extinction and Ignition





Large gas velocity

Moderate velocity



Small velocities

Nonuniform flow in the channel with wall temperature gradient

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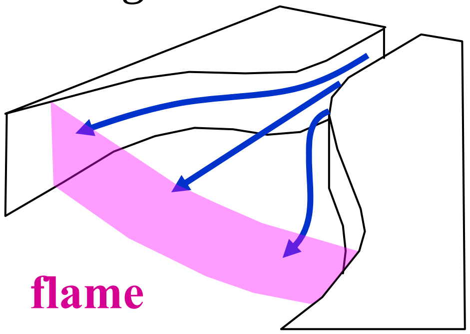
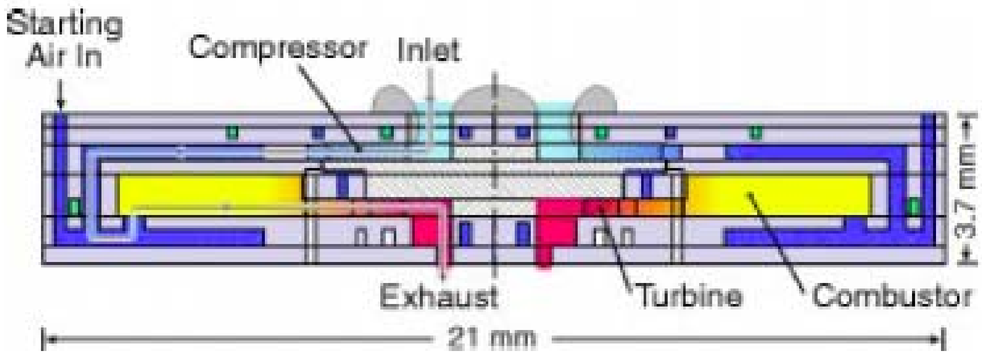
Flame stabilization in divergence flow behind channel narrowing



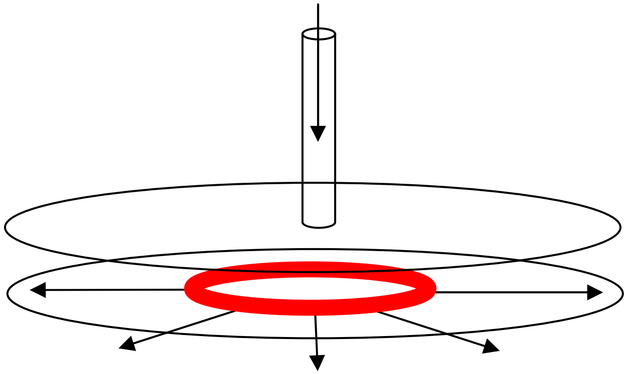
Example:

In MIT gas turbine combustion occurs in radial flow



Topical question

Description of flame propagation and stabilization in the divergence radial flow in microchannel with temperature gradient



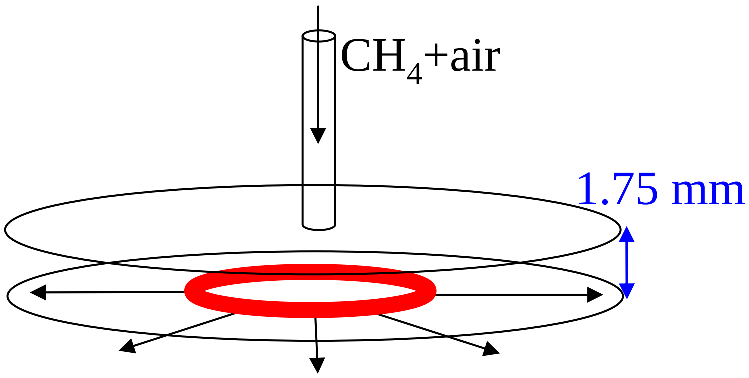
Radial flow between parallel disks

Objectives

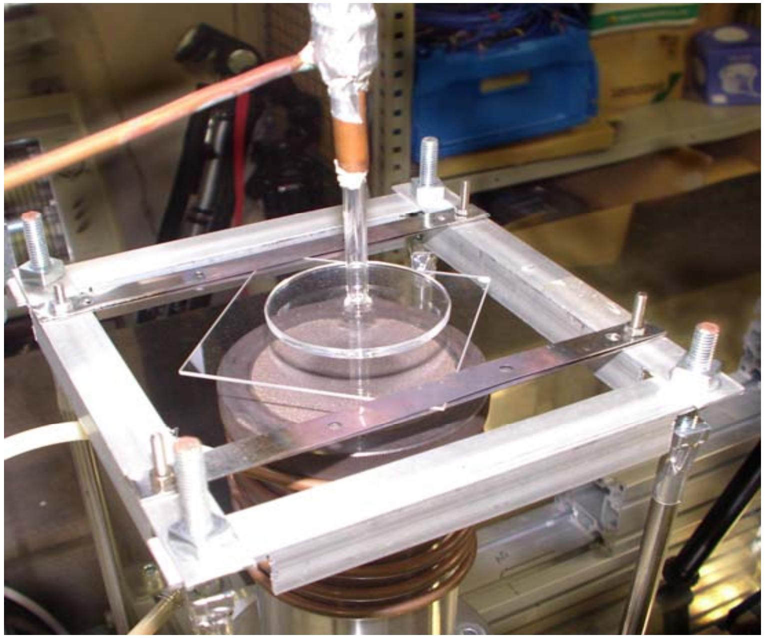
1. To investigate flame pattern formation in heated microchannel with radial flow, especially in the case corresponding to FREI phenomena.
2. How does gas flow rate affect on the flame pattern?
3. How does mixture content affect on the flame pattern?
4. To try reproduce experimentally observed patterns within frame of simple thermo-diffusion model. This modeling may be considered as preceding study before modeling with detailed chemistry and real flow characteristics to outline flame patterns diagram.

Experiments in radial channel with temperature gradient in the wall

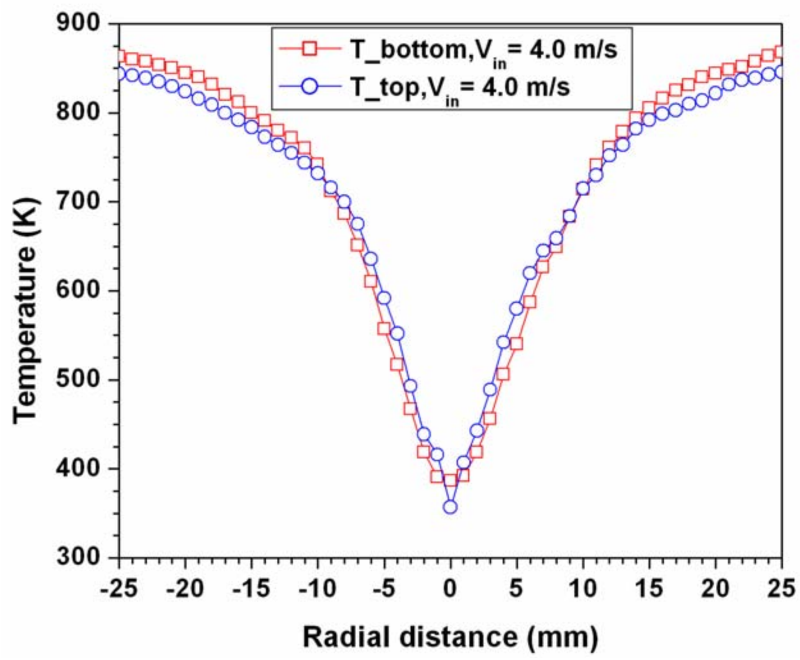
№6



Scheme of the experiments



Experimental installation

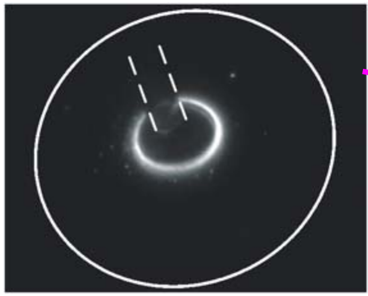


Flame recording:
image-intensified high-speed digital camera

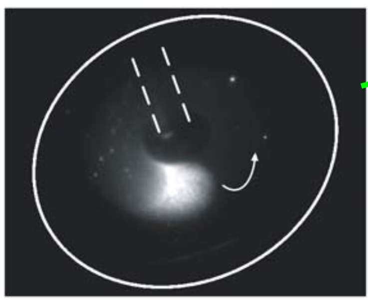
Flame pattern regime diagram

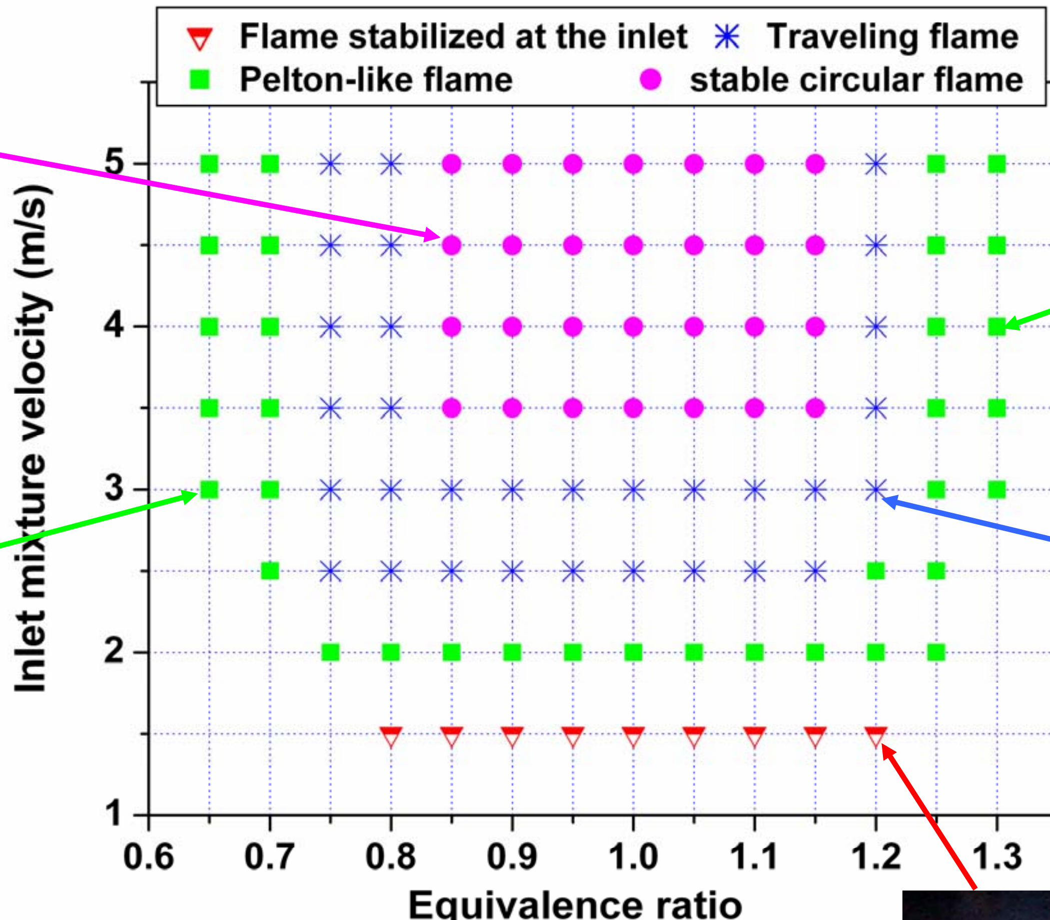
№7

Stable circular flame



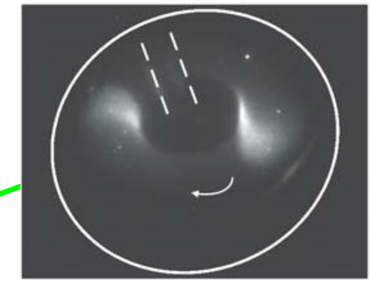
Single Pelton-wheel-like flame

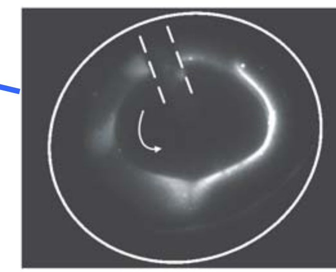




Regime diagram

Double Pelton-wheel-like flame





Traveling flame

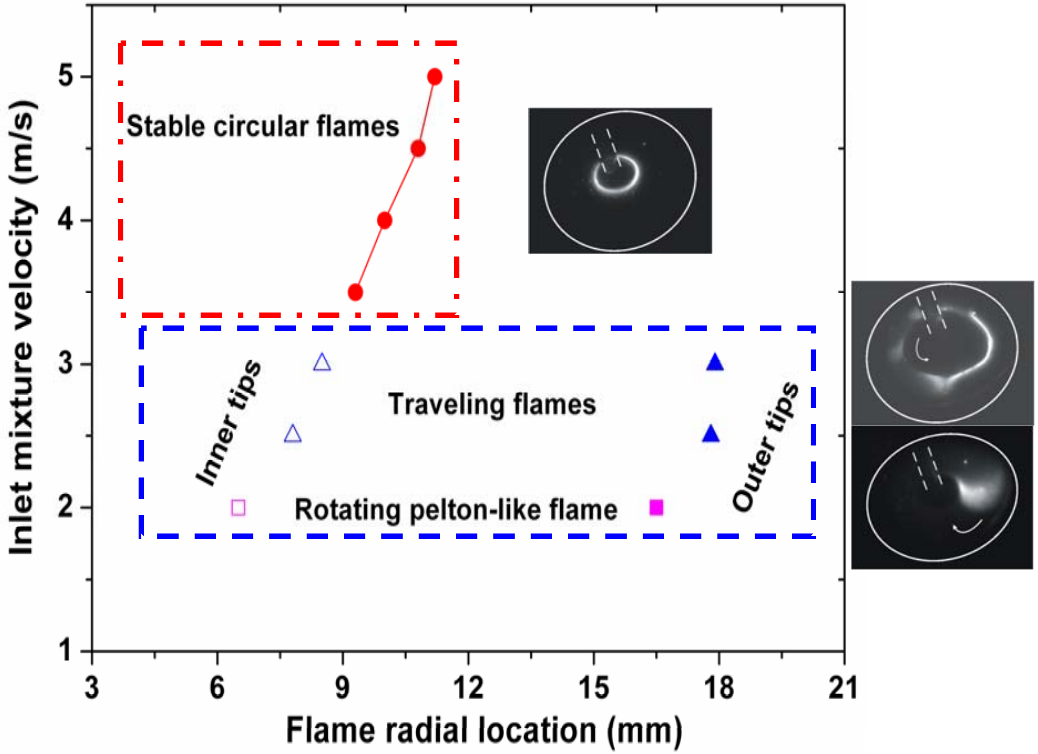
Cup-like flame (Side view)

Flame radial location vs inlet mixture velocity

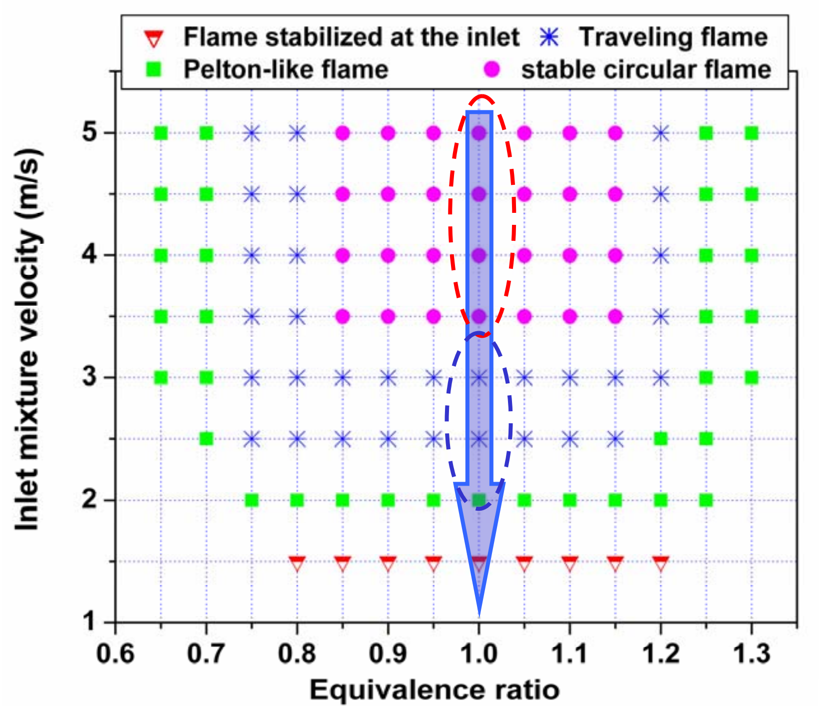
stoichiometric CH_4 –air mixture

№8

Experimental results



Regime diagram



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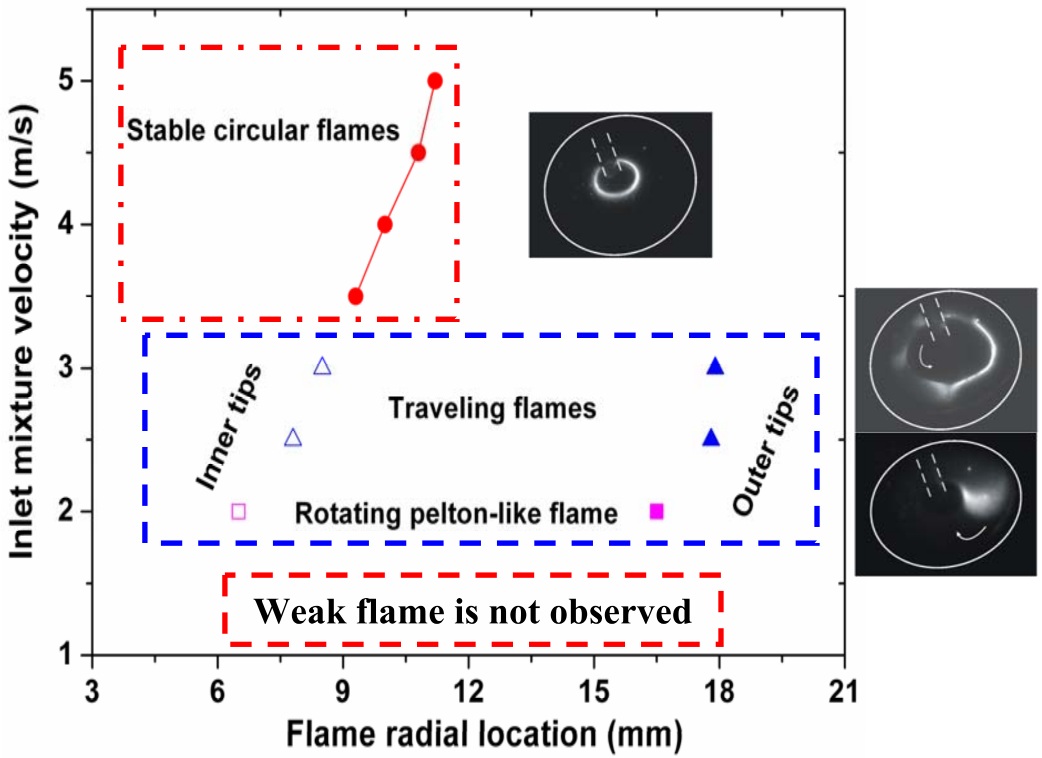
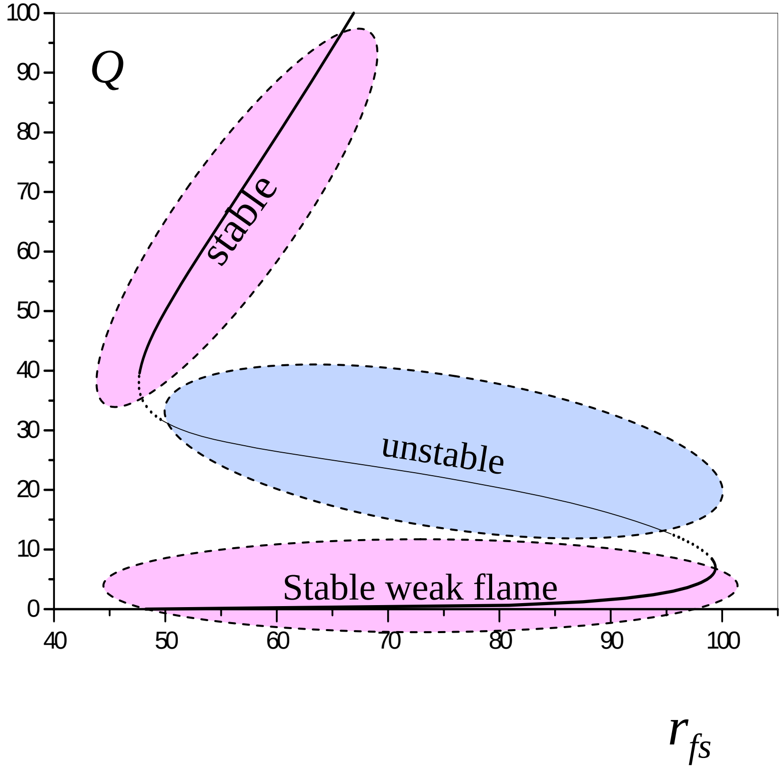
Flame radial location vs inlet mixture velocity stoichiometric CH_4–air mixture

Experimental results



Linear stability analysis of stationary solutions



2D thermo-diffusion model

№10

Heat exchange with wall

Heat release

Energy conservation:

$$\rho \ c_p \left(\frac{\partial T}{\partial t} + \left(\vec{V} \cdot \nabla \right) T \right) = \lambda \Delta T - \frac{2\alpha}{d}(T - \theta) + QW(Y_o, Y_f, T) \qquad (1)$$

Species conservation:

Oxidizer

$$\frac{\partial(\rho Y_o)}{\partial t} + \left(\vec{V} \cdot \nabla \right)(\rho Y_o) = D\Delta(\rho Y_o) - \nu W(Y_o, Y_f, T) \qquad (2)$$

Fuel

$$\frac{\partial(\rho Y_f)}{\partial t} + \left(\vec{V} \cdot \nabla \right)(\rho Y_f) = D\Delta(\rho Y_f) - W(Y_o, Y_f, T) \qquad (3)$$

Chemical Reaction Rate

$$W(Y_o, Y_f, T) = \rho A Y_o^a Y_f^b \exp\left(-E/RT \right) \qquad (4)$$

Boundary conditions and grid

№11

Computation domain: $r_0 < r < R_0$, $r_0 = 2$ mm, $R_0 = 40$ mm

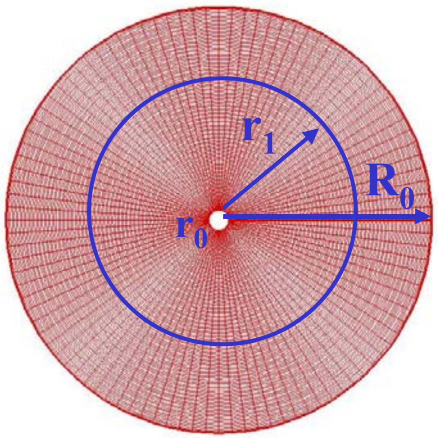
Non-uniform Grid: 1500 (radial points) × 350 (angular points) nodes.

Wall temperature profile:

$$r_0 < r < r_1: \qquad \theta = T_0 + (\Theta - T_0)\frac{r - r_0}{r_1 - r_0}$$

$$r_1 < r < R_0: \qquad \theta = \Theta$$

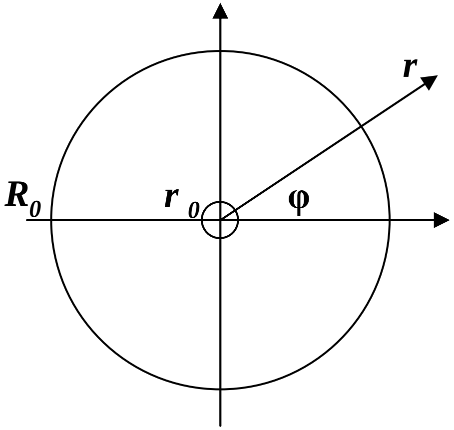
$r_1 = 25$ mm, $\Theta = 900$ K



Boundary conditions for the inlet and exit:

at the inlet ($r = r_0$): $T = T_0,\ Y_f = Y_f^{\,0},\ Y_o = Y_o^{\,0}$

at the exit ($r = R_0$): $\nabla T = \nabla Y_f = \nabla Y_o = 0$



Computation scheme: implicit finite–difference scheme

Results of numerical simulations

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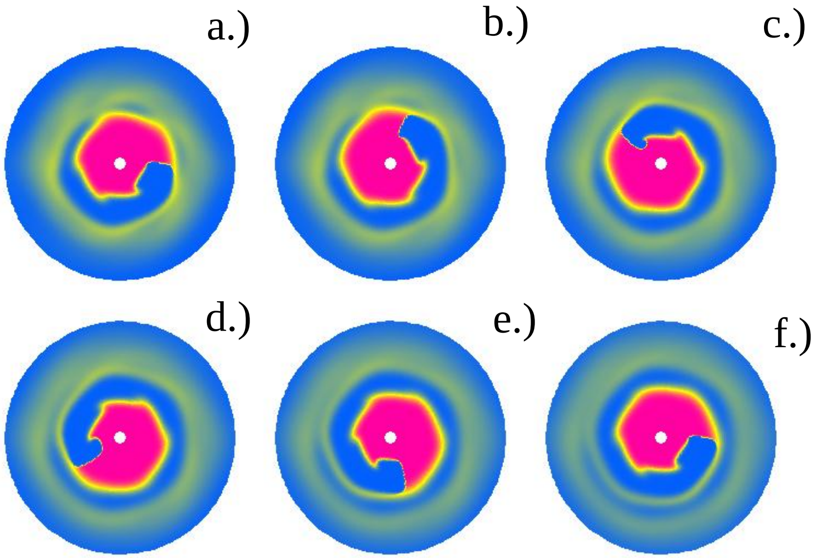
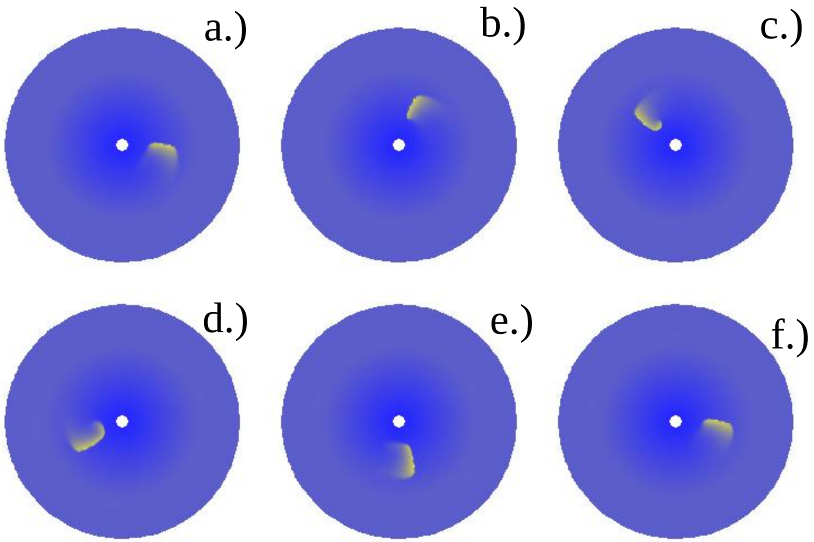


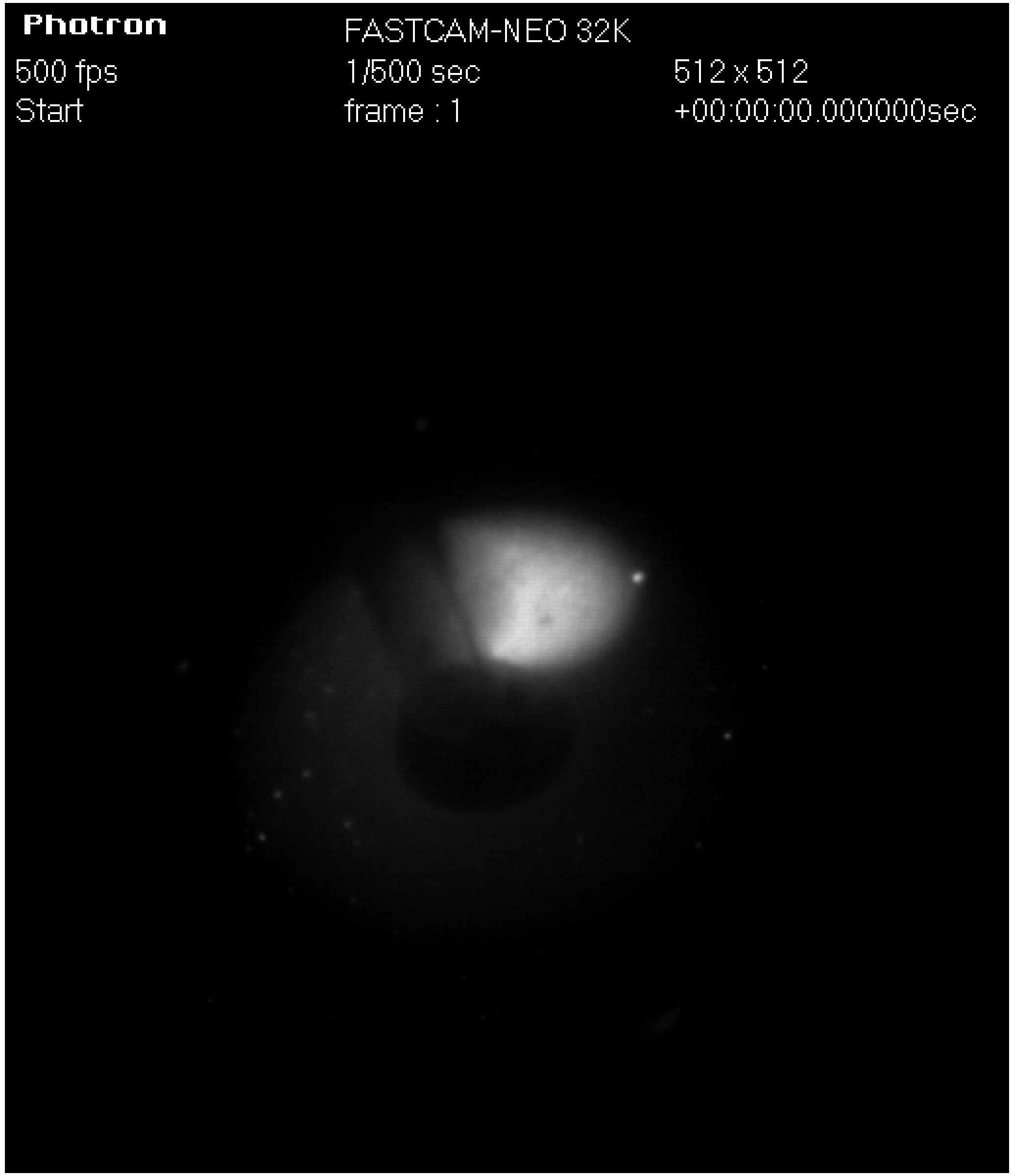
Shade graded fuel concentration distribution. Pink color – initial fuel concentration. Blue domain –zero fuel concentration



Shade graded temperature distributions in successive moments. Blue domain: $T_s < 900$ K

Time steps is 0.017 s, G = 0.001 m^2/s (middle part of S-shaped curve)

$G = V_0 r_0$, V_0 : inlet mixture velocity, r_0: radius of delivery tube.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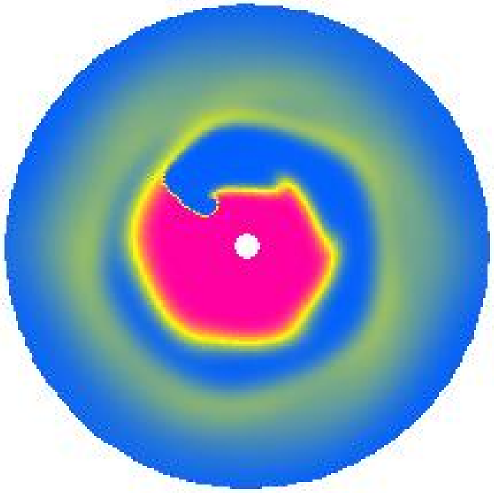
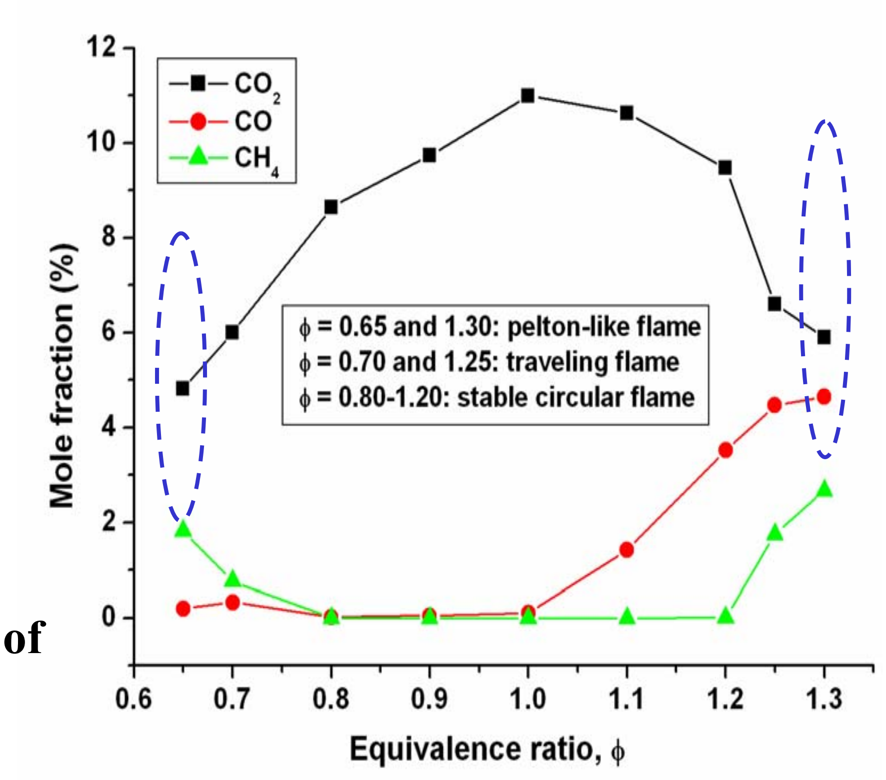
Combustion completeness



Fuel concentration distribution of single petal flame.



Combustion products vs equivalence ratio

The incompleteness of combustion was found just in the region corresponding to nonstationary regimes.

Two petals configuration

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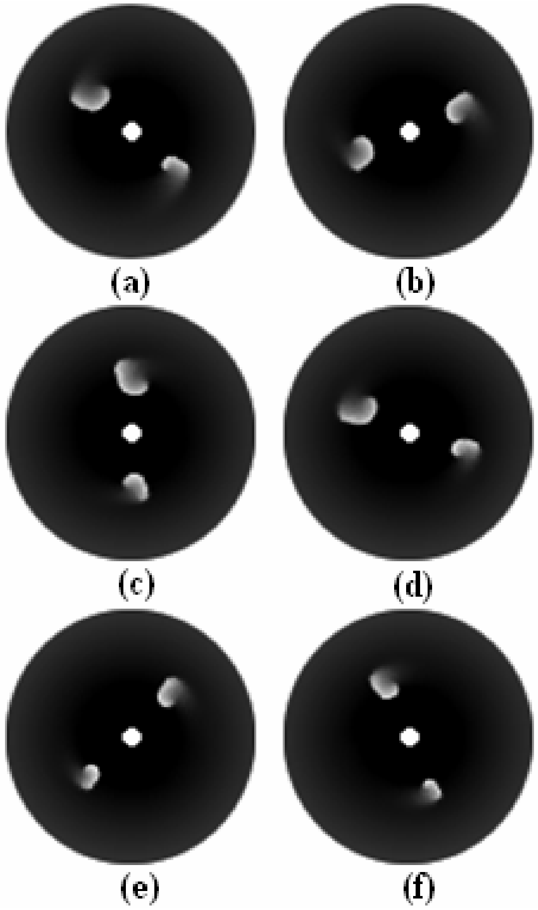
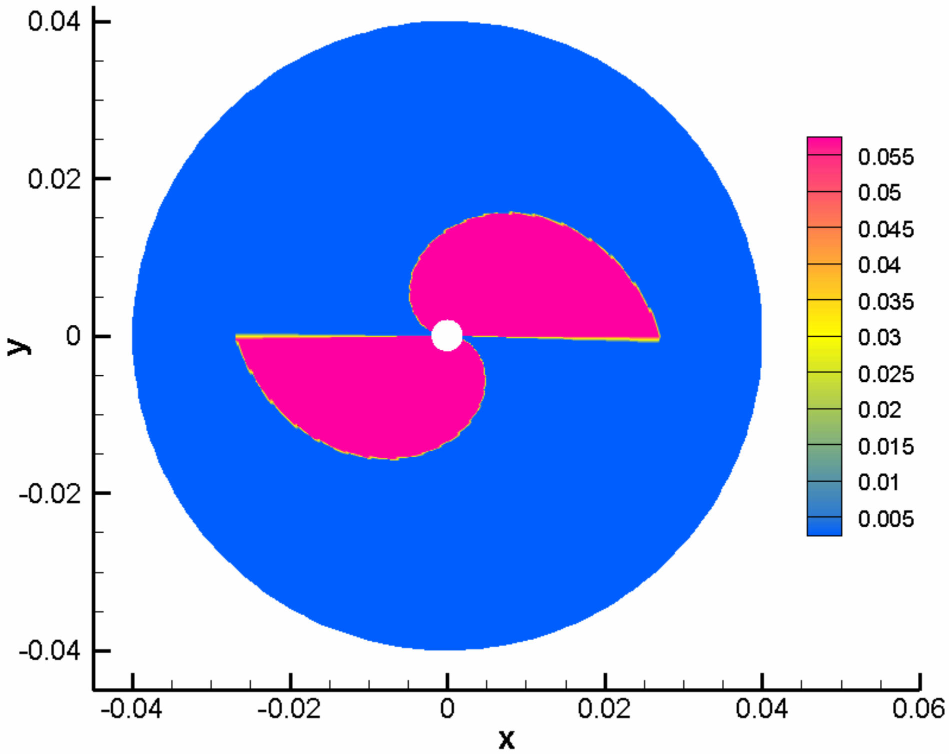
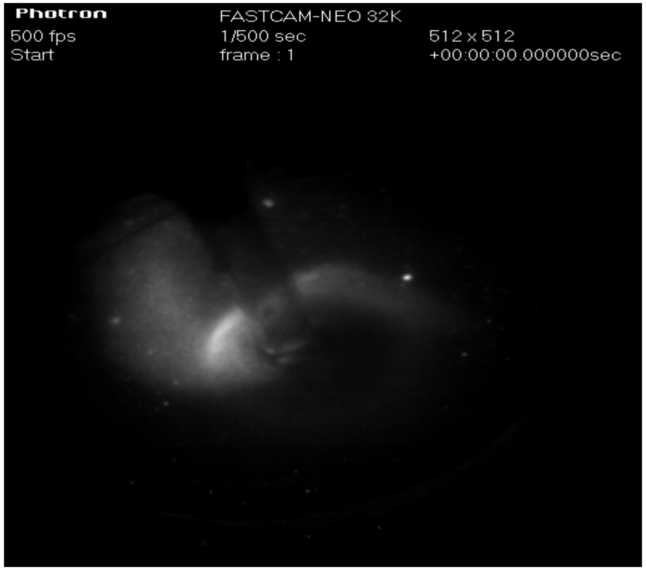


Temperature distributions: G = 0.0015 m^2/s (middle part of S-shaped curve), Black domain: Ts < 900 K

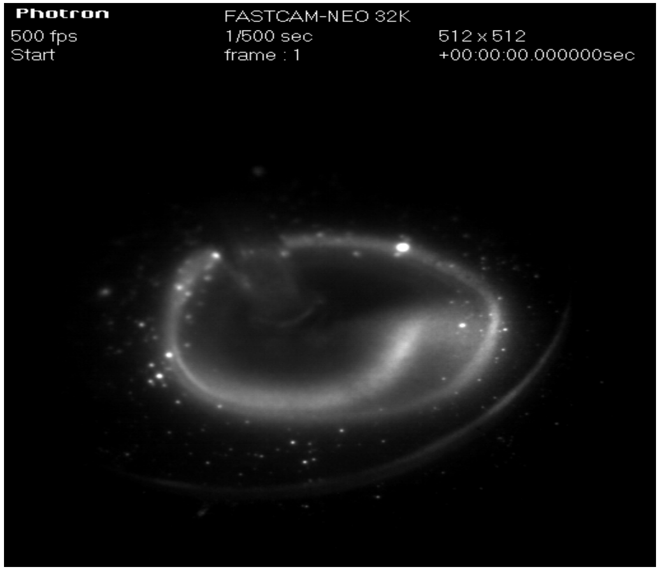


Evolution of fuel mass fraction during formation of two petal flame

Some other flame patterns



Tri-branched flame



Spiral-like flame

With increase of the gap between two quartz disks new patterns appears.

Is the thermo-diffusion model described these pattern?

The leading points of these structures move with tangential velocity that in 3-4 times exceeds burning velocity. What is the structure of the leading point?

Conclusions

- Different flame patterns were found in radial microchannel with temperature gradient in the wall and regime diagram was plotted.

- The existence of lower limit of gas flow rate corresponding to stable regime was confirmed by experiment.

- The structures with single and double wheels of Pelton-turbine-like flames were numerically reproduced by a simple thermo-diffusion model with global one-step chemistry.

- The mechanism of leakage of unburned gas at moderate flow rates was clarified.