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To cite this version:

Hugo Chouraqui, Christian Chauveau, Philippe Dagaut, Guillaume Dayma, Fabien Halter. Experimental and numerical studies of the influence of diluent on characteristic micro-scale combustion flame behaviour. 37th International Symposium on Combustion, Jul 2018, Dublin, Ireland. 10.13140/RG.2.2.25682.81608 . hal-01848556

HAL Id: hal-01848556

https://hal.science/hal-01848556

Submitted on 24 Jul 2018

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Experimental and numerical studies of the influence of diluent on characteristic micro-scale combustion flame behaviour

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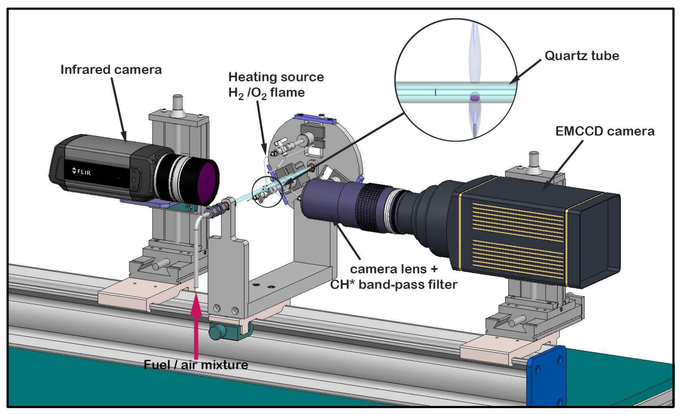
1. Goal of the study

- Growing need to improve knowledge in the field of small-scale combustion and take advantage of high energy density of fuel [1] in different applications such as portable power device [2], micro-satellite thrusters [3], heat sources [4].
- Previous studies have been done with fuel/air mixtures. Combustion of a CH_4/O_2 mixture with different diluents can improve the understanding of flame behaviour in micro-scale reactor by changing physical properties of the environment. Hence, be able to point out physico-chemical properties that play an important role in micro-scale combustion.

2. Experimental set-up

- Cylindrical quartz tube heated by 3 hydrogen/oxygen blowtorches.
- The temperature profile on the outer side is measured by a infrared camera A655sc.
- A spectroscopy EMCCD camera ProEM 1600 with a CH* band-pass filter (20BPF1_430) is used to detect the flame positions.
- CH_4/diluent mixture is supplied in a 1.85 mm internal diameter reactor. (Quenching distance of CH_4/air is 2.50 mm)



Schematic of the data acquisition system and micro-reactor [6]

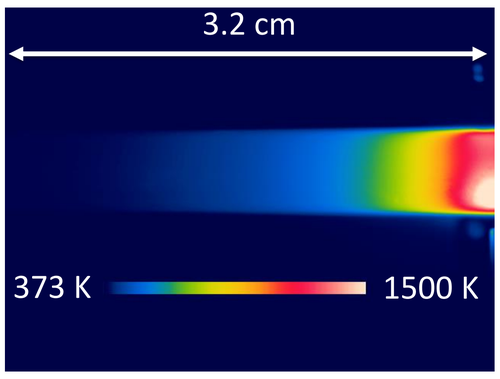
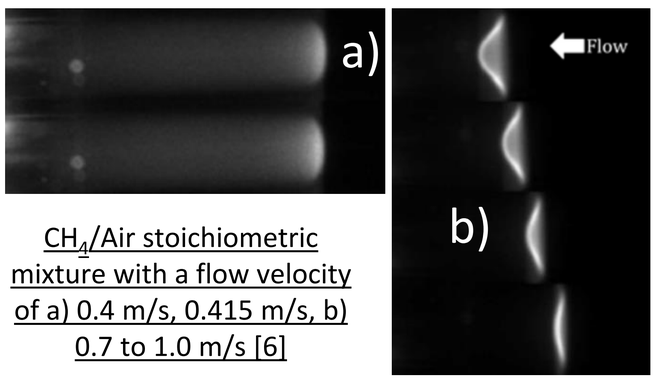


Image from FLIR camera of the external temperature for a stoichiometric mixture of CH_4/air, a flow velocity of 0.7 m/s, in a 1.85 mm internal diameter tube

3. Different flame behaviour

a) **FREI** (Flame with Repetitive Extinction and Ignition): the ignition occurs downstream in high temperature region and extinction occurs upstream in low temperature region.

b) **Stable flame**: flames with no relative motion with the reactor wall.



CH_4/Air stoichiometric mixture with a flow velocity of a) 0.4 m/s, 0.415 m/s, b) 0.7 to 1.0 m/s [6]

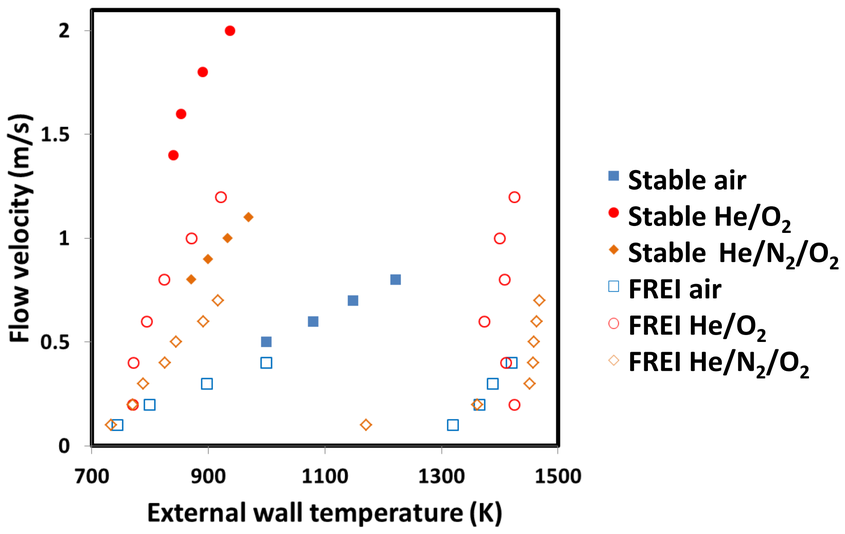
4. Experimental and numerical results

Diluent	O_2	He	N_2
Air	20%	0%	80%
$He/N_2/O_2$	21.18%	39.20%	39.62%
He/O_2	21.68%	78.32%	0%

Compositions of diluents used in this study in molar fraction

Diluent	Laminar burning velocity (cm/s)	Adiabatic flame temperature (K)
Air	30	2221
$He/N_2/O_2$	61	2367
He/O_2	119	2519

Laminar burning velocity and adiabatic flame temperature of a stoichiometric mixture CH_4/diluent

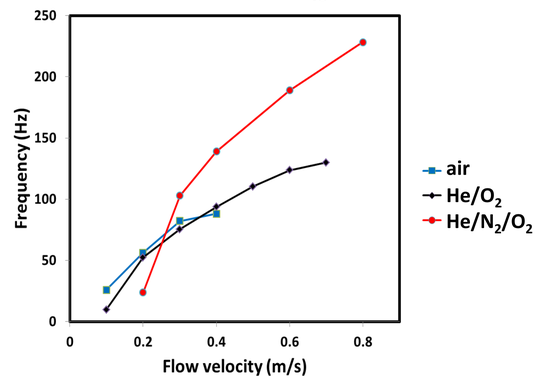


Flame position defined at the wall temperature as a function of the mixture flow velocity

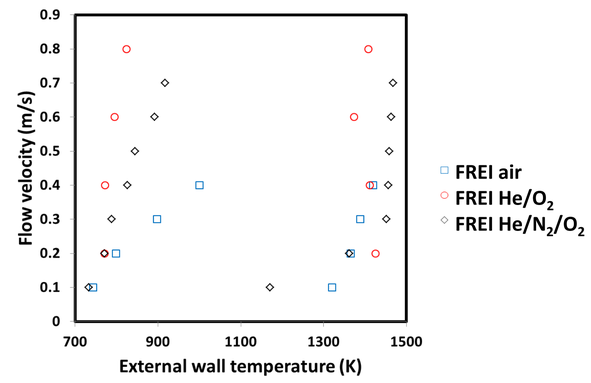
[1] A. C. Fernandez-Pello, "Micropower generation using combustion: Issues and approaches," *Proceedings of the Combustion Institute*, vol. 29, no. 1, pp. 883–899, Jan. 2002.
[2] K. H. Lee and O. C. Kwon, "Studies on a heat-recirculating microemitter for a micro thermophotovoltaic system," *Combustion and Flame*, vol. 153, no. 1, pp. 161–172, Apr. 2008.
[3] P. Galie, B. Xu, and Y. Ju, "Kinetic Enhancement of Mesoscale Combustion by Using a Novel Nested Doll Combustor," 2007.
[4] T. A. Wierzbicki, I. C. Lee, and A. K. Gupta, "Rh assisted catalytic oxidation of jet fuel surrogates in a meso-scale combustor," *Applied Energy*, vol. 145, pp. 1–7, May 2015.
[5] A. Di Stazio, "Caractérisation expérimentale de la dynamique de la combustion à micro-échelle," Thesis, Orléans, 2016.

4.1. FREI

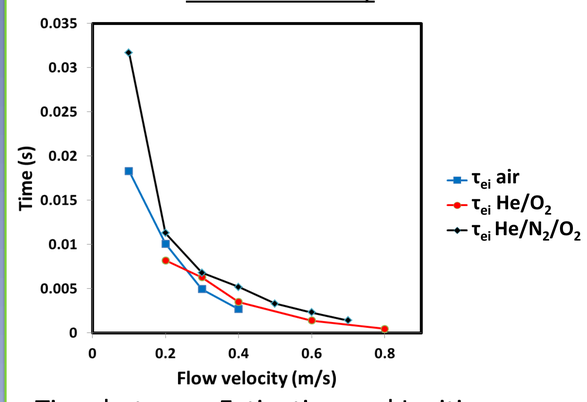
- For a given fuel/oxydant mixture: when the flow **velocity increases → frequency increases**.
- For a given flow velocity: when the flame **propagation speed of a mixture A is bigger than a mixture B → τ_{ie} in A is smaller than in B.**



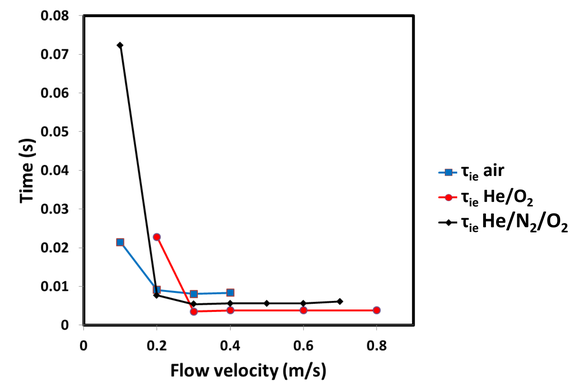
Frequency of FREI variation as a function of inlet velocity



Flame position defined as the external wall temperature as a function of flow velocity



Time between Extinction and Ignition



Time between Ignition and Extinction

4.2. Stable flame

Solution methods and solvers

- Steady state simulation
- The Stiff Chemistry Solver of ANSYS Fluent is used to solve the reactive flow
- PISO method for velocity-pressure coupling is used to solve the discretized form of the Navier-Stokes system
- A second order upwind spatial discretization is used and a least squares cell-based method for the evaluation of gradients

Geometry/ Meshing:

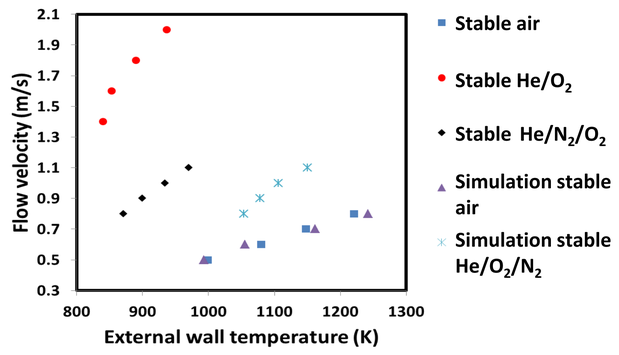
- A 2D-axisymmetric geometry
- Total length of 10 cm, inner diameter of 0.925 mm, external diameter of 3.0 mm
- Quadrilateral elements
- 25 elements to mesh the inner radius, 20 elements for the wall. A constant size mesh of 33 µm where the temperature is the highest, and a progressively bigger size toward the coldest region → 22500 elements for all the domain

Boundary conditions:

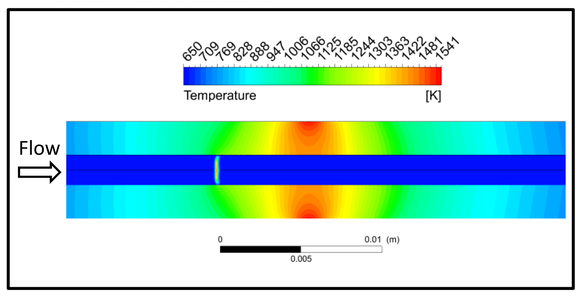
- Experimental external wall temperature is averaged and used as boundary condition
- A velocity inlet boundary condition is applied on the left part of the geometry, and a pressure outlet boundary condition (1 atm) on the right part

Models:

- A laminar viscous model
- The effect of enthalpy transport due to species diffusion in the energy equation
- Ideal gas
- Chemical, transport and thermodynamics properties are computed with the GRI-Mech 3.0 scheme



Stable flame position defined at the external wall temperature as a function of the mixture flow velocity



Wall temperature and flame front visualisation (CH* molar fraction) of the simulation of a CH_4/air mixture with an inlet velocity of 0.6 m/s

- For a given fuel/oxydant mixture: **flow velocity increases → the flame front goes toward colder wall reactor region**
- For a given flow velocity: when the **adiabatic flame temperature of a mixture A is bigger than a mixture B →** the **front flame is located to colder wall reactor region.**

5. Conclusions

- All characteristic flame behaviours are conserved with different diluents studied
- The increase in He molar fraction in diluent →
  a. FREI velocity domains increases
  b. Extinction is located to colder wall region
  c. Stable flame is located to colder wall region
- Flame/wall thermal interaction clearly identified experimentally with stable flames but not numerically

Acknowledgements

HC thanks the Ministry of Research en Higher Education (MESRI) for a PhD grant. Support from the CAPRYSSES project (ANR- 11-LABX-006–01) funded by ANR through the PIA (Programme d'Investissement d'Avenir) is gratefully acknowledged.