Development of stability diagrams of flame in diluted combustion

SEZGIN Erdinç, PESENTI Barbara, LUPANT Delphine and LYBAERT Paul

Faculté Polytechnique de Mons, Thermal Engineering & Combustion Unit, Mons, Belgium

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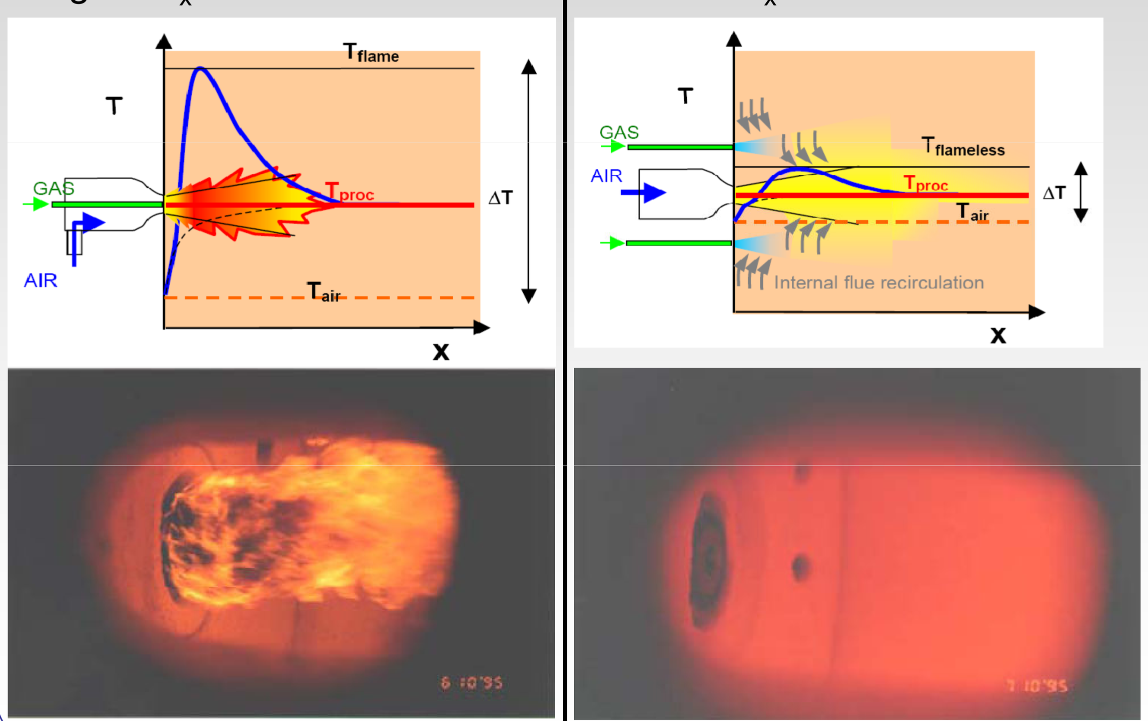
Background

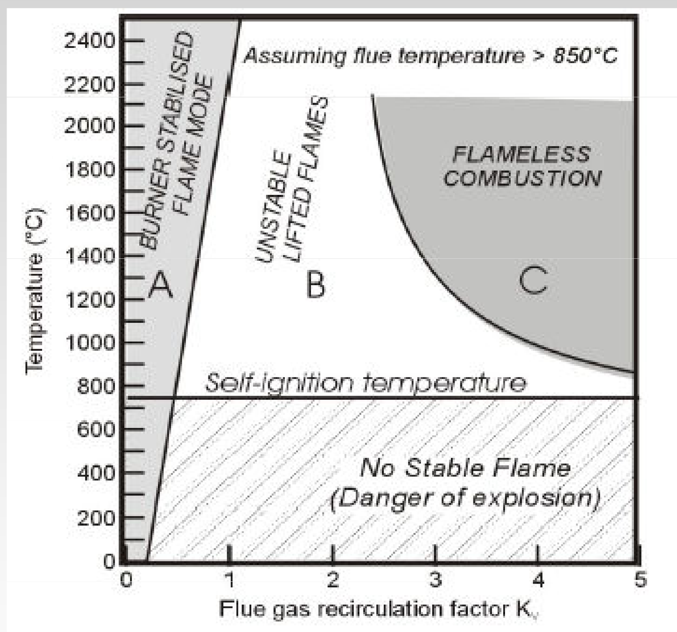
$$K_V = \frac{\dot{M}_{recirculation\ gas}}{\dot{M}_{fuel} + \dot{M}_{Air}}$$

Conventional Flame	Diluted combustion
- Flame front	- Volume combustion
- sharp gradient	- Homogeneous
- High NO_x emission	- Low NO_x emission



1. source : A. Milani, A. Saponaro: "Diluted Combustion Technologies", IFRF Combustion Journal, Article number 200101.)

→ Recirculation ratio (K_V) higher than a threshold



- Diagrams are often built for the couple methane-air or propane-air
- The temperature to be considered in the diagrams is not always clearly defined

Objectives

→ Collect experimental data to characterize combustion features of various fuel blends in diluted combustion conditions

- At first with CH_4 (reference fuel) : THIS WORK
- Fuels blends with industrial interest (mixture of CH_4, H_2, CO)

Combustion regime will be characterized by means

- of unburned content in flue gas,
- flue gas temperature,
- NOX emissions,
- intensity of the chemiluminescence emission of OH radical in the reaction zone.

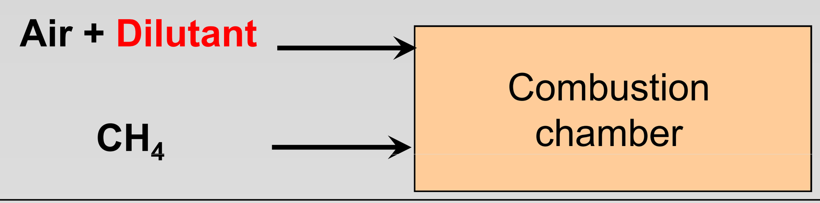
Operating parameters:

- temperature and O_2 content of the diluted reacting mixture
- Excess of O_2 relatively to the stoichiometric value

Data collected in these series are compared with information available in literature and used as reference values for the study of other fuel mixes and diluting species.

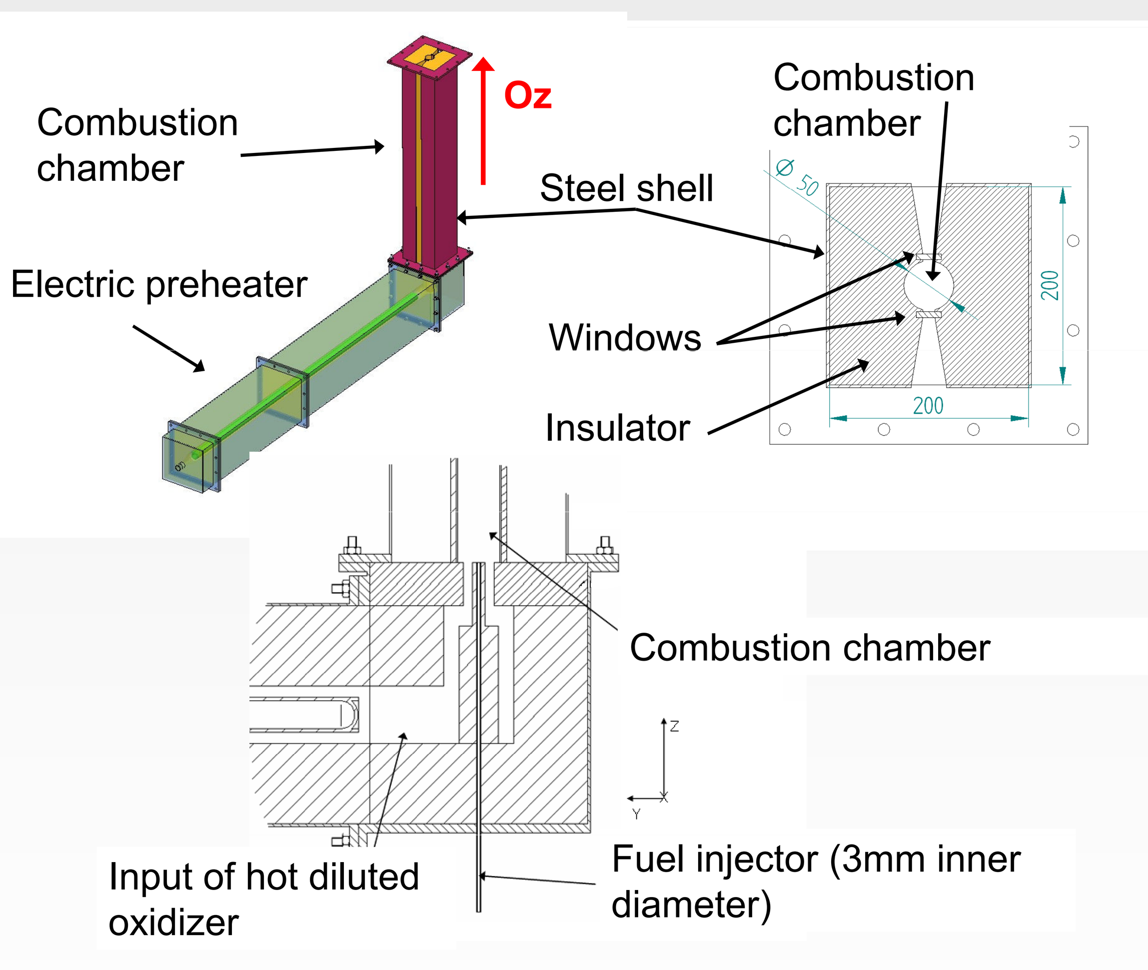
Experimental Device & Measuring equipment

- Cylindrical combustion chamber of 1200mm height and 50 mm diameter
- coflow configuration for injection of fuel & oxidizer
- Insulated
- 2 optical accesses
- electric preheater which allows the heating of the diluted oxidizer up to 1100°C
-mixing unit
-simulate the effect of recirculation by directly injecting the diluting species (N_2) into the oxidizer pipe. The amount of added inert gas (called here the dilutant) determines the dilution level.



Measuring equipment

- Inlet flow rate of reactants : controlled by mass flow meters (O_2, N_2, CH_4)
- Temperature of the diluted oxidizer at the inlet of the combustion chamber via a (standard S)
- Temperature at the exit of the combustion chamber via a fine wire thermocouple (Standard B)
- Chemiluminescence emissions of radical OH, CH and C2 :
- Composition of combustion gases ; the gases are extracted in the chimney, near the temperature measurement point



The dilution is here defined by the dilution factor K_V.

$$K_V = \frac{\dot{M}_{DILUTANT}}{\dot{M}_{fuel} + \dot{M}_{Air}}$$

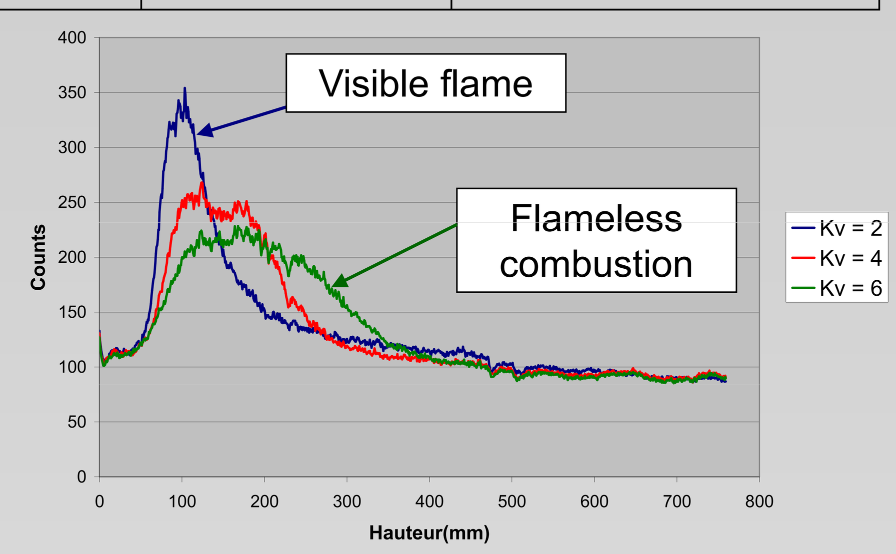
The methane firing rate was 3 kW.

Results & Discussion

Series	O_2 Excess	Dilution K_V	Preheating temp. [°C]
1	0%	2 ; 4 ; 6	1050
2	5%	1 to 5.5	950 -1000 - 1050

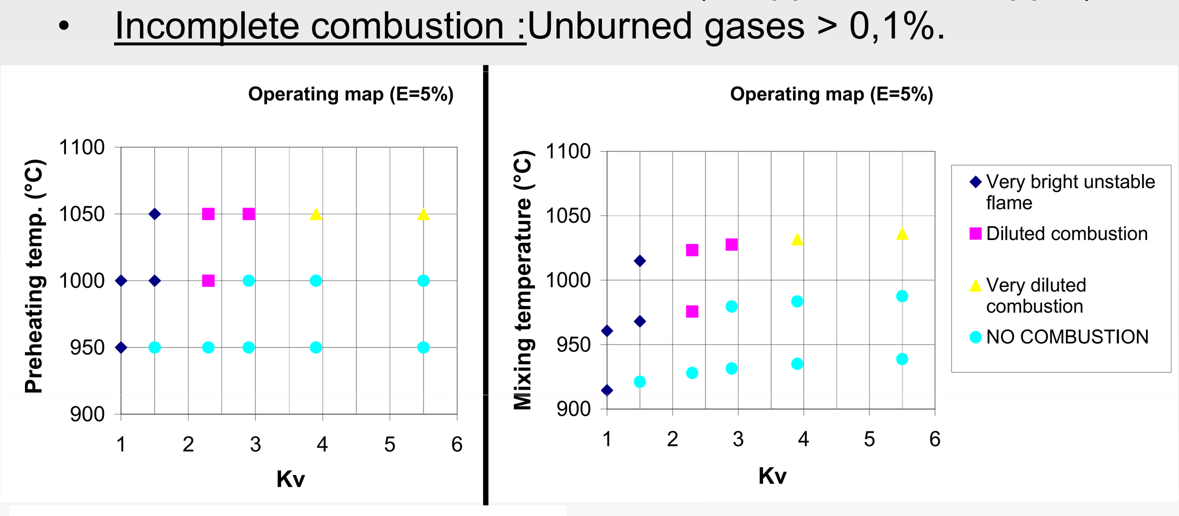
OH emission profile

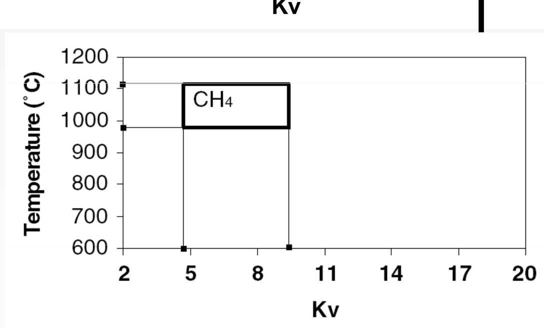
E=0%



4 combustion regimes have been distinguished:

- Very bright unstable flame:
  - highly luminous yellow flame
  - high OH, CH and C2 emission intensity
  - flame position highly unsteady
  - high level of NOX (order of magnitude : 70 ppm)
  - CO and CH4 ≈ 0 at the exit
- Diluted combustion
  - no visible flame
  - OH, CH and C2 emission intensity much lower
  - stable position of the reaction zone
  - NOX emission are low (±20 ppm)
  - CO ≤ 100 ppm
- Very diluted combustion
  - similar to diluted combustion but with increasing CO emission at the outlet (200ppm<CO<400ppm)
- Incomplete combustion :Unburned gases > 0,1%.

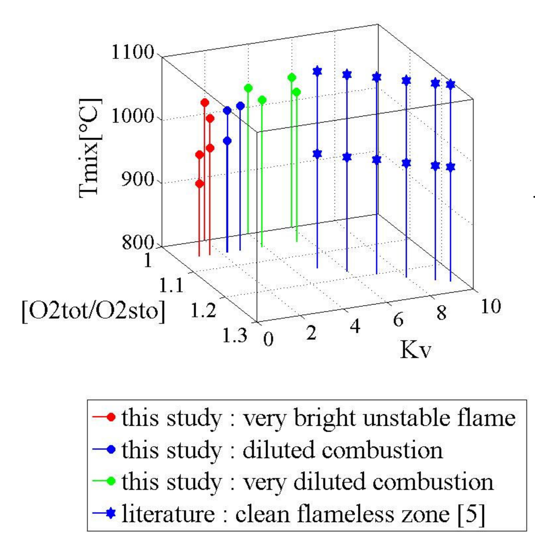




Scientific Literature : Flameless combustion zone is defined:

- CO<50ppm
- NOX<30ppm
- Disappearance of flame

→ Excess of O_2 should be define



$$\frac{\left(\frac{m_{O_2}}{m_{fuel}}\right)}{\left(\frac{m_{O_2}}{m_{fuel}}\right)_{stoic}} = \frac{m_{O_2\,(tot)}}{m_{O_2\,(stoic)}}$$

↘ 3D OPERATING MAP

Numerical Study

Modelling the combustion chamber

- With the COSILAB® code :
  - 1D (axial)
  - by a PLUG FLOW REACTOR (PFR)
  - detailed reaction mechanism (GRI-Mech 3.0) : 53 species and 325 reactions including NOx formation
- With FLUENT ® code :
  - 3D method (CFD)
  - 2 step mechanism (with CO as an intermediate species)
  - NO_x are computed in a post-processing step

		NO_x (ppm, at 3% O2, dry basis)		
Kv	Preheating temp.	Experimental	Cosilab	FLUENT
1	950°C	75	115	9
2,9	1000°C	4	8	0
1,5	1000°C	67	77	2
2,9	1050°C	21	12	0
3,9	1050°C	13	9	0

Severely underestimated !

The NOx content in flue gases computed with detailed chemistry in COSILAB® are in fairly good agreement with measured values, especially if we compare to the values computed with an extremely simple combustion model in FLUENT®.

Conclusions

- The combustion chamber was **properly designed** for the study of diluted combustion with a firing rate of 3kW. The setup is able to provide a range of dilution conditions allowing to observe flame and flameless combustion for methane.
- The experimental results show that the **global excess of O_2** is an important parameter for diluted combustion. So, a 3D operating map including the excess has been built
- Observation of **4 different combustion regimes**
- Not good agreement of NOx emission with CFD modelling. Modelling with a simple **plug flow reactor** using detailed mechanism show **good prediction of NO_X** but the location of reaction zone isn't accurate.
- In a future step, combustion characteristics of **CH_4/CO/H_2** gas blends with various diluted oxidizers will be studied on the test rig
- Efforts will be made in the **modelling approach** to allow the combination of a combustion model taking kinetic effects into account through a sufficiently extended reaction scheme, with rigorous flow computation as in CFD model.