POLYTECH.MONS

Thermal Engineering & Combustion Laboratory

WORK IN PROGRESS

Development of stability diagrams of flame in diluted combustion

SEZGIN Erdinç
Research Assistant
Erdinc.Sezgin@fpms.ac.be

OUTLINE

- Introduction
- Objective
- The experimental apparatus
- Experimental study
- Numerical study
- Conclusions and perspectives

INTRODUCTION

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

New rapidly developing combustion technology :

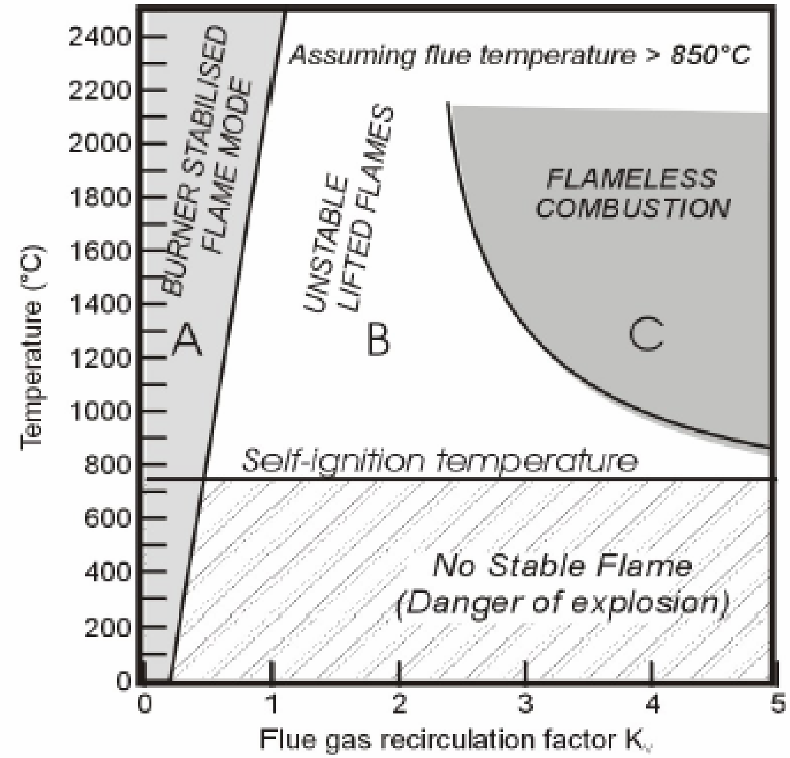
- High-temperature air combustion HTAC
- MILD combustion
- Flameless oxidation

Generally, the dilution is characterized by a number that is the recirculation ratio

2 fundamental requirements :

- The process temperature must be above the mixture autoignition temperature
- The recirculation ratio must be higher than a threshold

?



- Diagrams are often built for the couple methane-air or propane-air

Lack of information with other gases blends, namely gases containing CO and H_2.

-The temperature to be considered in the diagrams is not always clearly defined

-The influence of the nature of the dilutant can also be interesting to study in order to be able to classify the most favorable dilutant in the diluted combustion.

OBJECTIVE

Recall

→*Develop a methodology for building stability diagrams in diluted combustion for various* ***fuel/oxidiser*** *couples*

→ *Design an experimental apparatus*

→ *for various mixtures of gaseous fuels*

→ *for various combustion regime for a range of operating conditions*

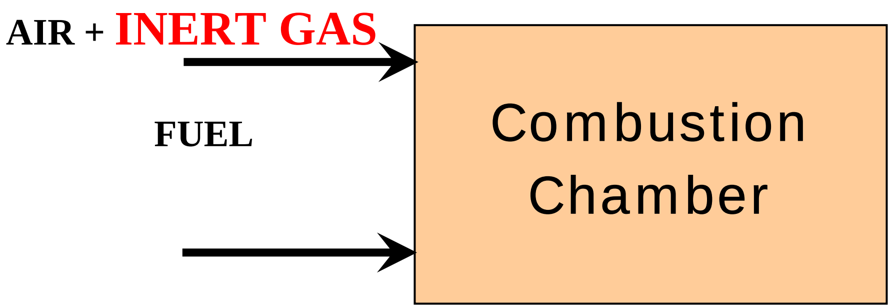
→ Experiment with methane as fuel and nitrogen or carbon dioxide as dilutant

→Compare with the numerical study

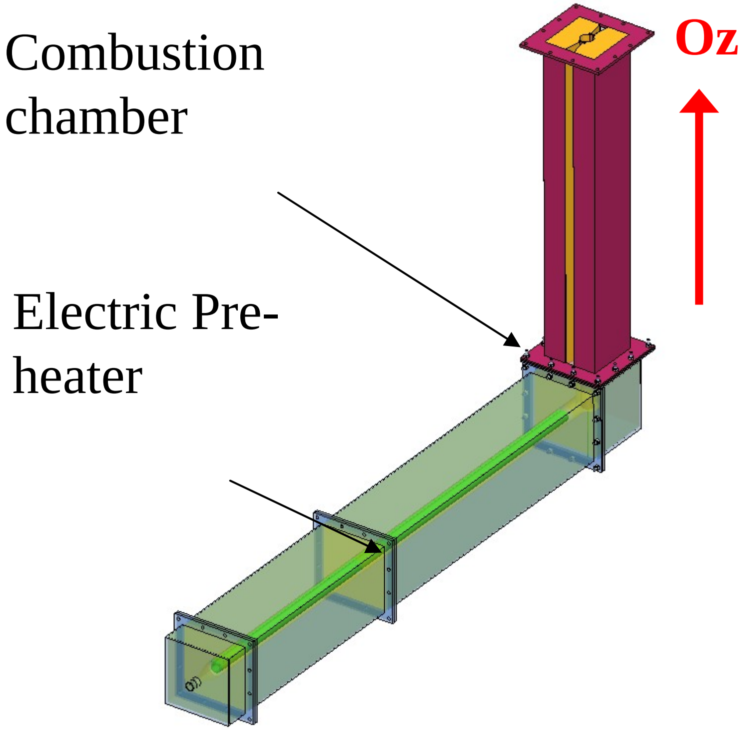
THE EXPERIMENTAL APPARATUS

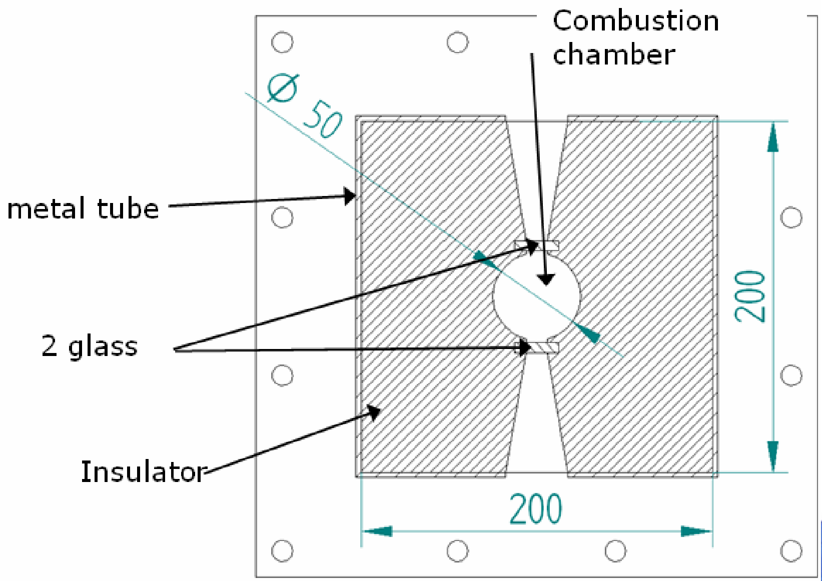
In practice, the dilution is obtained aerodynamically by internal recirculation in the combustion chamber

Difficult to regulate the rate of recirculation K_V ($1 \rightarrow 8$)



The recirculation will be figured, in the new experimental setup, by vitiating the combustion air by inert gases (N_2, CO_2) at high temperature





We had got the following design

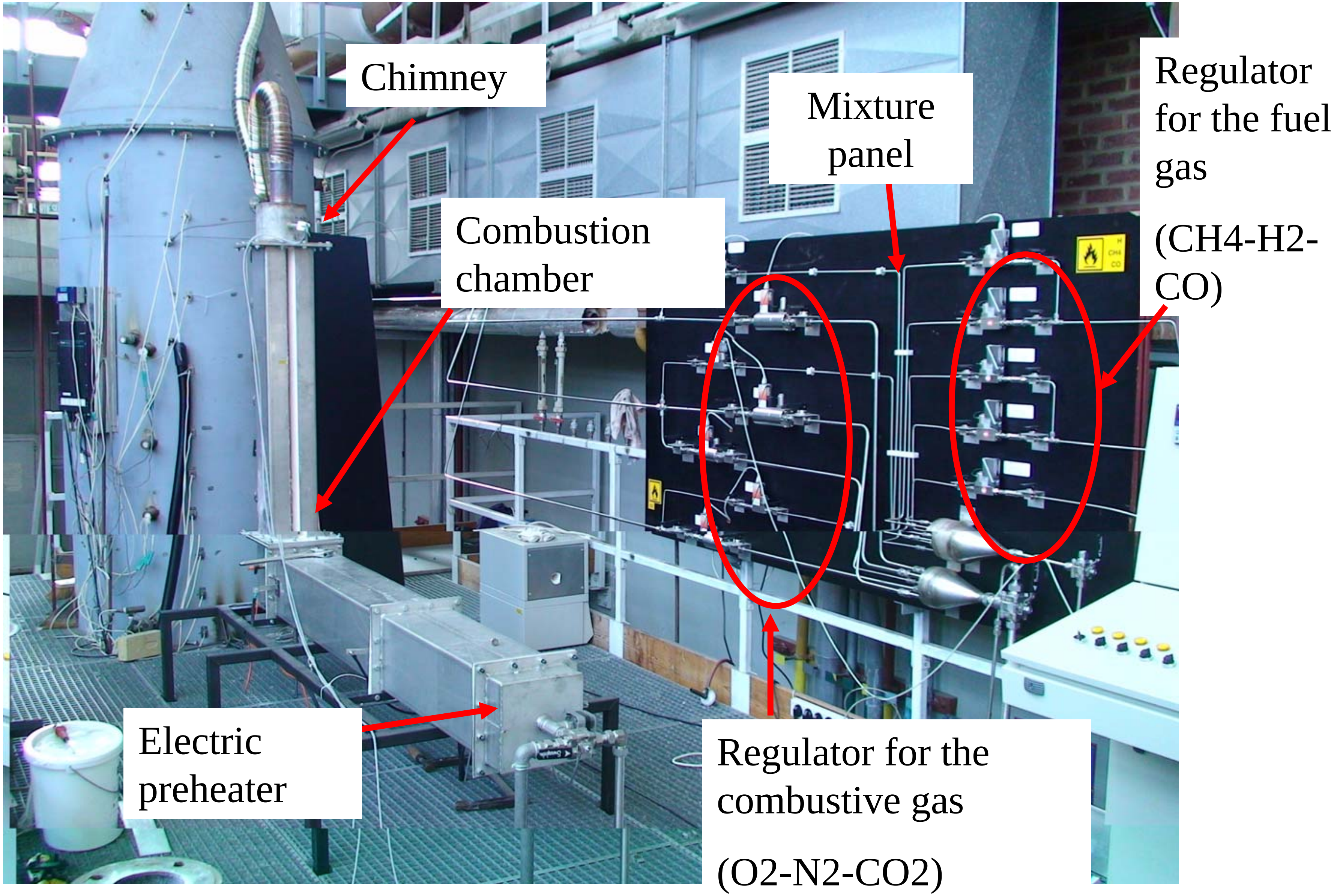
- with a coflow configuration for the fuel injection

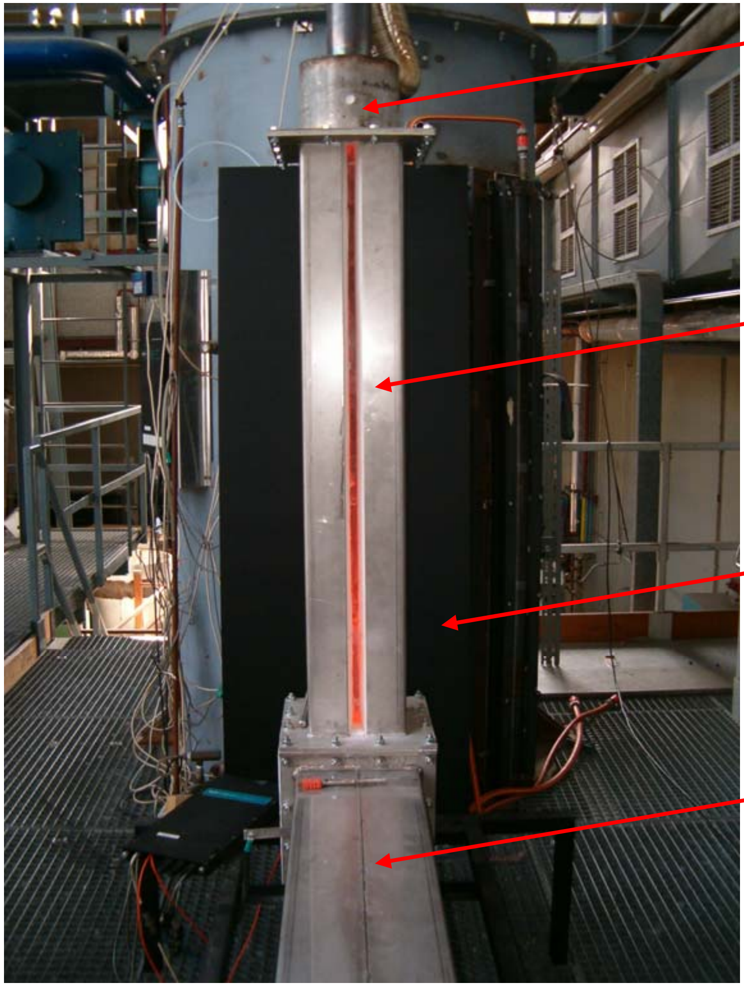
- a cylindrical combustion chamber of 1200 mm height and 50 mm diameter

- two optical accesses

- electric pre-heater : to preheat the diluted combustive till 1100°C

- panel of mixture to prepare the combustive and the fuel gas


Chimney
Mixture panel
Regulator for the fuel gas
(CH4-H2-CO)
Combustion chamber
Electric preheater
Regulator for the combustive gas
(O2-N2-CO2)



Chimney

Combustion chamber
Square metal tube

Black panel

Preheater

The measured data

The installation equipped with various sensors and measuring devices to determine:

- Temperature at the inlet of the combustion chamber

- Temperature at the exit of the combustion chamber in the chimney

- Flows of the reactants entering in the chamber thanks to the regulators

- Imagery of chimiluminescence of radical OH, CH and C2 :

- The composition of combustion gases

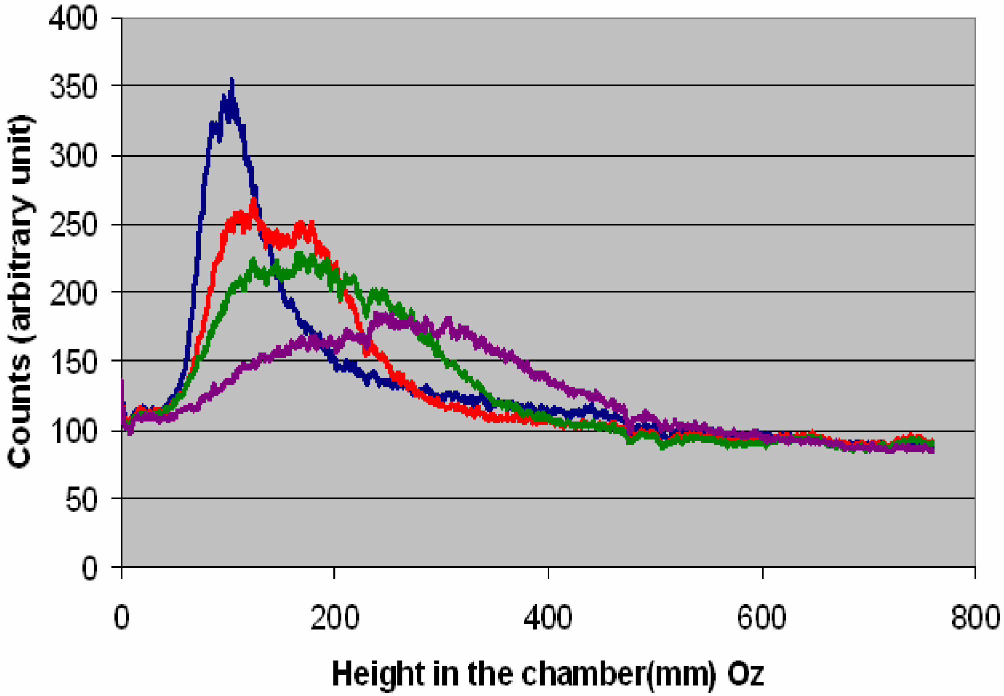
EXPERIMENTAL STUDY

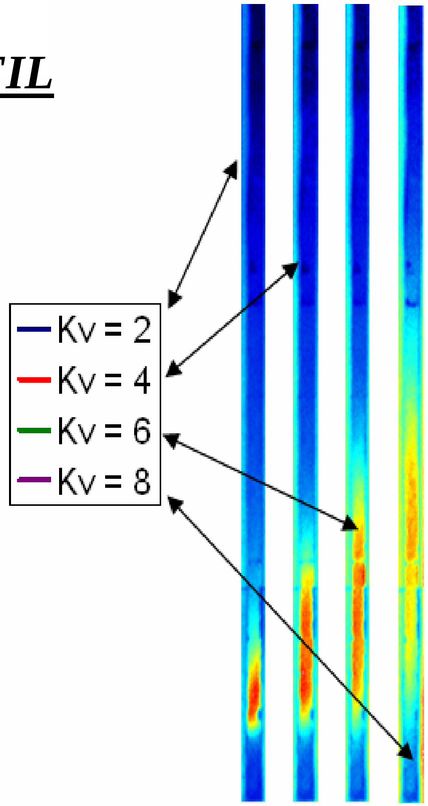
$$K_V = \frac{\dot{M}_{DILUTANT}}{\dot{M}_{fuel} + \dot{M}_{Air}}$$

Preliminary test

- Combustible: CH_4 - P = 3kW
- Choice of the combustive: air – E = 0%
- Temperature of pre-heating: 1050°C
- Nature of the dilutant: N_2
- Dilution: K_v = 2 - 4 - 6 - 8

OH PROFIL





Oz

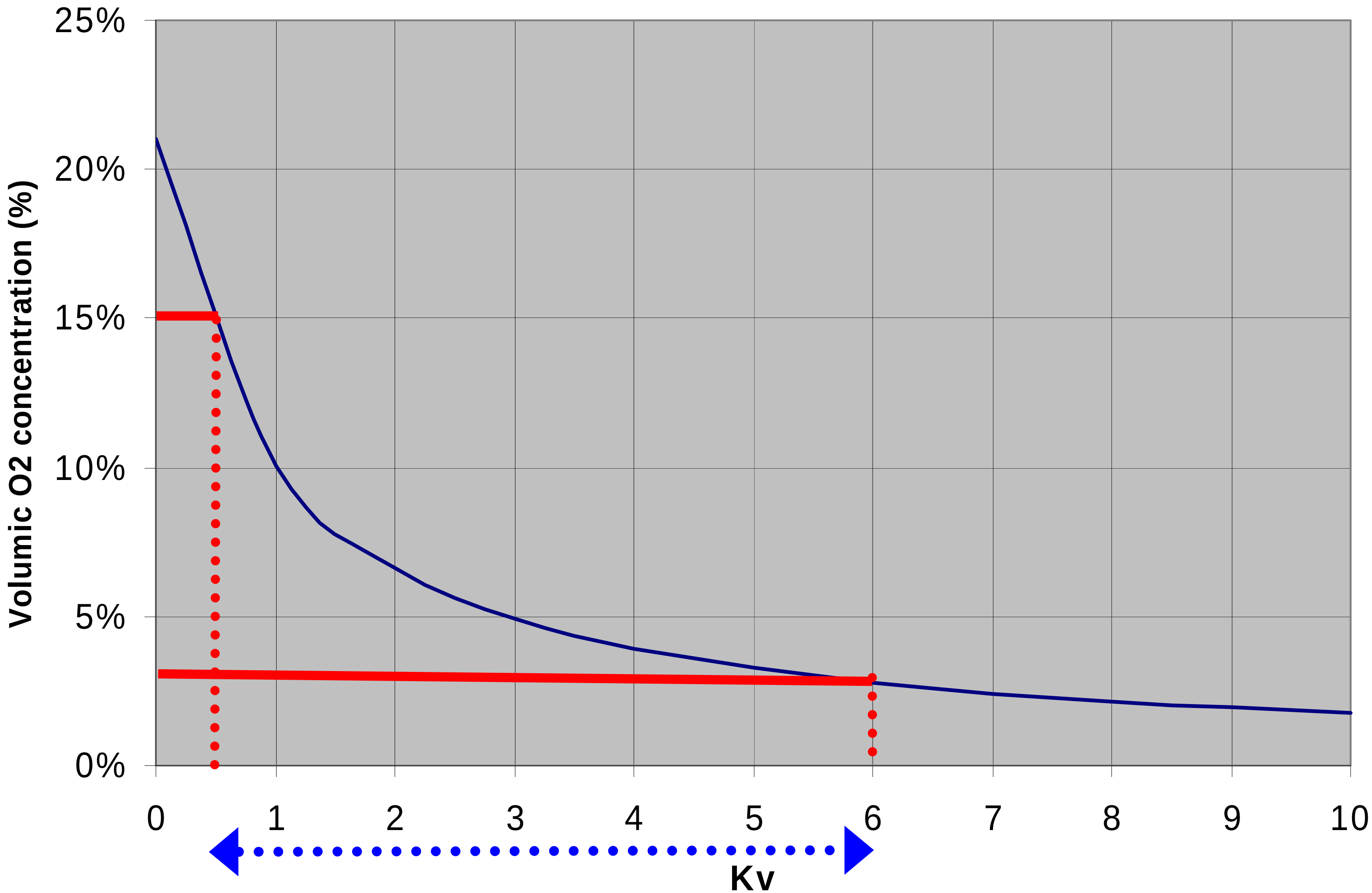
Experimental study

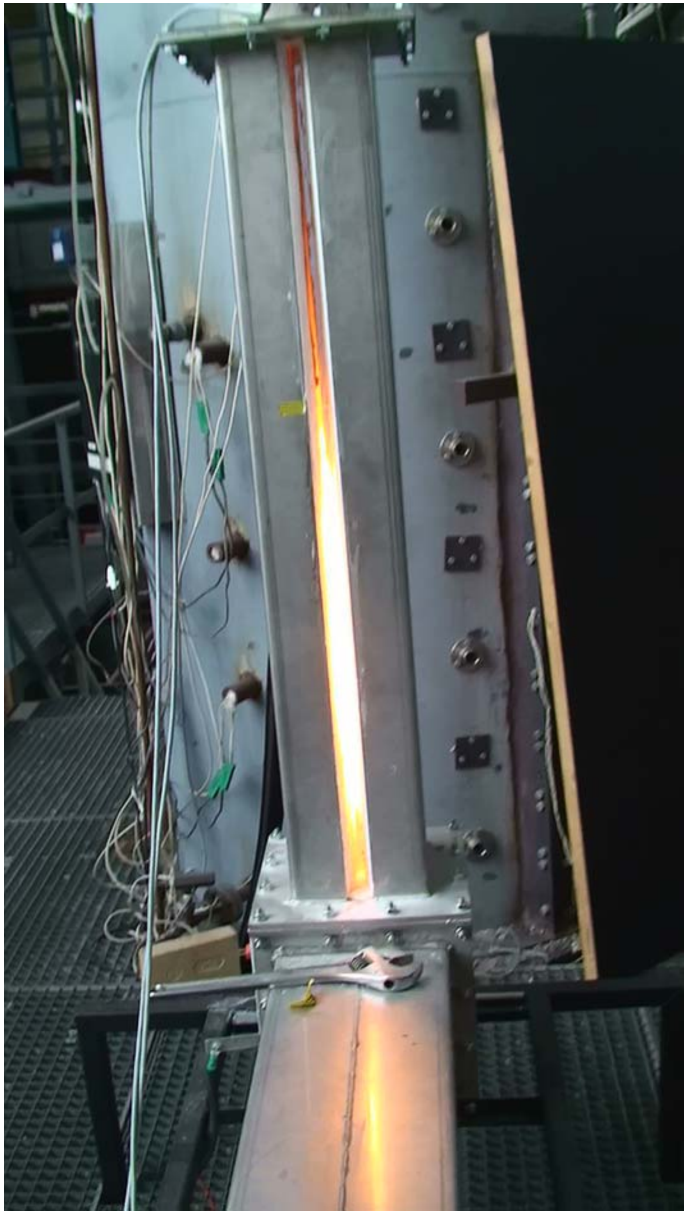
For easily comparison → define dilution by the O_2 concentration in the diluted combustive.

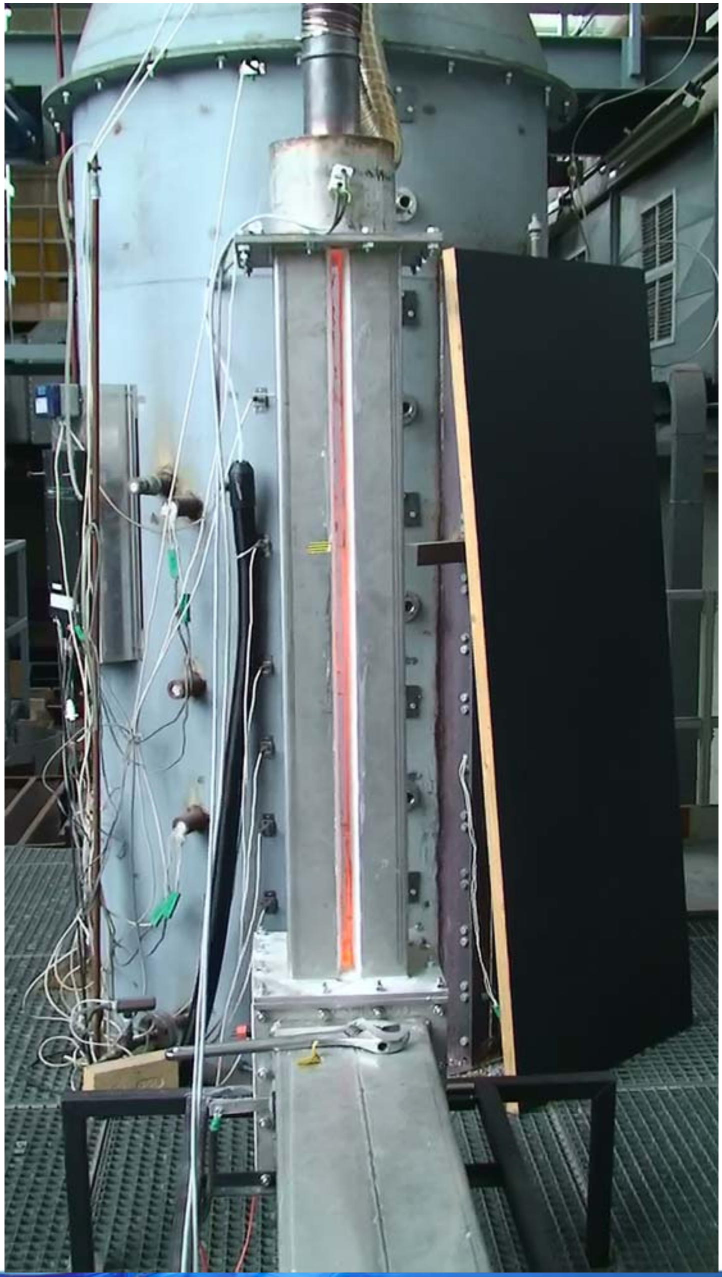
We will vary the oxygen concentration in a range corresponding to the variation of Kv from 0 to 6 with air like combustive

- Combustible: CH_4 – P = 3 kW
- Choice of the combustive: oxygen
- Excess of oxygen: 5%
- Temperature of preheating: 950°C - 1000°C - 1050°C
- Nature of the dilutant: N_2 or CO_2
- Dilution: from 3% to 15% of oxygen in the diluted combustive

Correspondence Kv- O2 concentration







T = 1050°C												
O2 concentration	15%		10%		8%		7%		4%		3%	
Dilutant	N2	CO2	N2	CO2	N2	CO2	N2	CO2	N2	CO2	N2	CO2
CO	*	*	81	213	82	467	*	1000	1282	NO C.	2040	NO C.
NO	*	*	103	2,5	72	2,36	*	2,2	19	NO C.	13,89	NO C.

T = 1000°C												
O2 concentration	15%		10%		8%		7%		4%		3%	
Dilutant	N2	CO2	N2	CO2	N2	CO2	N2	CO2	N2	CO2	N2	CO2
CO	*	*	21	494	25	NO C.	*	NO C.	592	NO C.	NO C.	NO C.
NO	*	*	63	1,71	41	NO C.	*	NO C.	6,38	NO C.	NO C.	NO C.

T = 950°C												
O2 concentration	15%		10%		8%		7%		4%		3%	
Dilutant	N2	CO2	N2	CO2	N2	CO2	N2	CO2	N2	CO2	N2	CO2
CO	*	160	89	NO C.	86	NO C.	*	NO C.	NO C.	NO C.	NO C.	NO C.
NO	*	2,4	70	NO C.	33	NO C.	*	NO C.	NO C.	NO C.	NO C.	NO C.

NUMERICAL STUDY

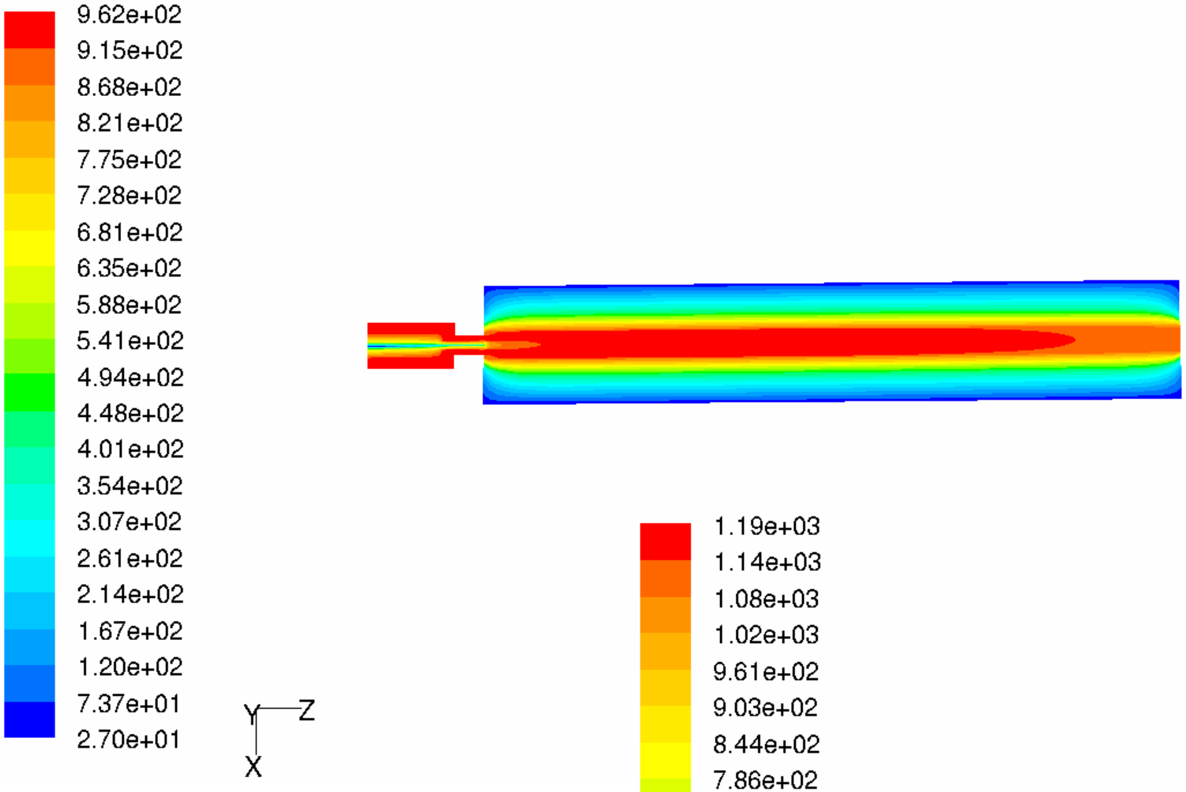
The numerical study consists in carrying out simulations CFD on Fluent® code in the combustion chamber while varying the dilution, the temperature of injection and the nature of the dilutant.

- excess of oxygen is fixed at 5%

-power injected by fuel (CH_4) : 3 kW

For two dilutants, namely nitrogen and carbon dioxide, and for different molar oxygen concentration (2% - 4% - 6%), the temperature of injection of diluted combustive was modified.

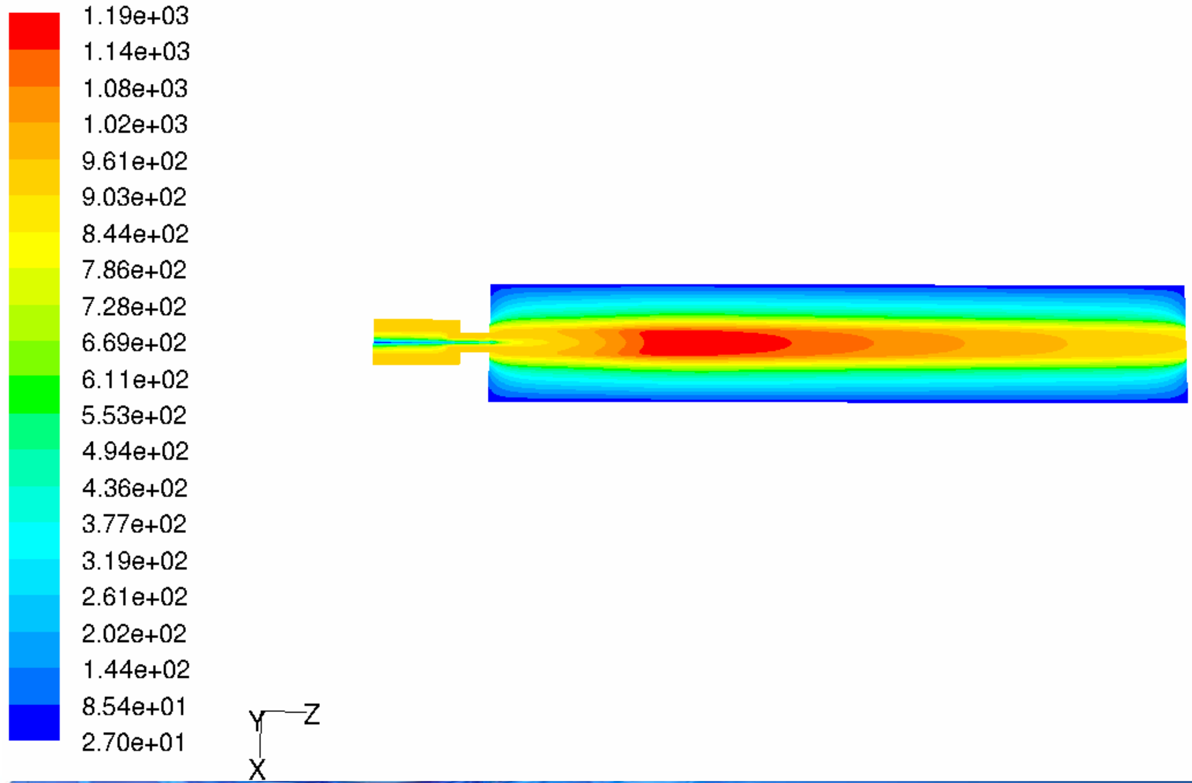
The combustive is constituted by the quantity of oxygen required to have an oxygen excess of 5% compared to stoichiometry and the dilutant (CO_2 - N_2) required to have the wished dilution.



O_2 concentration : 4%

T injection : 950 °C

Dilutant : CO_2

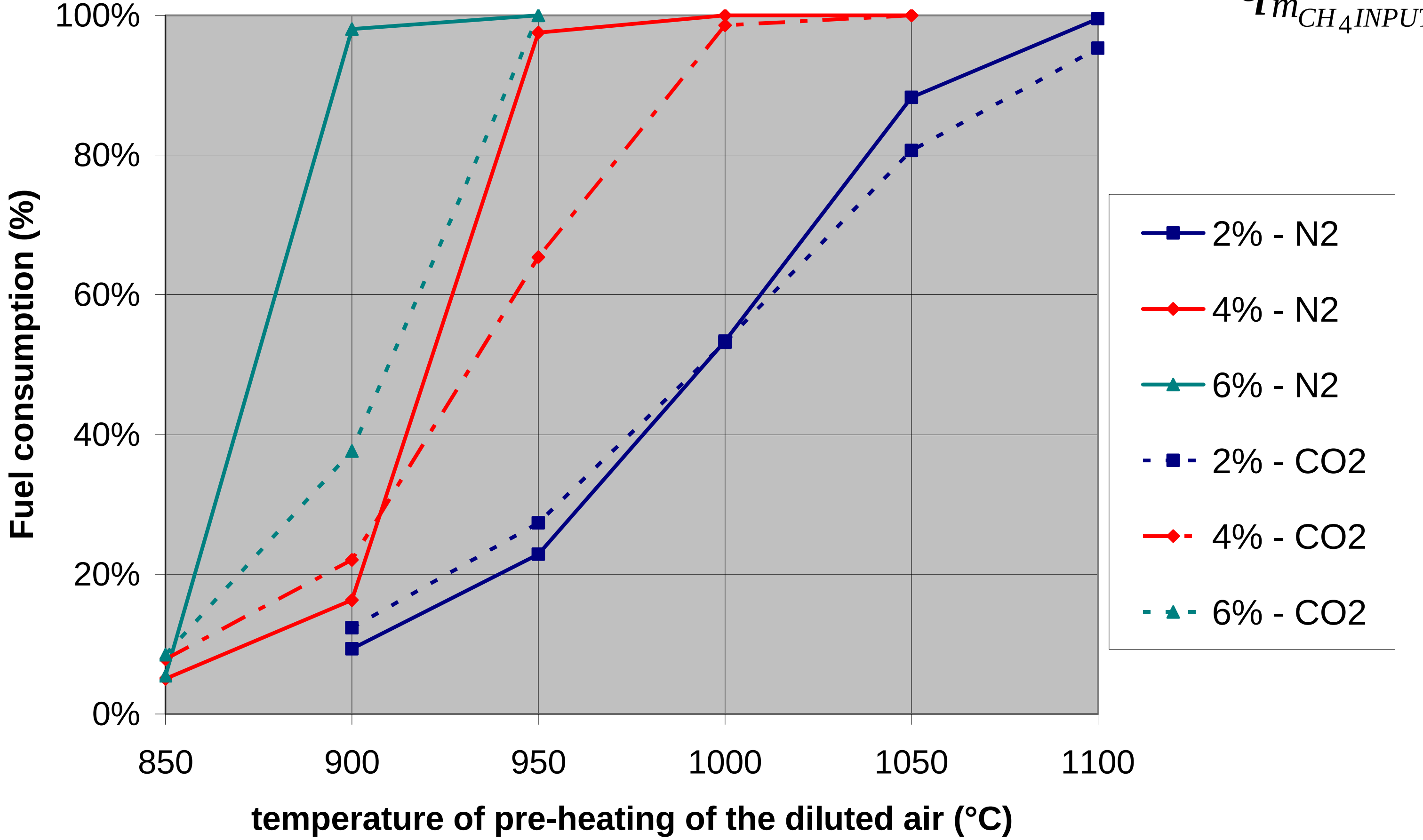


O_2 concentration : 6%

T injection : 950 °C

Dilutant : CO_2

$$\frac{q_{m_{CH_4 INPUT}} - q_{m_{CH_4 OUTPUT}}}{q_{m_{CH_4 INPUT}}}$$



CONCLUSIONS & PERSPECTIVES

It is more difficult to ensure a good combustion with carbon dioxide as dilutant compared to nitrogen for the same molar oxygen concentration in the experiment.

While in the numerical studies, there isn't a big difference between the 2 dilutants.

Others more detailed numerical studies are in progress: in the simulation of this paper, the reaction is modelled by only one global reaction. It is interesting to simulate with a two step reaction with CO as an intermediate species.

The experiment results are also in progress in order to have more points to compare and an investigation is being made in order to limits the measurement imprecision.

I wish to thank the Walloon Government for continuous financial support of research in the framework of the IEA

RÉGION WALLONNE

THANKS FOR YOUR ATTENTION

Development of stability diagrams of flame in diluted combustion

SEZGIN Erdinç, LUPANT Delphine, PESENTI Barbara, LYBAERT Paul

Faculté Polytechnique de Mons
Thermal Engineering & Combustion Laboratory
Rue de l'Epargne, n°56
B-7000 MONS
BELGIQUE
Phone : +32 (0)65 37 44 62 ; Fax : +32 (0)65 37 44 00
E-mail : Erdinc.Sezgin@fpms.ac.be

(Sub – Tasks 2.1 H & 2.1 I)

Abstract

In the scientific literature, a few studies were realized to characterize the combustion diluted with fuels containing hydrogen and CO and also to study the influence of the inert gas composition. So, the aim of this project is to characterize diluted combustion in a broader way. But first of all, it is interesting to characterize the experimental apparatus and the numerical methods with methane like fuel. This work relates to the study of the behaviour of combustion with methane and the influence of nitrogen and CO2 like dilutant.

1. Introduction

This project concern the rapidly developing combustion technology that has been given different name:
- High-temperature air combustion HTAC
- Mild combustion
- Flameless oxidation

The essence of this technology is that fuel is oxidized in an environment that contains a substantial amount of inert gases and some, typically more than 3-5% of oxygen [2].
The interest of this technology is that a mixture of reactants diluted with combustion products, at a temperature above autoignition, can achieve the targets of high process efficiency and low pollutant emissions.
Generally, the dilution is characterized by a number that is the recirculation ratio (i.e., the ratio between the recirculation gases mass and the incoming mixture mass).

.

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

.

With $\dot{M}_{recirculation\ gas}$ = mass flow of recirculation gas

$\dot{M}_{fuel}$ = mass flow of fuel

$\dot{M}_{air}$ = mass flow of air

It is admitted that this ratio must be higher than a threshold (e.g., 4 for methane and 3.5 for ethane [1]).

Figure 1 shows a schematic diagram of the stability limits for different combustion modes.

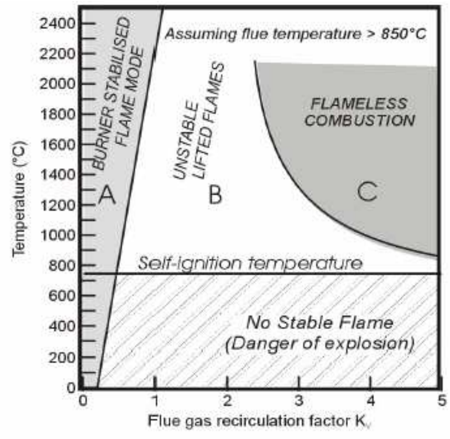


Figure 1: Stability diagram

Where Area 'A': corresponds to traditional stable combustion
Area 'B': corresponds to an unstable combustion
Area 'C': corresponds to the diluted combustion

This kind of diagram has been made for the couple methane-air or propane-air. There is a lack of information about diluted combustion with exotic gases containing CO and of H_2.
And it is not always very clear if the temperatures indicated on the diagram are for the furnace or for the incoming gas or for combustion products.
The influence of the nature of the dilutant can also be interesting to study in order to be able to classify the most favorable dilutant in the diluted combustion.

Therefore, this work falls under a broader project which consists of the construction of an experimental apparatus (design and construction), of experiments with different type of fuel and dilutant and in the mean time of numerical studies which is referred to it.

2. Objectives

The goal of this paper is to describe the experimental apparatus while referring to the constraints and the plans explained in the previous article [3]. We describe the results obtained by the experiments with natural gas as fuel and nitrogen or carbon dioxide as dilutant. With these results, we obtain a data base which allows the characterization of the combustion chamber and the observation of the different combustion mode.
A numerical study with the CFD Fluent® code was realized and has been compared with the experimental results.

3. The experimental apparatus

a. Overall view and recall

For recall [3], the experimental apparatus has to answer very specific constraint:
- allow a very broad range of recirculation ratio as well as a perfect control of the incoming mixture composition
- provide a thermically controllable environment, while allowing an optical access for the visualization of the combustion zone
- the installation has to allow the study of different couples fuel/combustive.

We had got the following design with a coflow configuration for the fuel injection and a cylindrical combustion chamber of 1200 mm height and 50 mm diameter (Figure 1 & 3). This chamber has two optical accesses.

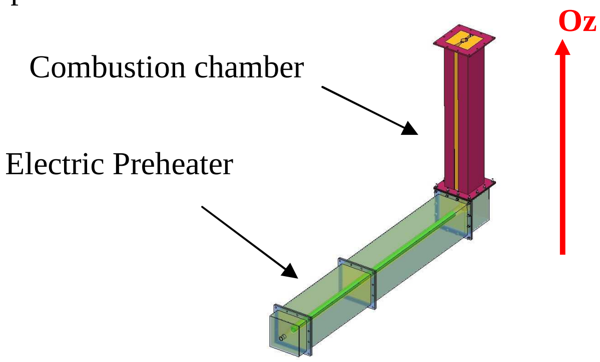


Figure 1: Design of the experimental apparatus

After the design work assisted by numerical CFD studies [b], the different elements of the installation were ordered then gone up in our laboratories.
On the figure 2, we can see some elements of the installation:
- The combustion chamber
- The electric preheater which allows the pre-heating of the diluted combustive at a temperature varying from the ambient temperature until a maximum of 1100°C
- The panel of mixture: this mixture station will allow obtaining the combustive and the fuel at the desired proportions thanks to the regulators

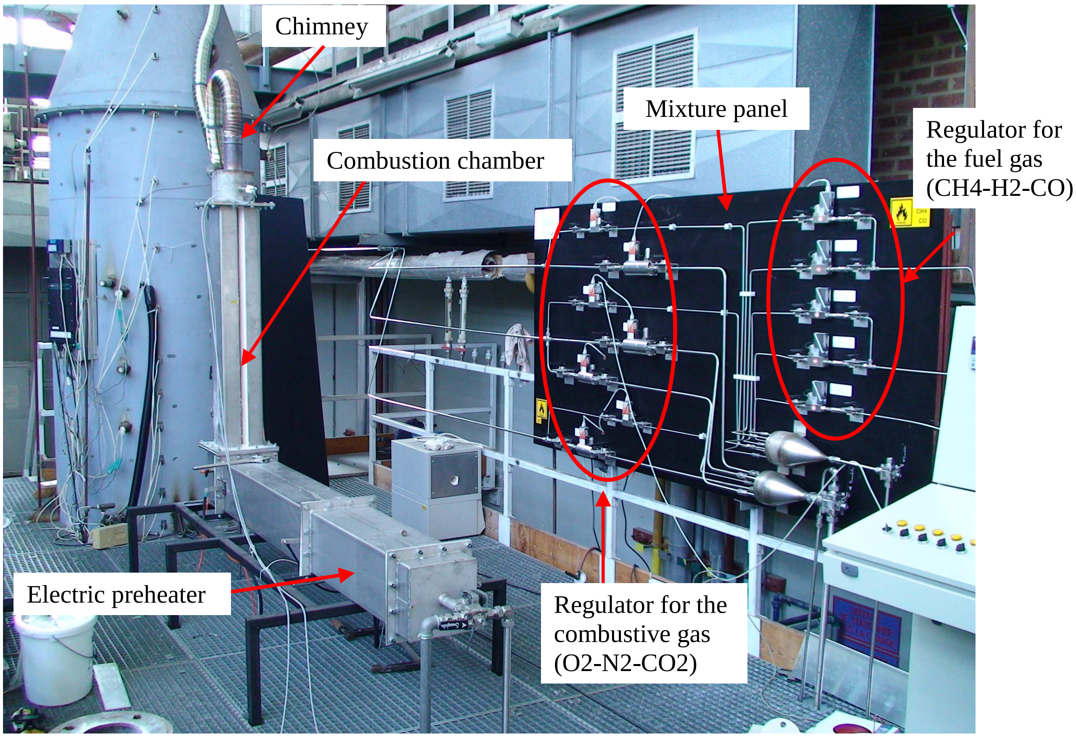


Figure 2: Experimental apparatus

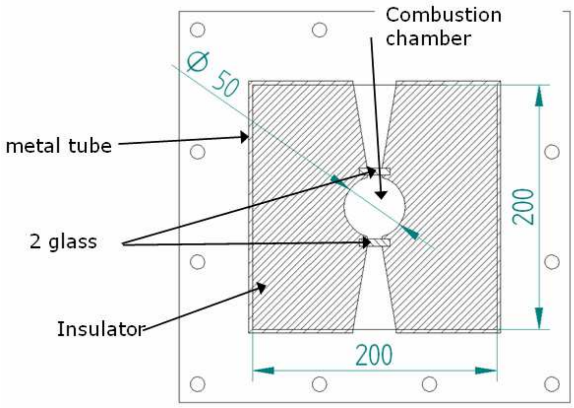


Figure 3: Cross-section of the combustion chamber

b. The measured data

The installation will be equipped with various sensors and measuring devices to determine:
- the temperature at the inlet of the combustion chamber via a thermocouple of control on the outlet side of the preheater
- the temperature at the exit of the combustion chamber in the chimney. This temperature will be measured via a fine thermocouple (Standard B (Pt-30% Rh/Pt-6% Rh))
- the flows of the reactants entering in the chamber thanks to the regulators
- the imagery of chimiluminescence of radical OH, CH and C_2 :
The cartography of spontaneous emission of the radicals in UV is possible with using an intensified camera and thanks to the optical access in the chamber
- The composition of combustion gases
The gases will be extracted in the chimney, near the temperature measurement and will be send towards the analyzers

4. Experimental study

a. Preliminary test

For these preliminary tests, the parameters are:
- Combustible: methane
- Combustible power: 3 kW
- Choice of the combustive: air
- Excess of oxygen: 0%
- Temperature of pre-heating: 1050°C
- Nature of the dilutant: nitrogen
- Dilution: Kv = 2 - 4 - 6 - 8

The dilution is obtained by diluting the combustive with inert gas according to this relation:

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

The cartographies of spontaneous emission of radicals OH in UV have been got. The rough images obtained are treated in order to obtain the profile of the intensity of these emissions according to the height of the combustion chamber (figure 4). The H=0 in X-coordinate corresponds to the base of the combustion chamber.

We can easily notice the extension of the zone of combustion when the recirculation ratio increases what is explained by:
- the dilution delays the mixture of fuel and the combustive
- the dilution decreases the concentrations and also the reaction speed of combustion

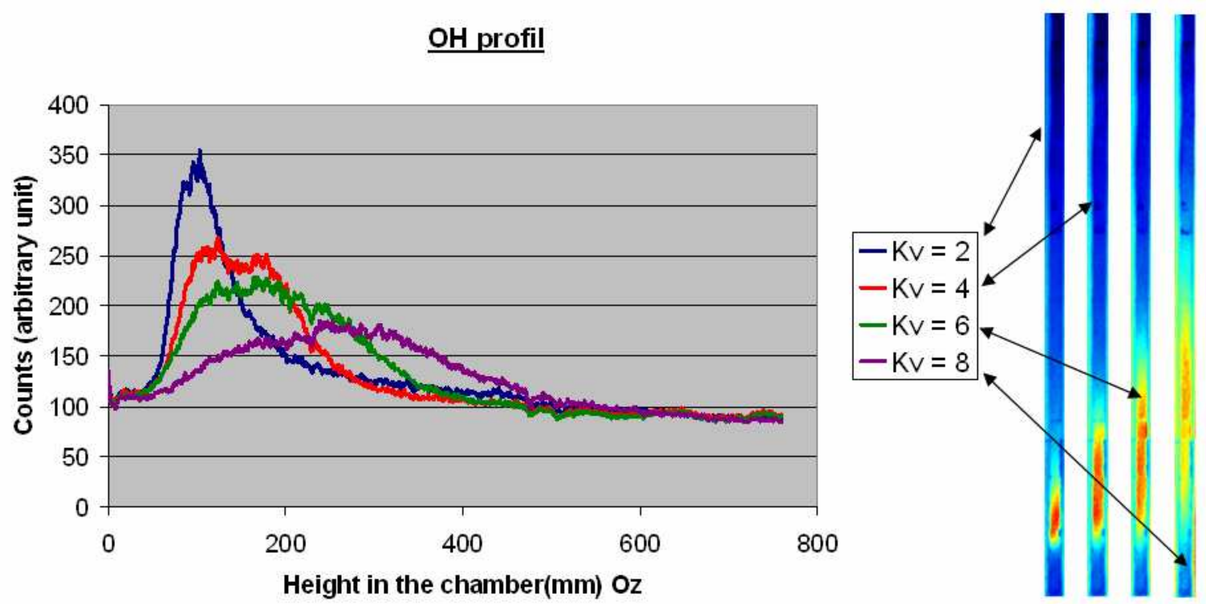


Figure 4: OH profile this preliminary test

b. Experimental study

The experimental study will be done with methane as fuel. The power injected by fuel is fixed to 3 kW.
In order to have results which can easily be compared, we will define dilution by the oxygen concentration in the diluted combustive.
In that case, we will obtain graphs with any dilutant, for example nitrogen or carbon dioxide or a mixture of this 2 gas.
We will vary the oxygen concentration in a range corresponding to the variation of Kv from 0 to 8 with air like combustive.

The parameters of this study are:
- Combustible: methane
- Combustible power: 3 kW
- Choice of the combustive: oxygen
- Excess of oxygen: 5%
- Temperature of preheating: 950°C - 1000°C - 1050°C
- Nature of the dilutant: nitrogen or carbon dioxide
- Dilution: from 3% to 15% of oxygen in the diluted combustive

Table 1 shows the experimental results; only the concentrations of CO and NO in the flue gas are indicated.

T = 1050°C												
O2 concentration	15%		10%		8%		7%		4%		3%	
Dilutant	N2	CO	N2	CO	N2	CO	N2	CO	N2	CO	N2	CO
CO	*	*	81	213	82	467	*	1000	1282	NO C.	2040	NO C.
NO	*	*	103	2,5	72	2,36	*	2,2	19	NO C.	13,89	NO C.

T = 1000°C												
O2 concentration	15%		10%		8%		7%		4%		3%	
	N2	CO	N2	CO	N2	CO	N2	CO	N2	CO	N2	CO
CO	*	*	21	494	25	NO C.	*	NO C.	592	NO C.	NO C.	NO C.
NO	*	*	63	1,71	41	NO C.	*	NO C.	6,38	NO C.	NO C.	NO C.

T = 950°C												
O2 concentration	15%		10%		8%		7%		4%		3%	
	N2	CO	N2	CO	N2	CO	N2	CO	N2	CO	N2	CO
CO	*	160	89	NO C.	86	NO C.	*	NO C.	NO C.	NO C.	NO C.	NO C.
NO	*	2,4	70	NO C.	33	NO C.	*	NO C.	NO C.	NO C.	NO C.	NO C.

Table 1: Experimental results : CO & NO values in ppm

(means that no experiment for this case – NO C. means that for this case, there isn't combustion in the chamber)*

5. Numerical study

Figure 5 shows the modeling of the furnace (the quarter) to make numerical studies.

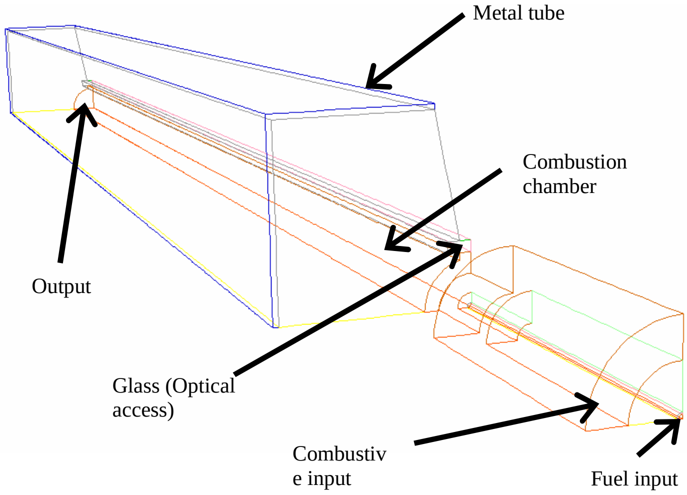
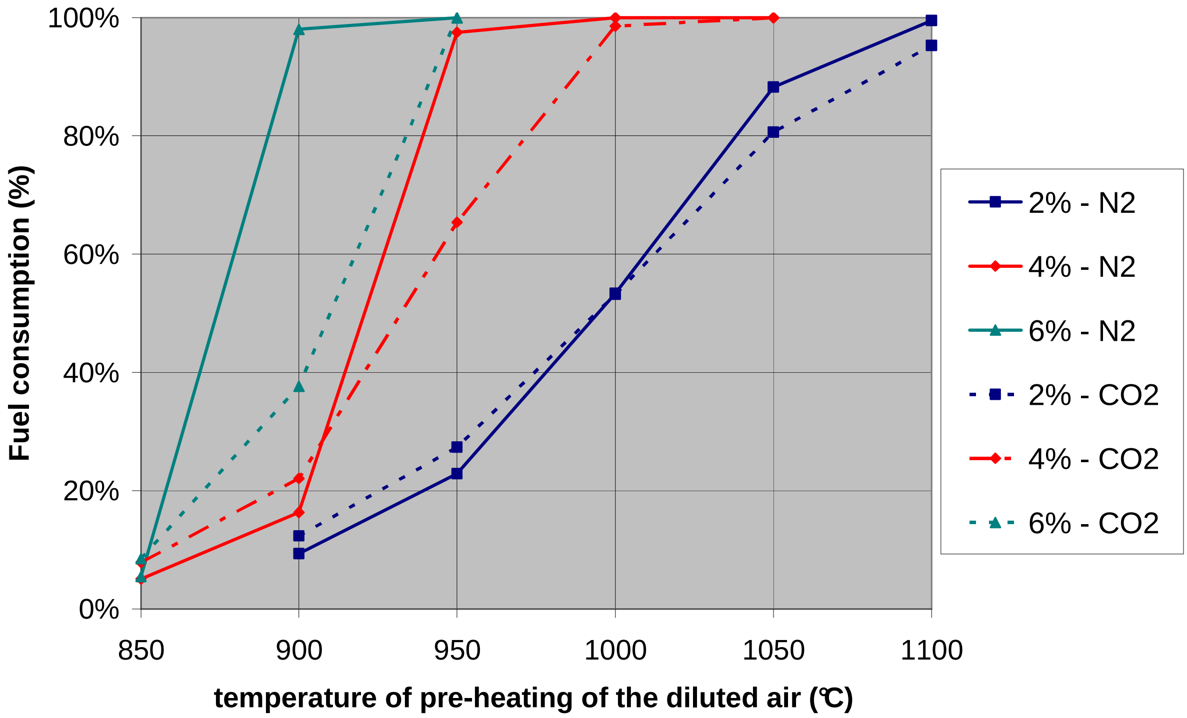


Figure 5: Furnace modeling

The numerical study consists in carrying out simulations CFD on Fluent® code in the combustion chamber while varying the dilution, the temperature of injection and the nature of the dilutant. The excess of oxygen is fixed at 5% and the power injected by fuel (CH_4) remains to 3 kW.

Fuel consumption is defined by this relation:

$$\frac{q_{m_{CH_4 INPUT}} - q_{m_{CH_4 OUTPUT}}}{q_{m_{CH_4 INPUT}}}$$



For two dilutants, namely nitrogen and carbon dioxide, and for different molar oxygen concentration (2% - 4% - 6%), the temperature of injection of diluted combustive was modified.
The combustive is constituted by the quantity of oxygen required to have an oxygen excess of 5% compared to stoichiometry and the dilutant (CO_2 - N_2) required to have the wished dilution.

The influence of the dilutant is different when the fuel consumption is weak or important.
For low fuel consumption, the dilution with CO_2 leads to a little less unburned residues.
For important consumption, the N2 is better to ensure a minimum of unburned residues.

6. Results and conclusions

As shown in table 1, it is more difficult to ensure a good combustion with carbon dioxide as dilutant compared to nitrogen for the same molar oxygen concentration in the experiment.
While in the numerical studies, there isn't a big difference between the 2 dilutants.
Others more detailed numerical studies are in progress: in the simulation of this paper, the reaction is modelled by only one global reaction. It is interesting to simulate with a two step reaction with CO as an intermediate species.
The experiment results are also in progress in order to have more points to compare and an investigation is being made in order to limits the measurement imprecision.

Acknowledgements

This work has been performed in the framework of the IEA « Implementing Agreement for a Program of Applied Research, Development and Demonstration in Energy Conservation and Emissions Reduction in Combustion ». The authors wish to thank the Walloon Government for continuous financial support of this program since 1992.

References

[1] de Alessandro Cavigiolo, Mauro A. Galbiati, Alessandro Effugio, Davino Gelosa and Renato Rota, *'Mild Combustion in a laboratory-scale apparatus'*

[2] Marco Mancini, Patrick Schwoppe, Roman Weber, Stefano Orsino, *On mathematical modelling of flameless combustion,* Combustion and Flame 150 (2007) 54-59

[3] Sezgin Erdinç, Lupant Delphine, Pesenti Barbara, Lybaert Paul, *Development of stability diagrams of flame in diluted combustion*, 28th Task Leader Meeting