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Thermal Engineering & Combustion Laboratory (FPMs)
Thermodynamics Laboratory (ULg)

# Feasibility study of the diluted combustion in a semi-industrial boiler at low temperatures

**Sub - Tasks 2.1 H & 2.1 I**

RÉGION WALLONNE

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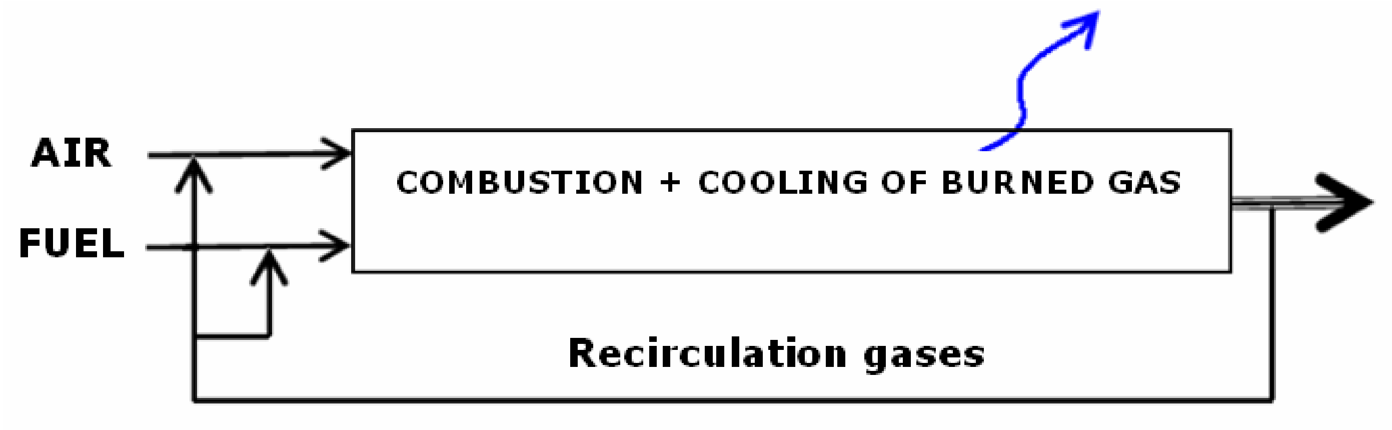
# Contents

# 1. Introduction

Diluted combustion (technology mainly used in high temperature process furnaces, to lower the NOx emissions) ➔ high process thermal efficiency with low pollutant emissions




Principle of diluted combustion : high level of dilution of the reactants with flue gases ➔ slower reaction in a much larger volume than in classical combustion ➔ lower local heat release ➔ more homogeneous temperature field in the furnace, without peak values responsible of high thermal NOx formation

Requirements: - the process temperature must be above the mixture self-ignition temperature

- the recirculation ratio Kv must be higher than a threshold

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

Our boiler combustion chamber differs from a furnace mainly in geometrical confinement (Ratio L/D >>) and thermal confinement (specific firing rate >>):

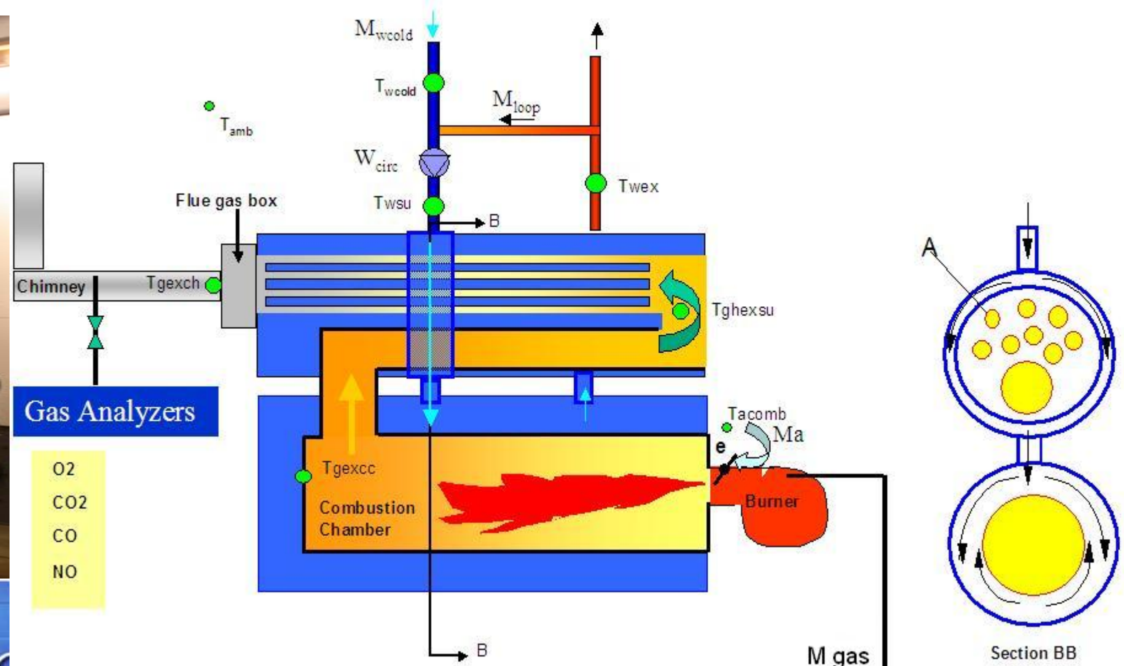
- the high ratio L/D and the high specific firing rate (kW/m³) $\succ\prec$ recirculation ratio requirement

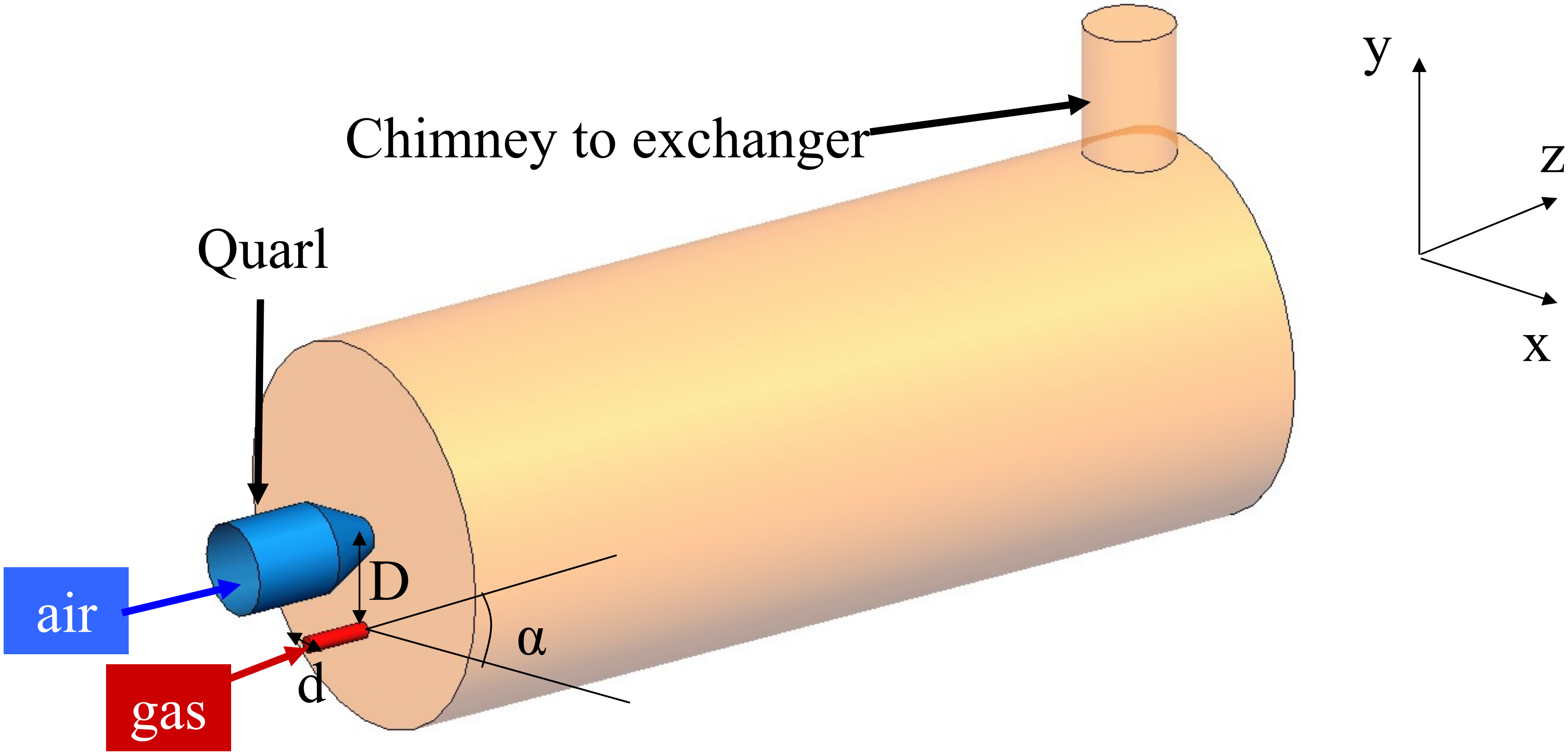
- low wall temperature (water-cooled)$\succ\prec$ process temperature above self-ignition requirement

➔ Feasibility study of the diluted combustion in a semi-industrial boiler at low temperatures (without preheating the combustion air)

# 2. Experimental setup

- Viessmann boiler (ULg), $P_{nom}$ = 370kW, subdivised in 2 parts: Cylindrical combustion chamber (length = 1,41m , diameter = 0,56 m) water-cooled and the heat exchanger with the chimney between them
- Burner: natural gas jet-burner (Eclipse Thermjet 100). The burner can reach a flame velocity of 150m/s for a maximal input of 293 kW






3 parameters for the direct injection :
- length D (max~150mm)
- angle α
- diameter d

Experimental measurements:

- the mass flow rate of natural gas and air at burner inlet
- the composition of combustion gases at the exit of the boiler
- the temperature of the reactants at the inlet of the burner
- the temperature at the exit of the combustion chamber via K thermocouple
- the temperature in the combustion chamber at different location via thermocouples (Standard B (Pt-30% Rh/Pt-6% Rh))
- the imaging of chimiluminescence of radical OH with using an intensified CCD camera with the appropriate filters and thanks to the optical access in the chamber.

Local temperature measurements:

flue gases temperature profiles measured with a probe provided with two thermocouples of the same type and different diameter.

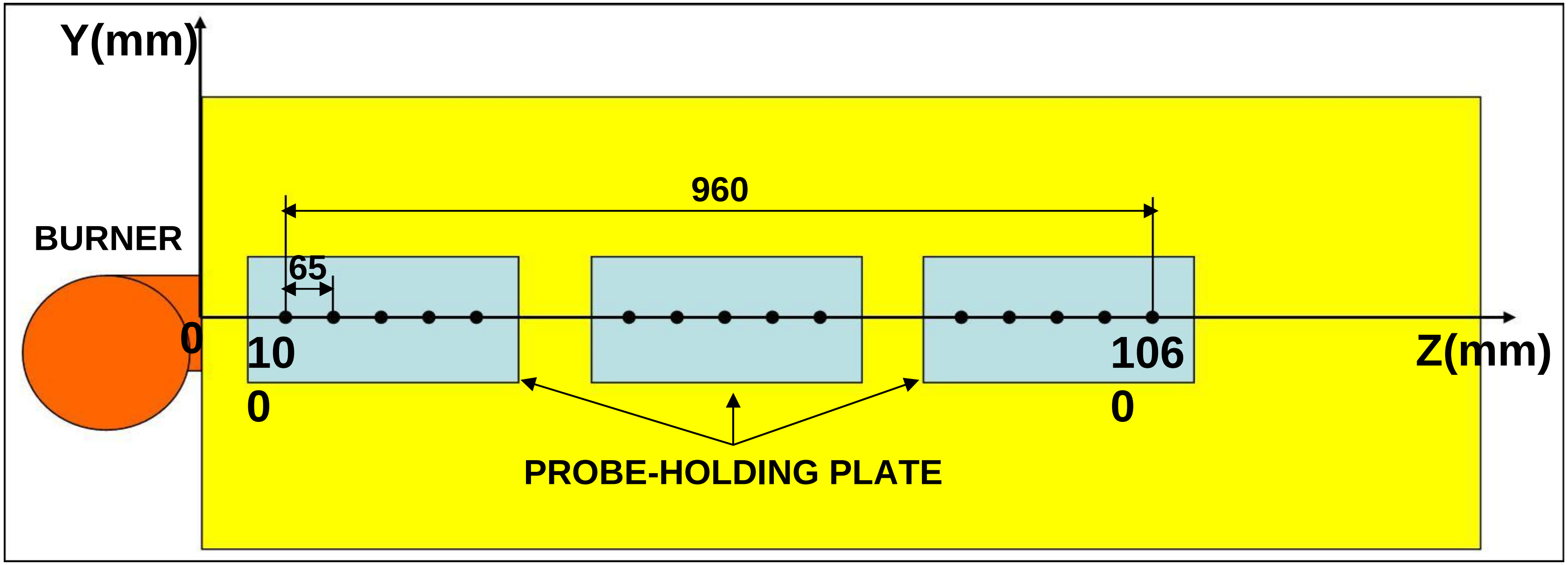
This allows the correction of the measured temperatures from error due to radiative transfer between thermocouple and wall.

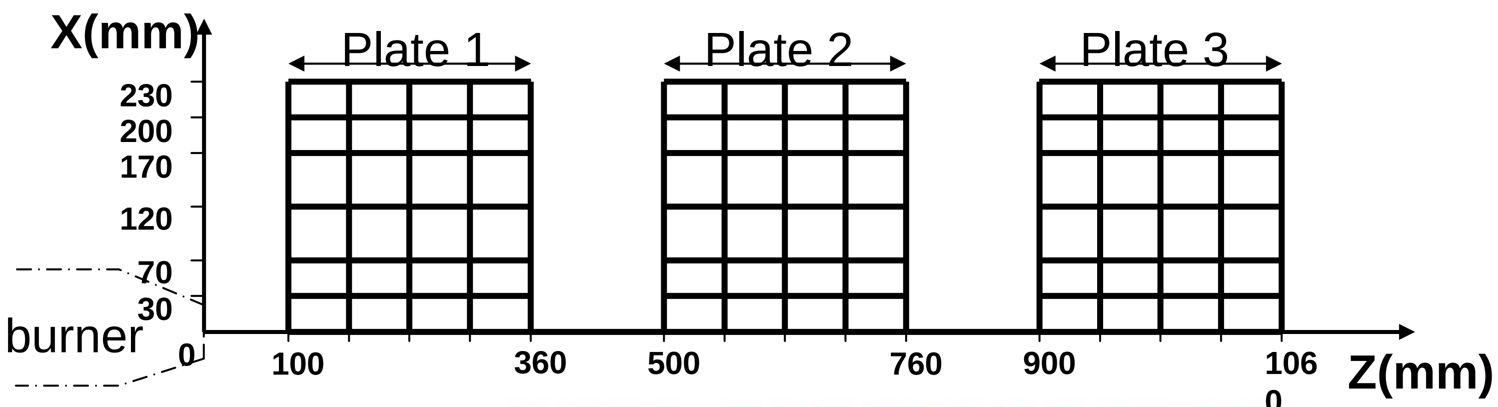
$$T_f = T_1 + \frac{T_1 - T_2}{\sqrt{\frac{d_2}{d_1}} * \left(\frac{T_2^4 - T_w^4}{T_1^4 - T_w^4}\right) - 1}$$

$T_f$ flue gases temperature
$T_1$, $T_2$ temperature of thermocouple 1 and 2
$T_w$ temperature of the chamber wall
$d_1$, $d_2$ diameter of thermocouple 1 and 2 with
$d_1$ = 500 µm and $d_2$ = 350µm

Local temperature measurements :

3 (plate) x 5 (holes) x 7 (radial measurements) = 105 temperature in plane XZ

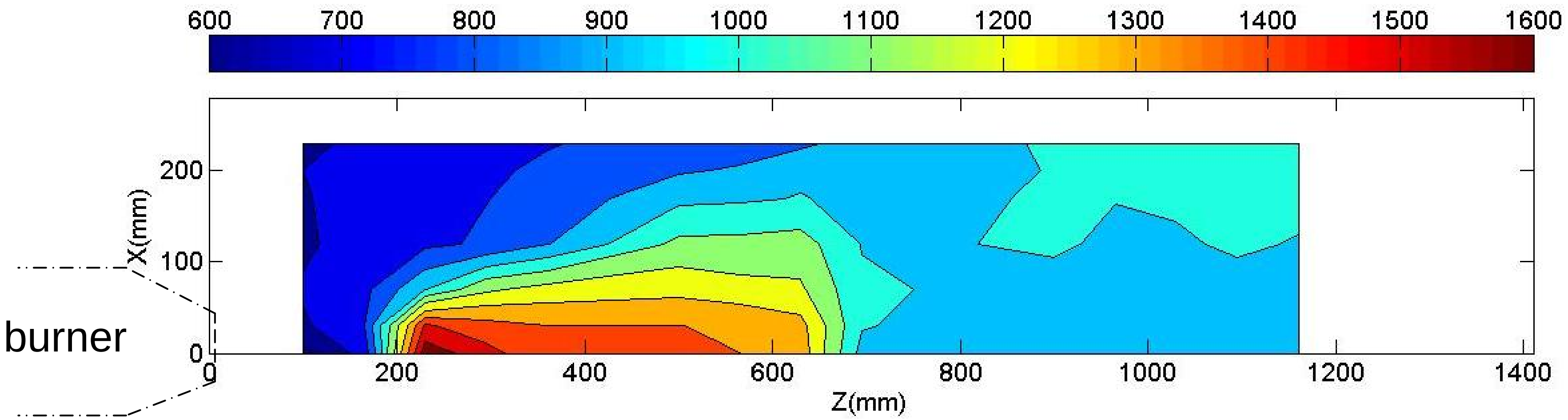


# 3. Experimental study

Temperature profile measurements for three cases:

1) firing rate 200 kW, excess air 15 %
2) firing rate 200 kW, excess air 3 %
3) **firing rate max (~ 300kW), excess air 3 %**

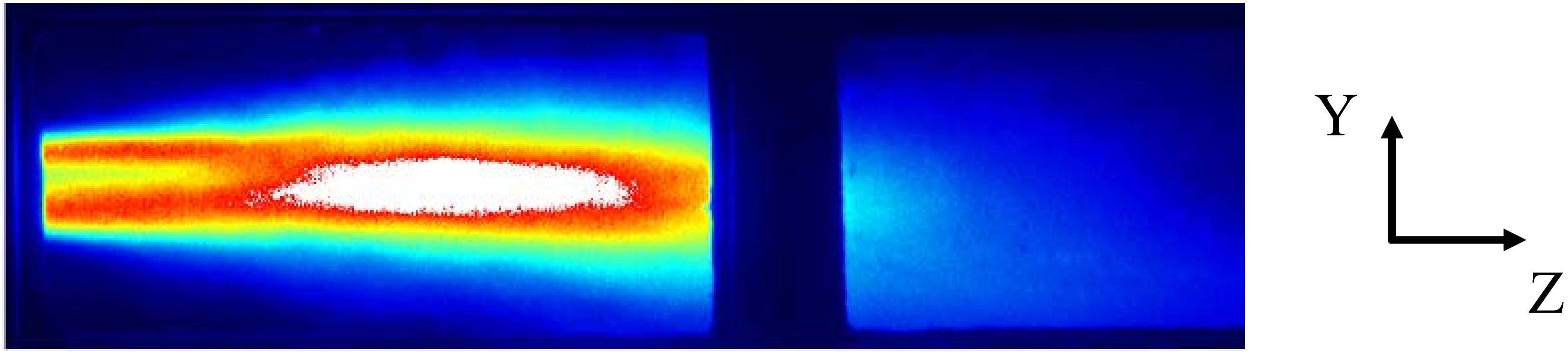


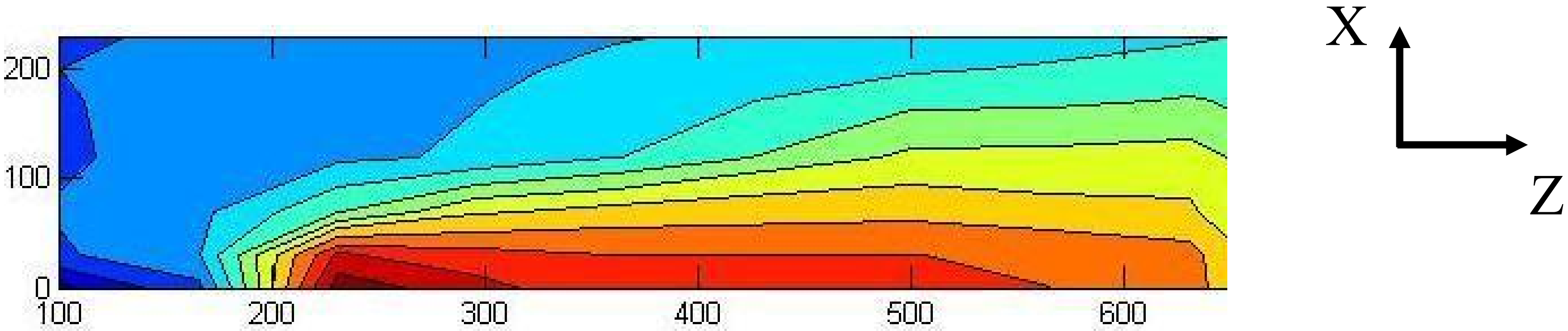

- temperature above the threshold temperature of 800°C nearly everywhere in the chamber
- coolest zone in the combustion chamber is around the nozzle of the burner.

# OH imaging

Firing rate = 290 kW, Excess air = 3%

• maximal temperature corresponds to maximal release of OH radicals



# 4. Numerical study

Recall

- First CFD study ➔ selection of a jet burner and a secondary gas injector able to generate good condition for the diluted combustion : sufficient dilution and temperature of the air and gas jets before they meet in the combustion chamber of the boiler

- Parametrical study ➔ determination of the gas injector position under the quarl D = 150 mm, $\alpha$ = 11° , d = 24 mm

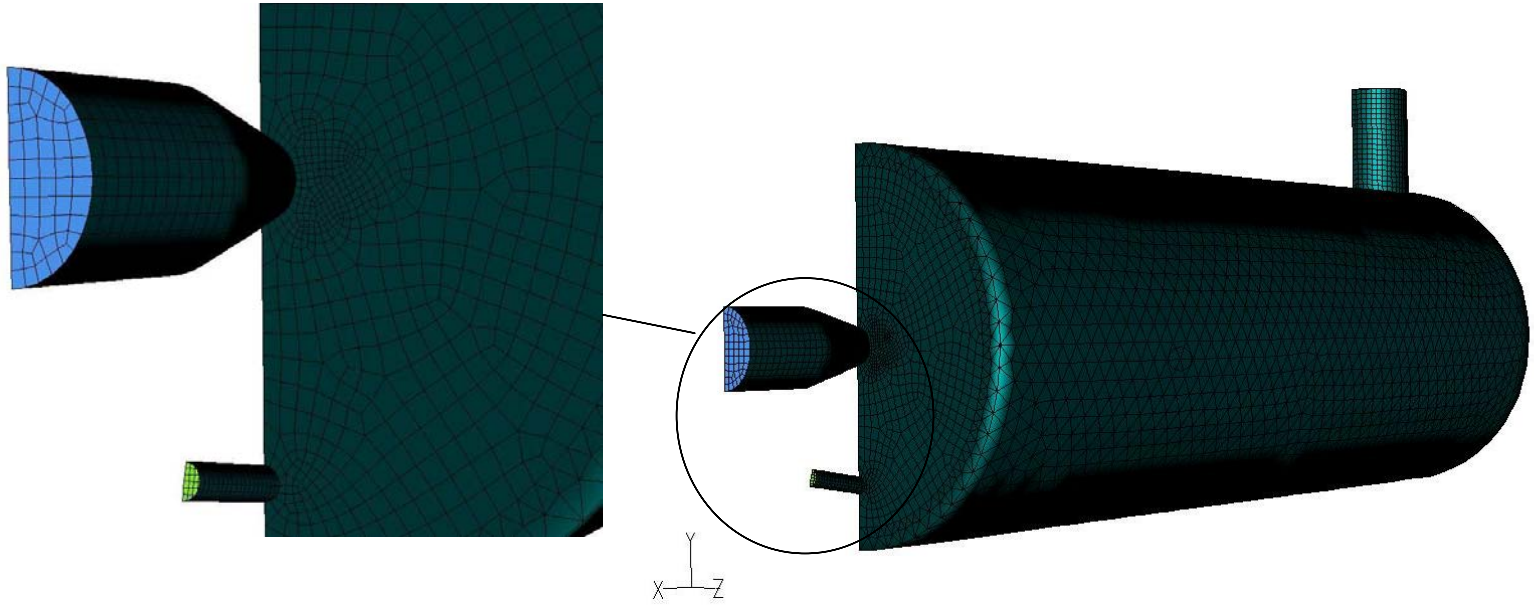
Numerical study

- experimental/numerical comparison

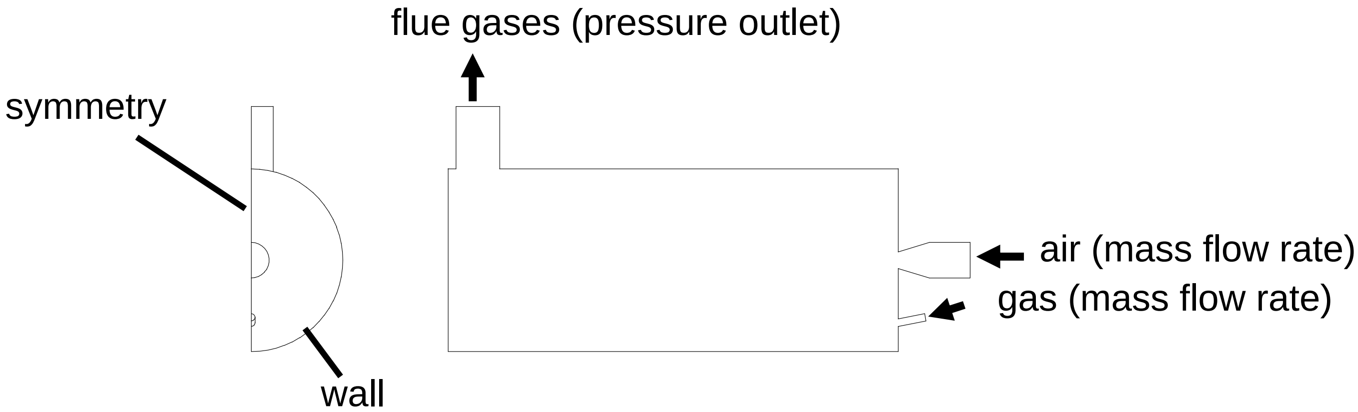
- influence of thermal input and excess air

- numerical characterization from classical combustion to diluted combustion

- ½ (burner + combustion chamber) modelled
- Maximal use of  hexahedral cells grid
- Grid refined in zones with high velocity and temperature gradients and at the exit of the air and gas injector ➔ numerical results independent to the meshing.
- 25000 cells



## Boundary conditions

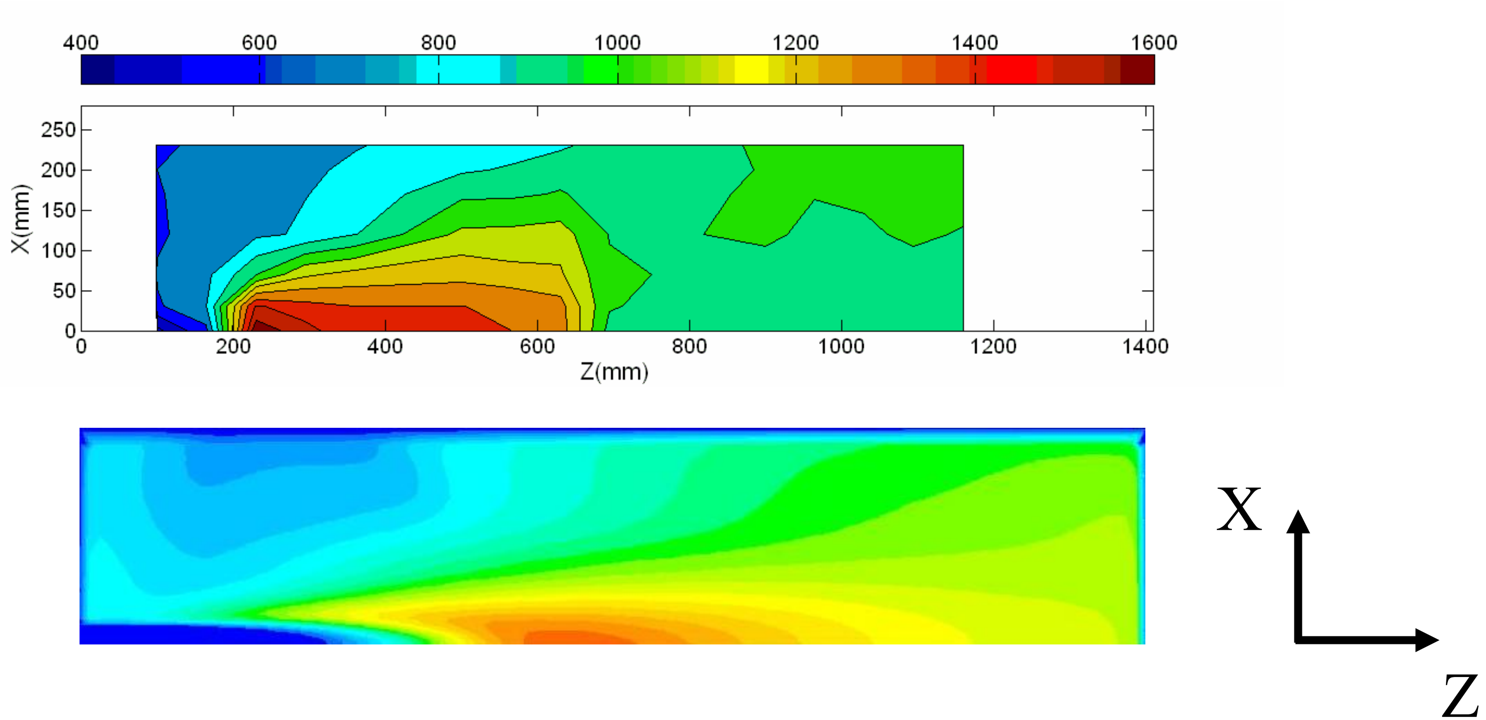



## Models

- Turbulence = standard k-ε model (with standard wall functions)
- Radiative heat transfer = discrete ordinates approach (3x3 angles)
- 2-step mechanism CxHy-Air with CO as an intermediate species (Westbrook & Dryer kinetic parameters)
- "Eddy-Dissipation Model" with modified mixing parameters (A=0.6, B=10+20)

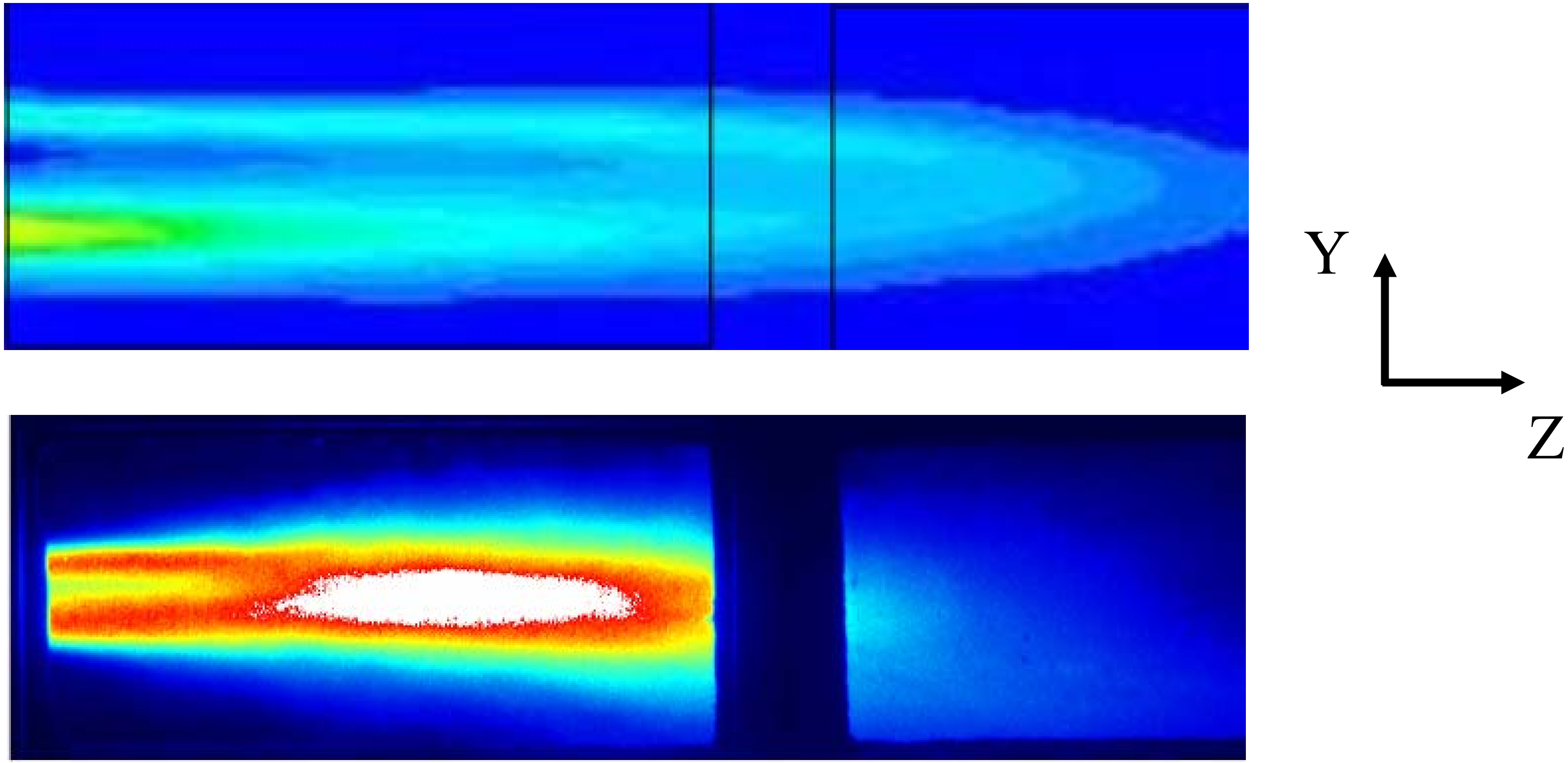
# experimental ←→ numerical (P=290kW, E=3%)

- temperature field similar
- flame longer numerically than experimentally

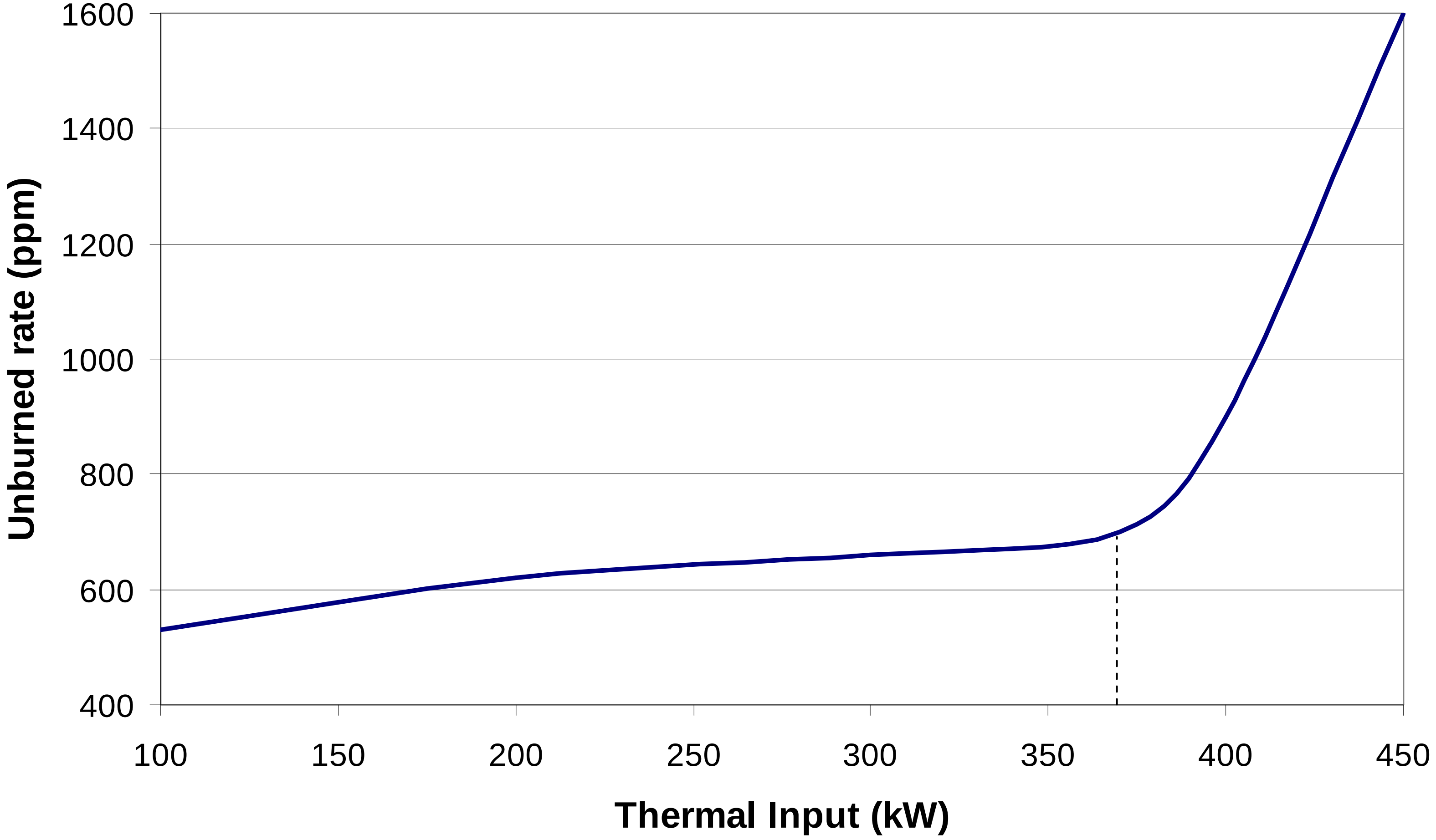


# OH imaging ←→ numerical heat release (P=290kW, E=3%)

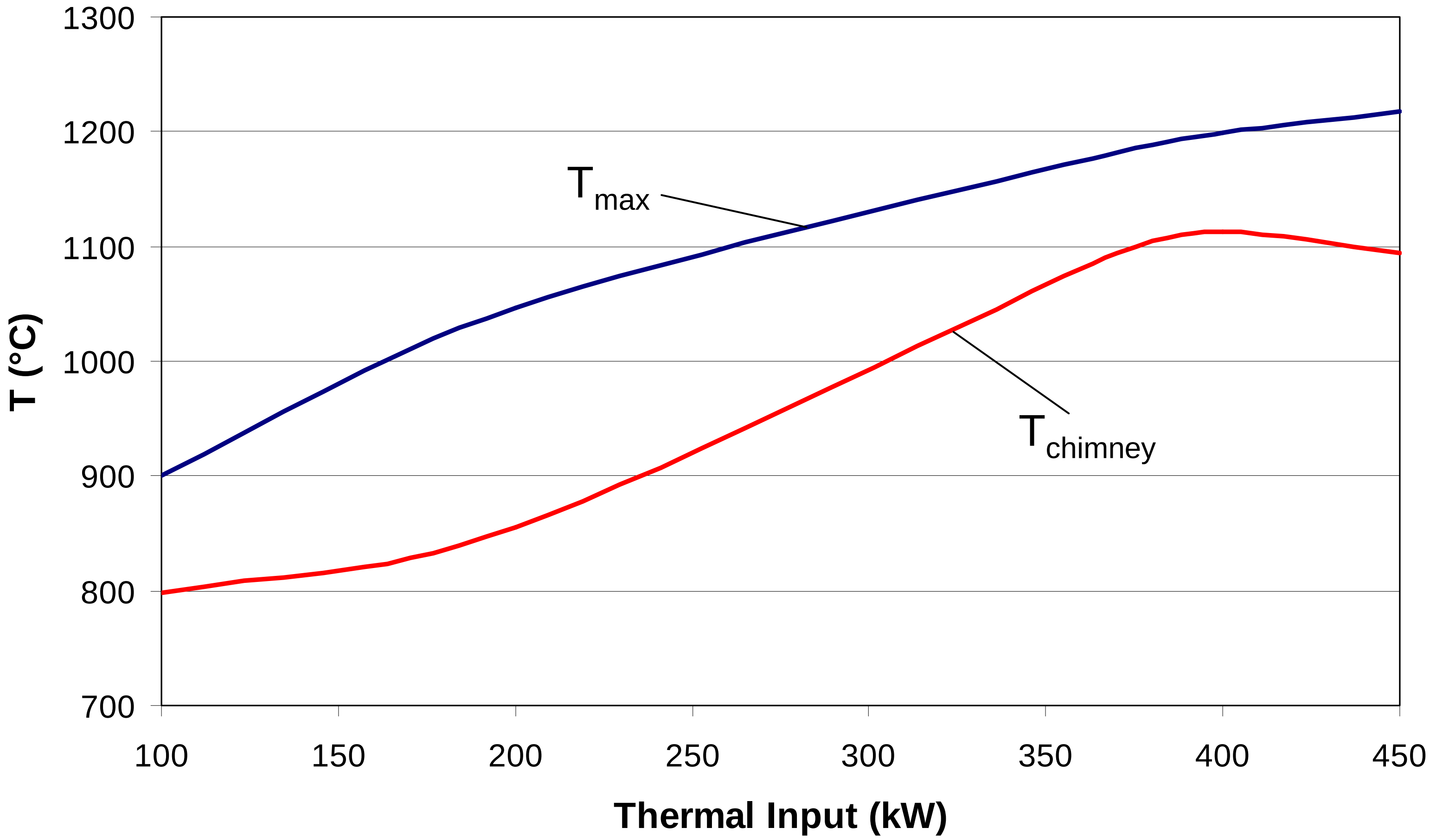
- reaction zone shape similar
- broader reaction zone numerically



# Thermal input influence



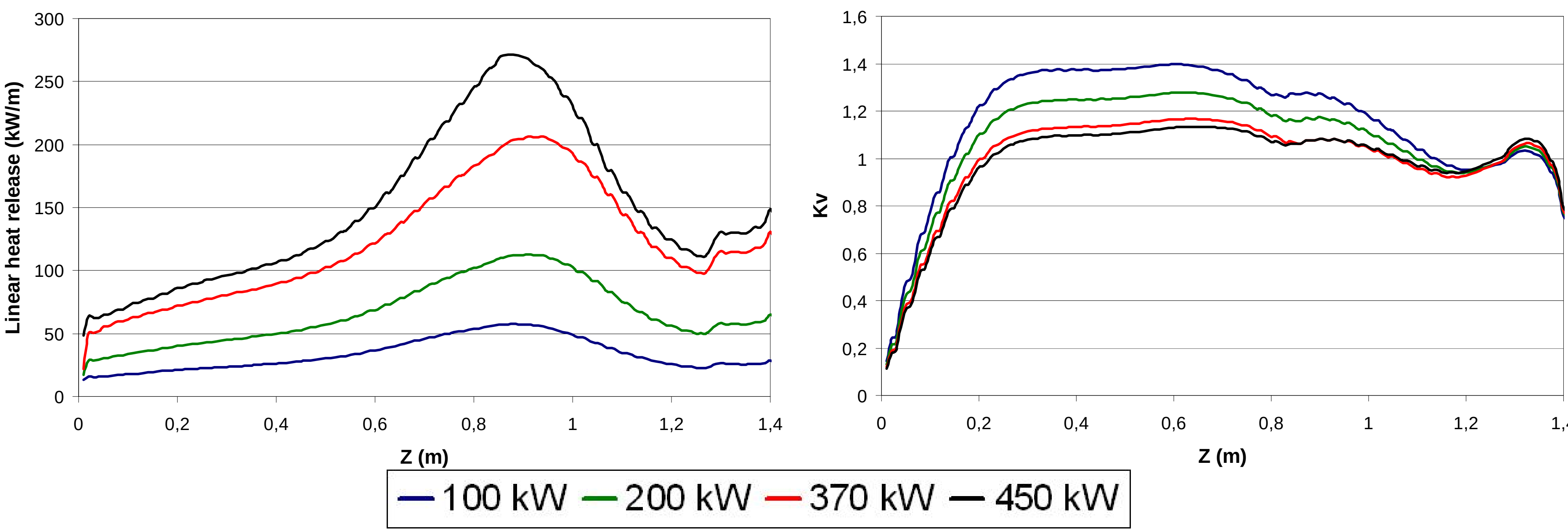
# Thermal input influence



# Thermal input influence

• linear heat release = integral of the volumetric heat of reaction in planes perpendicular to the Z-axis

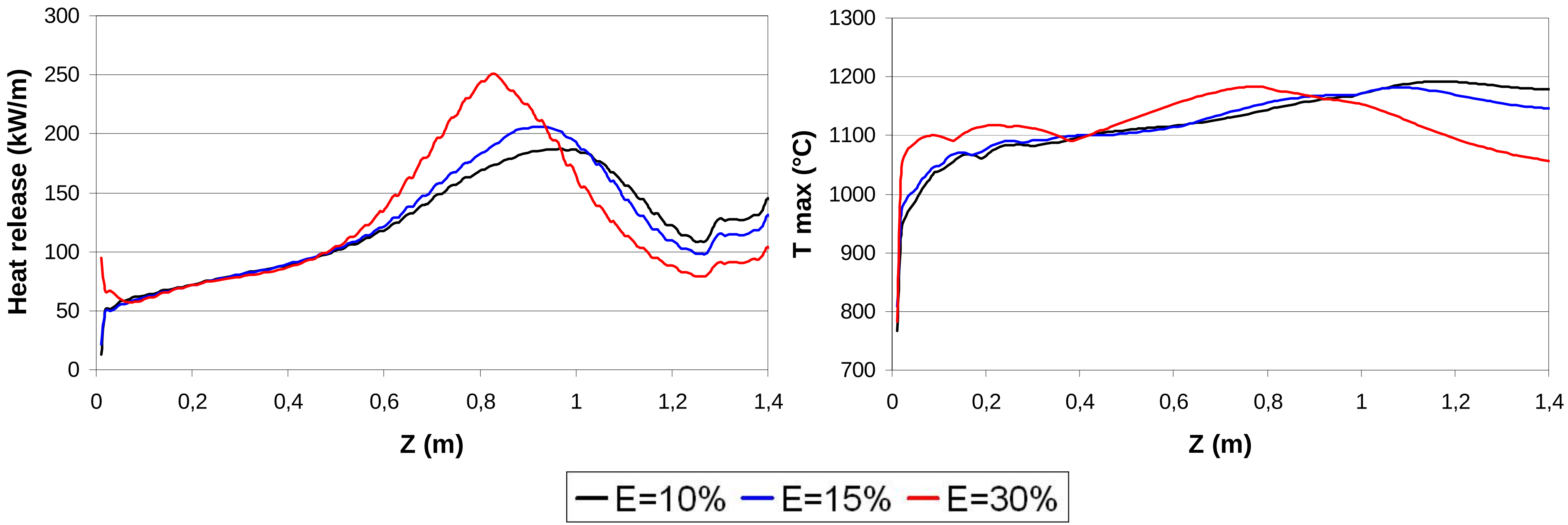
• thermal input ↓ ➔ specific firing rate (kW/m³) ↓ and Kv ↑ ➔ more homogenous linear heat release but temperature level ↓
➔ best compromise thermal input =370 kW



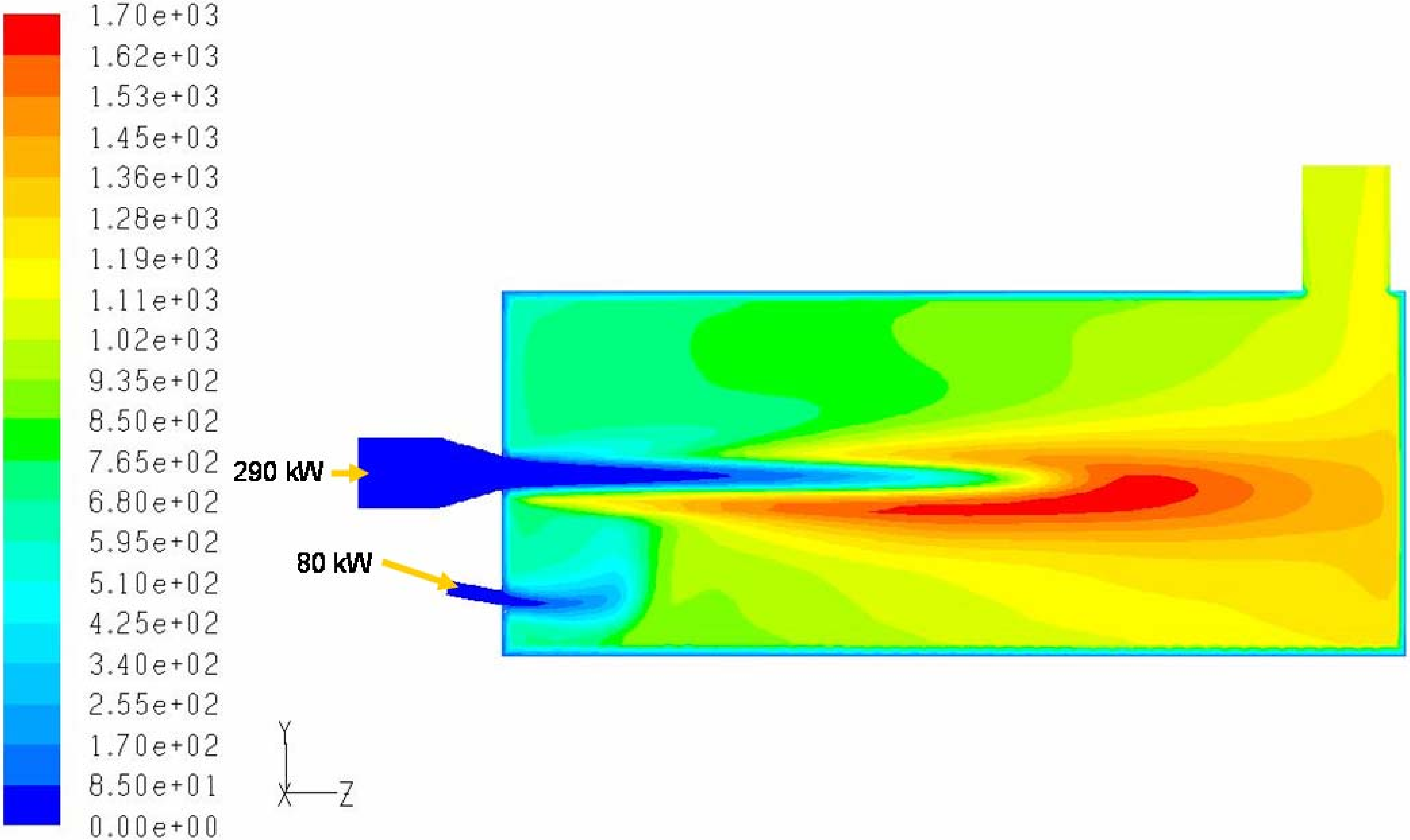
## Excess air influence

• excess air ↑ ➔ reactant dilution ↓ ➔ heat of reaction field less homogeneous and the maximum ↑ and moves to the injector exit

• excess air has to be high enough to limit the unburned rate at the exit of the combustion chamber ➔ excess air fixed to 10% for next simulations.



# numerical characterization from classical combustion to diluted combustion



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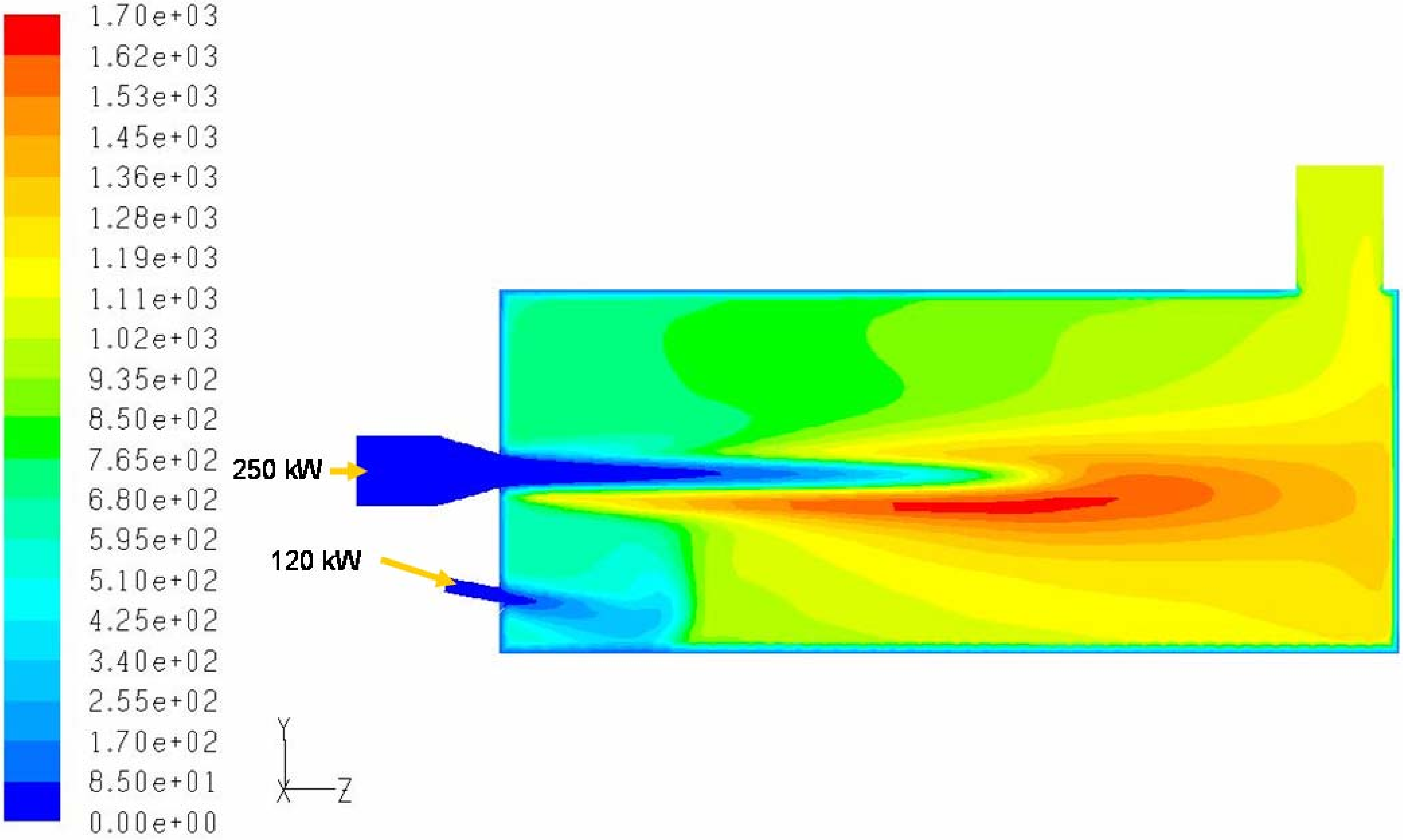

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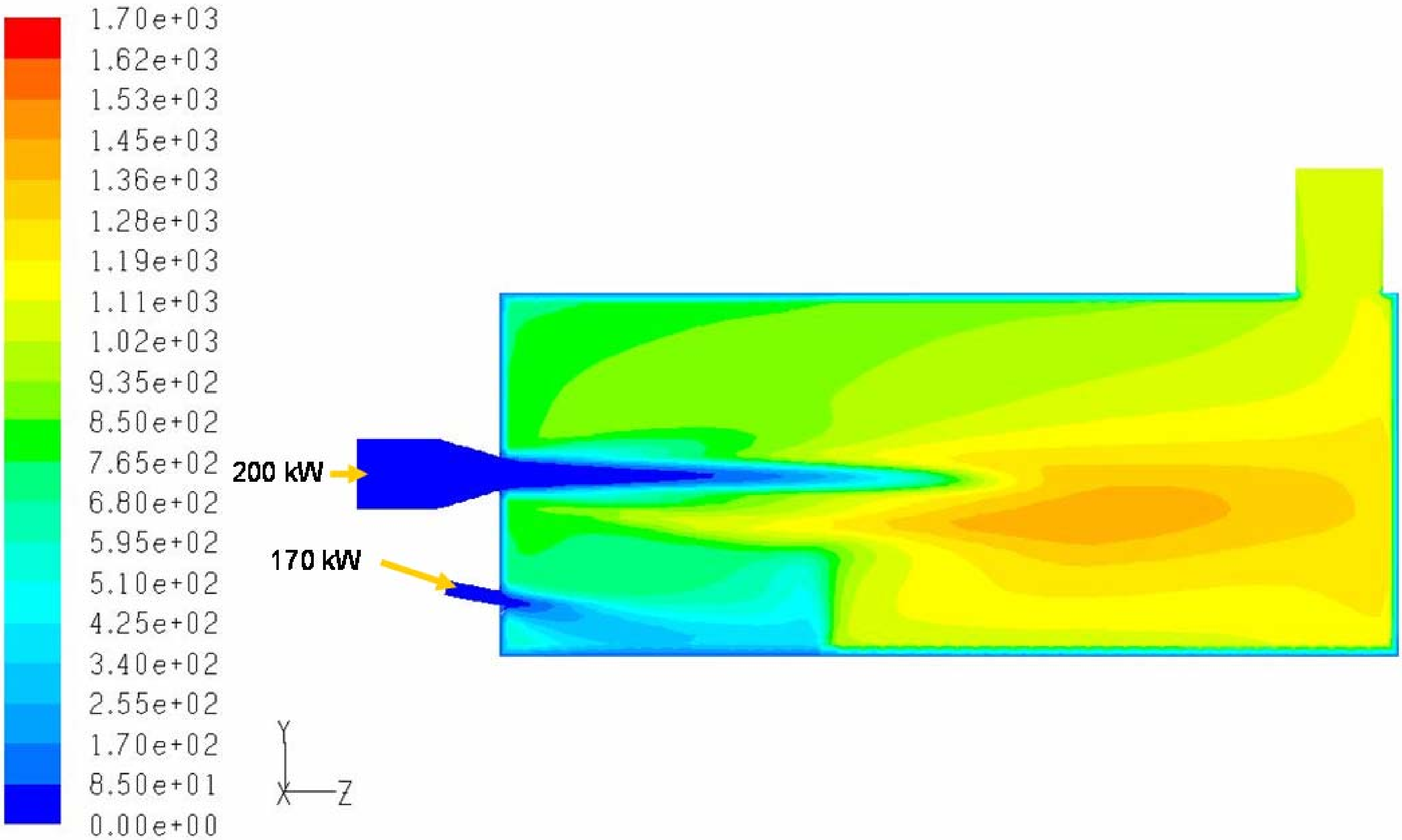

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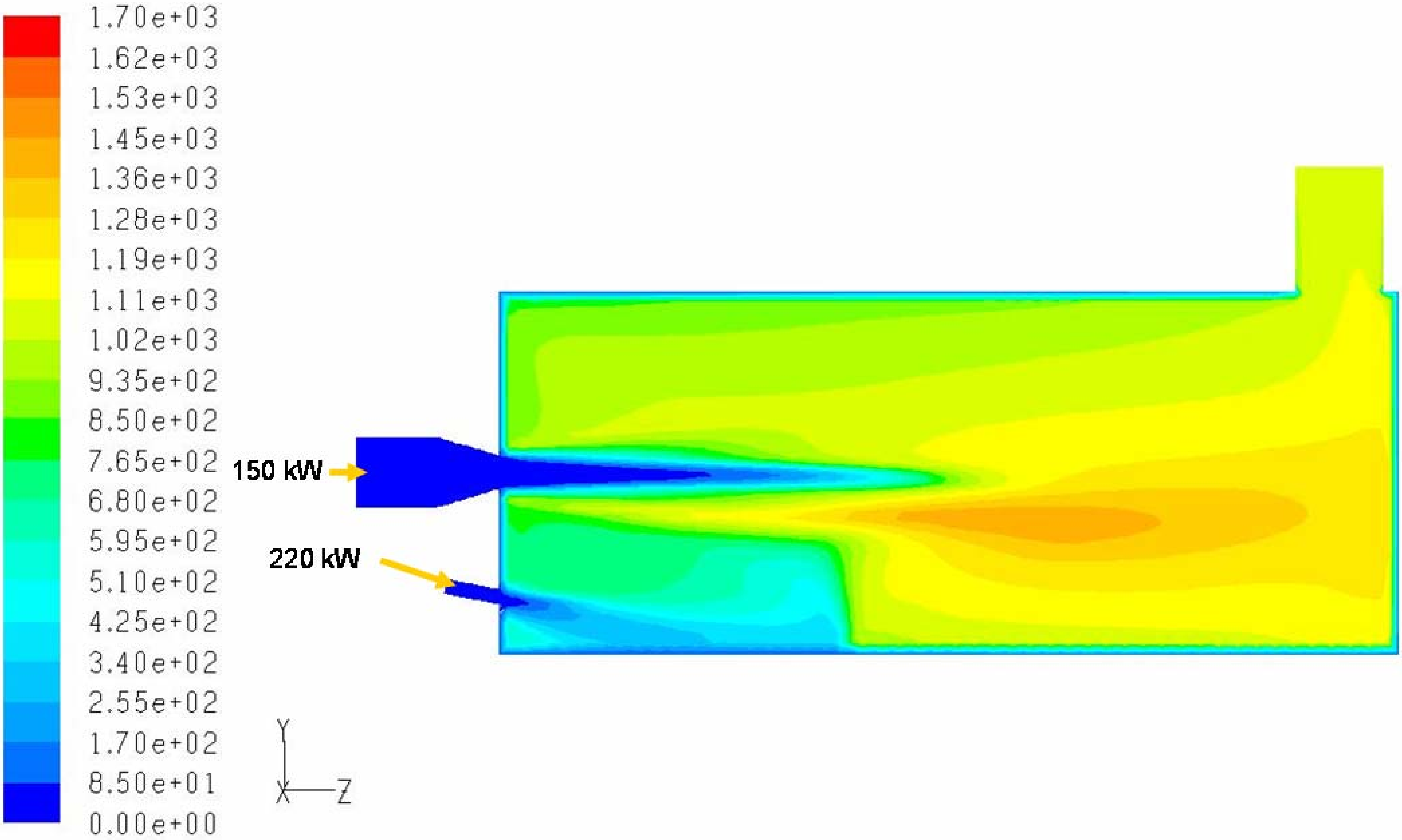

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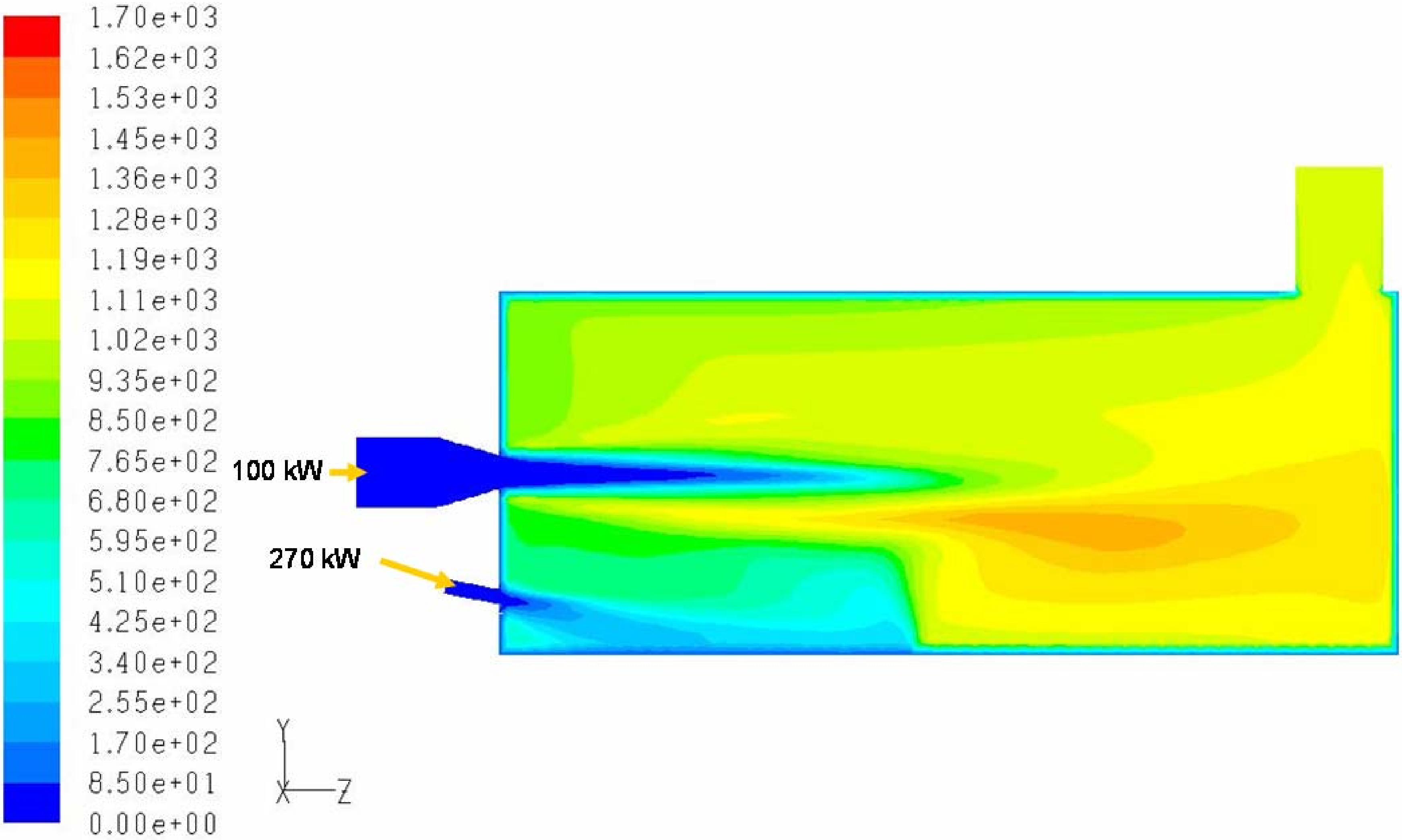
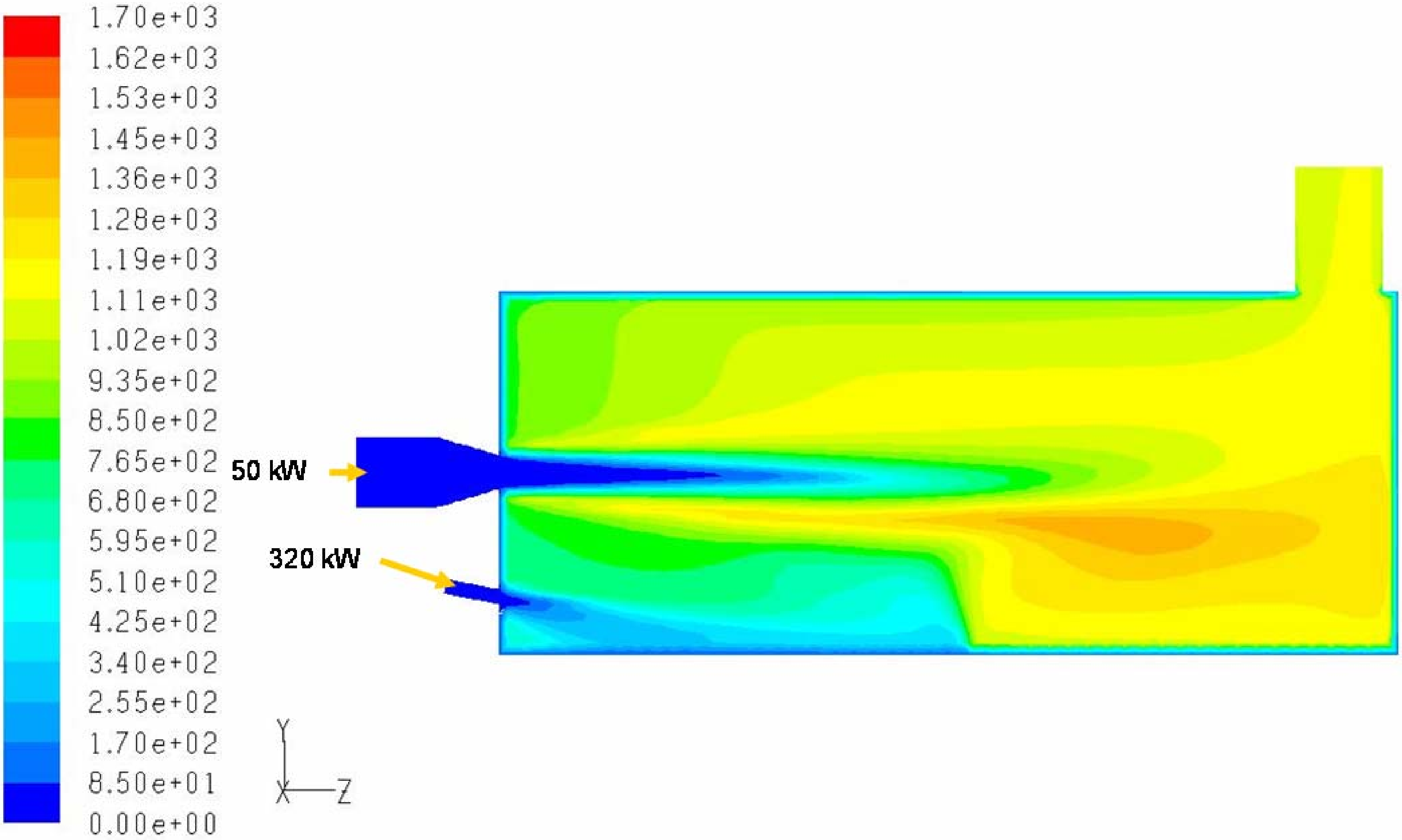
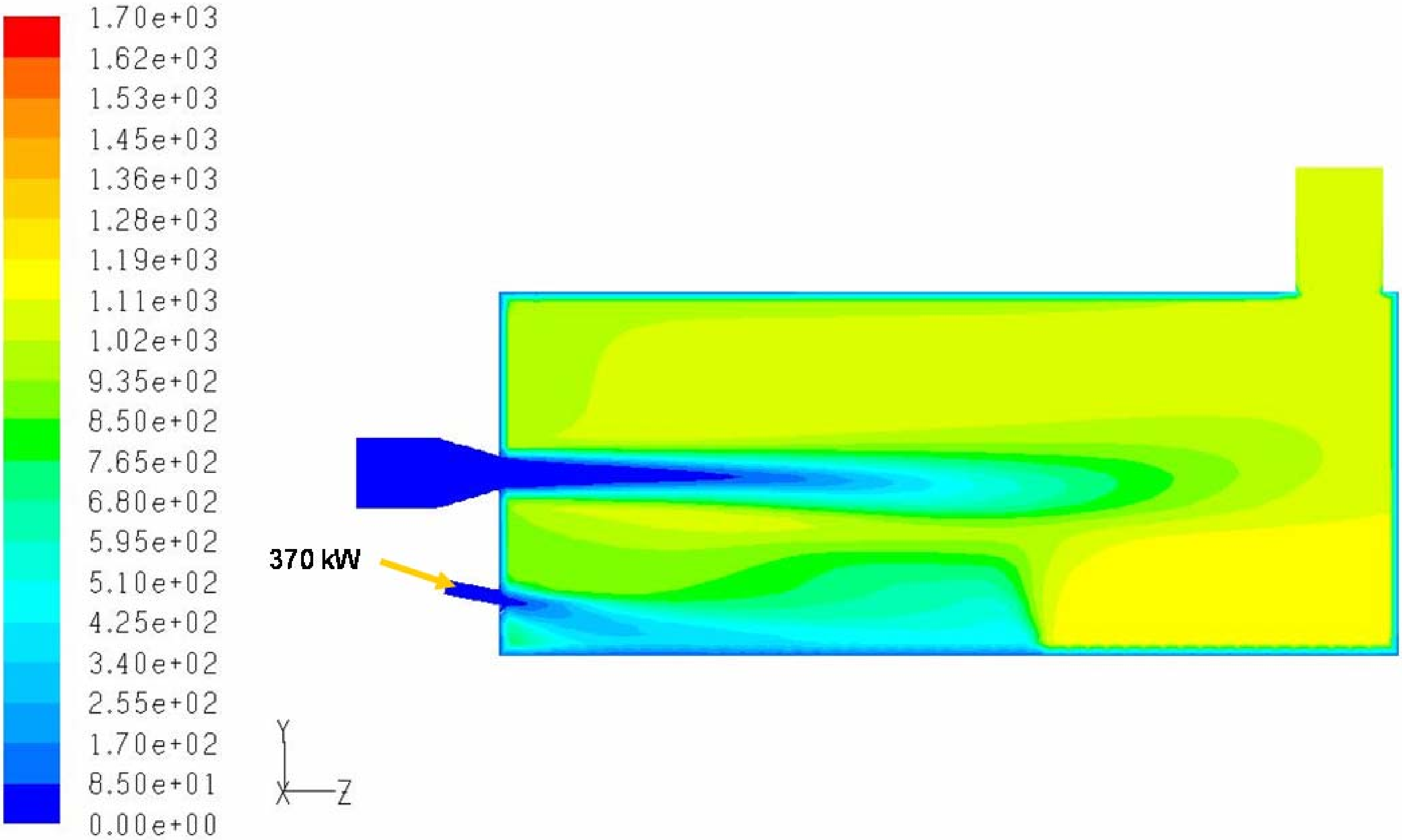


# numerical characterization from classical combustion to diluted combustion

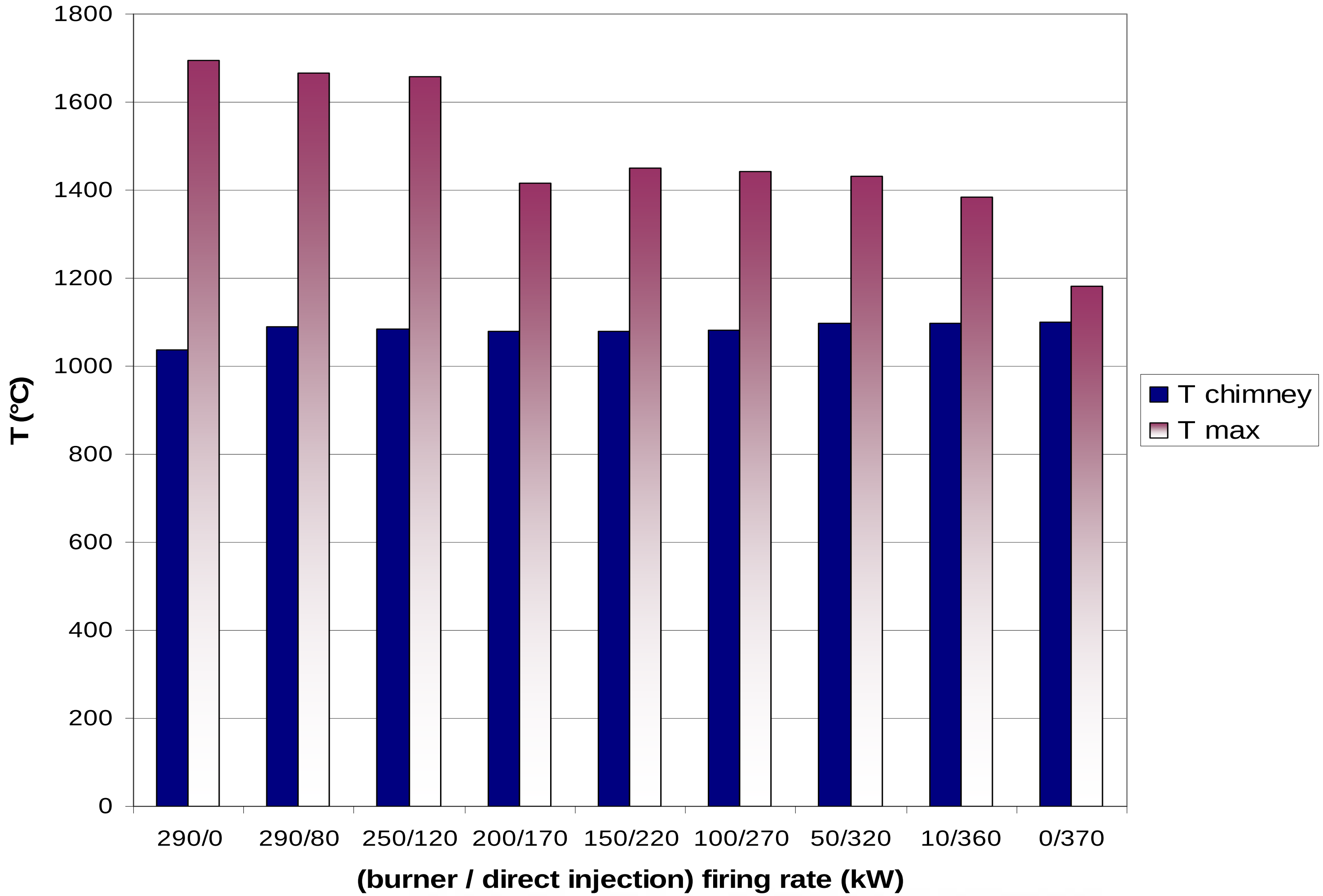


# numerical characterization from classical combustion to diluted combustion



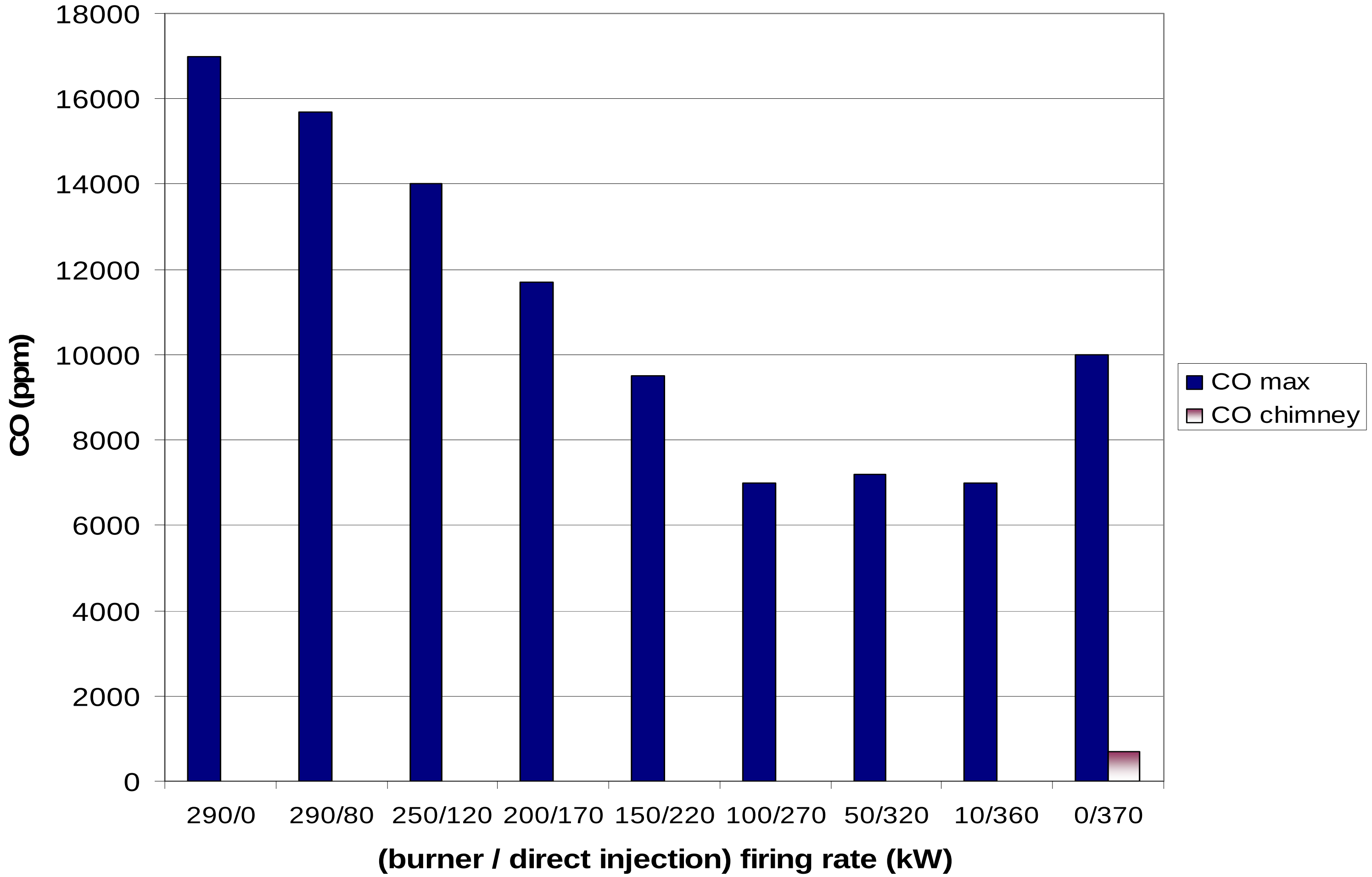
# numerical characterization from classical combustion to diluted combustion

- T max under 1350 only in 0/370



# numerical characterization from classical combustion to diluted combustion

- 700 ppm at the chimney for 0/370



# 5. Conclusions

*Done*

- Preliminary CFD study has been performed
- Parametrical study : D = 150 mm, $\alpha$ = 11° and d = 24 mm
- Experimental study in classical combustion mode
- Numerical simulation with adjustment of the parameters

*Following of the work*

- Secondary injector installation
- Feasibility study in diluted combustion mode

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**THANKS FOR YOUR ATTENTION**

# Feasibility study of the diluted combustion in a semi-industrial boiler at low temperatures

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(Sub - Tasks 2.1 H & 2.1 I)

## Abstract

The diluted combustion (called also flameless oxidation) has been already applied in furnaces technology to get high process thermal efficiency with low $NO_x$ emissions. The aim of this work is to assess the technical feasibility and highlight the specific problems of application of diluted combustion in a medium scale boiler. The main difficulty is due to the high geometrical confinement and heat losses of a typical boiler combustion chamber, which could prevent from getting the minimum level of reactants dilution and temperature needed to reach diluted combustion regime.

The idea is to perform direct injection of the air and the gas in the combustion chamber in order to get a high dilution of the reactants and a mixture temperature above the auto-ignition threshold. The test bench consists in a Viessmann hot water boiler (nominal output power = 370 kW). The combustion chamber of this boiler is cylindrical and water-cooled.

A preliminary CFD study (Fluent ®) has first been performed to select on the market a jet burner (to be used for the preheating of the combustion chamber) and to determine the position of the air and gas injectors able to generate the requirements of diluted combustion. Then, the boiler-burner set has been characterized experimentally in normal combustion regime in order to adapt the boundary conditions to the heat balance. The temperature has been measured in several locations in the combustion chamber at different firing rate and excess air. The selected burner provides as expected the required preheating and the generated flame doesn't impact the bottom of the combustion chamber. The results obtained experimentally confirm the simulation results in normal combustion regime. The last part of this work will consist in the determination of the feasibility of the diluted combustion in this boiler.

Keywords: diluted combustion, boiler, CFD study, direct injection, recirculation, mild combustion, natural gas

## Introduction

Diluted combustion technology, also called “flameless oxidation”, allows high process thermal efficiency with low pollutant emissions. This technology is today mainly used in high temperature process furnaces, to lower the $NO_x$ emissions. The principle consists in providing a high level of dilution of the reactants with flue gases before combustion reaction occurs, to get a slower reaction in a much larger volume than in classical combustion [1]. The resulting lower local heat release leads to a more homogeneous temperature field in the furnace, without peak values responsible of high thermal $NO_x$ formation [1,2,3,4]. There are two fundamental requirements: the process temperature must be above the mixture self-ignition temperature (for methane-air: 500°C theoretically, 800°C practically) and the recirculation ratio ($K_v$), which is an image of the dilution rate, must be higher than a threshold. The recirculation ratio (Equation 1) corresponds to the ratio between the recirculation gases mass and the incoming mixture mass.

$$K_V = \frac{\dot{M}_{recirculation\ \ gas}}{\dot{M}_{fuel} + \dot{M}_{Air}} \qquad \text{(Equation 1)}$$

At the moment, a lot of studies in this field have been realized to understand the phenomenon and its limit of application [5,6]. The majority of these studies concerns high temperature process furnaces with preheating of the combustion air.

In this study, the aim is to apply the principles of diluted combustion without preheating of the combustion air in the combustion chamber of a semi-industrial boiler, which differs from a furnace mainly in geometrical and thermal confinement. Safe diluted combustion conditions request that the reactant mixture temperature remains above its self-ignition level everywhere in the furnace. In the case of a boiler where the combustion chamber is water-cooled, the very high wall heat losses are therefore not compatible with the self-ignition temperature requirement. That is the reason why a preliminary study is necessary to assess the technical feasibility of the diluted combustion in a semi industrial boiler at low temperature (without preheating of the combustion air).

In this work, diluted combustion is performed by using direct injection of the reactants into the combustion chamber of a boiler. A jet burner is first used for preheating the combustion chamber with classical combustion. When the mixture self-ignition temperature is reached, combustion air and gas are then injected separately into the combustion chamber. Combustion in diluted mode in the boiler is first studied by CFD modelling, which will be validated by an experimental study on a semi-industrial boiler test bench.

## Principle

A jet-burner (high velocity injection) will be used to preheat the combustion chamber with a classical flame. The selected burner is a natural gas jet-burner (Eclipse Thermjet 100) [7]. The burner can reach a flame velocity of 150m/s for a maximal input of 293 kW.

In short, the jet burner will be first used in a classical flame combustion mode, in order to heat up the combustion chamber above the mixture self-ignition temperature level. When the temperature is high enough, we pass gradually from a classical combustion operation to a diluted combustion mode, by using the jet burner as the air injector and adding a second separated injector for the gas.

The position of the secondary gas injector is very important because it determines the level of dilution of the reactant before they meet. All the possible locations have been examined numerically and the best solution has been found to place the secondary gas injector under the burner [7]. The gas injector diameter has to be optimized to get the better condition for diluted combustion.

## Experimental setup

The test bench consists of a boiler from Viessmann (Figure 1) whose nominal output power is about 370 kW, and which is located at the Thermodynamics Laboratory of University of Liège (ULg, Belgium). Optical access is available through quartz windows placed in one side wall (see Figure 1). For temperature measurement, the quartz windows are replaced by probe-holding plate (Figure 3). The probe allows a local measurement of temperature and the extraction of the flue gases towards the analyzers.

Figure 1: Viessmann Boiler

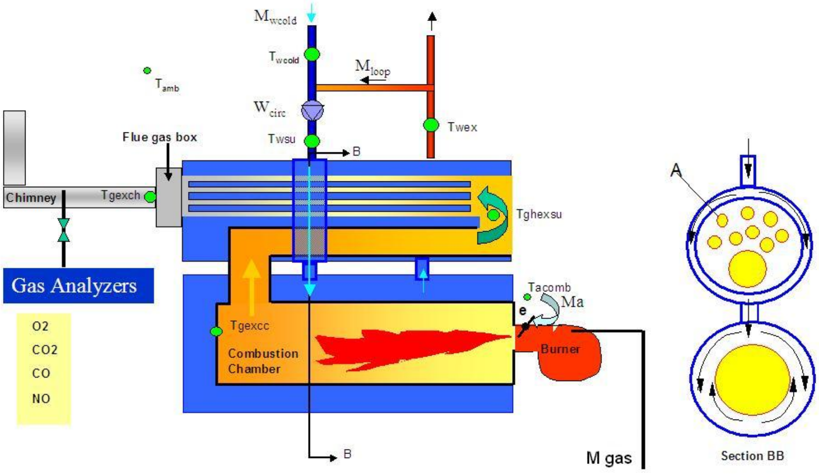


Figure 2: schematic view of the boiler

As it can be seen on Figure 2, the boiler can be subdivided in 2 parts: the combustion chamber and the heat exchanger with the chimney between them. The combustion chamber is cylindrical (length = 1.41 m, diameter = 0.56 m) and water-cooled. The combustion air is provided by a fan (SODECA CMA-528-2T-1). The jet burner is a Thermjet 100 (maximal firing rate 293 kW).

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

- the mass flow rate of natural gas at burner inlet
- the mass flow rate of air at burner inlet
- the composition of combustion gases at the exit of the boiler and in the combustion chamber at different location
- the temperature of the reactants at the inlet of the burner
- the temperature at the exit of the combustion chamber via K thermocouple
- the temperature in the combustion chamber at different location via thermocouples (Standard B (Pt-30% Rh/Pt-6% Rh))
- the imaging 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 CCD camera with the appropriate filters and thanks to the optical access in the chamber.

The flue gases temperature profiles are measured with a probe provided with two thermocouples of the same type and different diameter. This allows the correction of the measured temperatures from error due to radiative transfer between thermocouple and wall. The gas temperature is given by [8]:

$$T_f = T_1 + \frac{T_1 - T_2}{\sqrt{\frac{d_2}{d_1} * \left( \frac{T_2^4 - T_w^4}{T_1^4 - T_w^4} \right)} - 1} \qquad \text{(Equation 2)}$$

Where Tf is the gas temperature
T1, T2 are the temperature of thermocouple 1 and 2
Tw is the temperature of the wall of the combustion chamber
d1, d2 are the diameter of thermocouple 1 and 2 with d1 = 500 µm and d2 = 350µm

Five access points are available on each probe-holding plate (Figure 3) and seven temperature measurements are made radially. In total, temperature is measured on plane XZ at the 105 grid points plotted on figure 4 for each case.

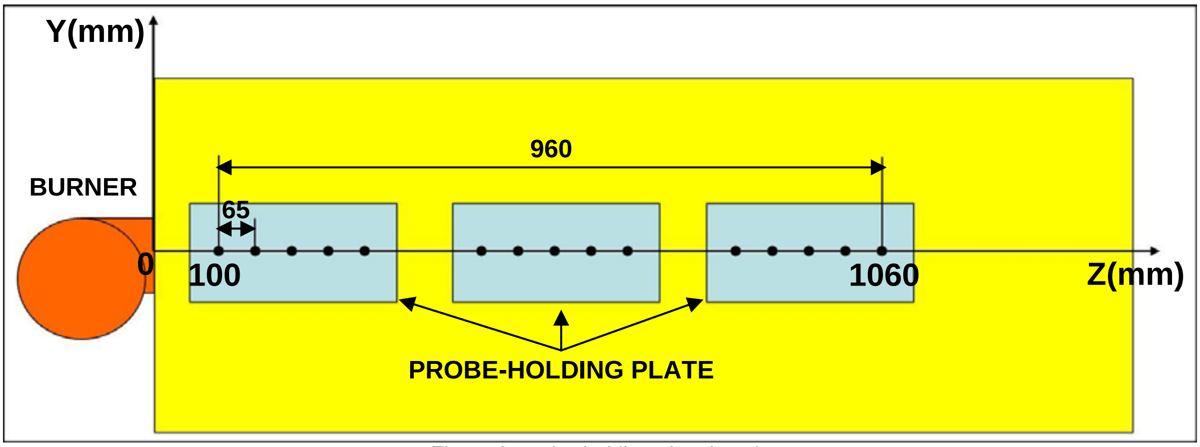


Figure 3: probe-holding plate location

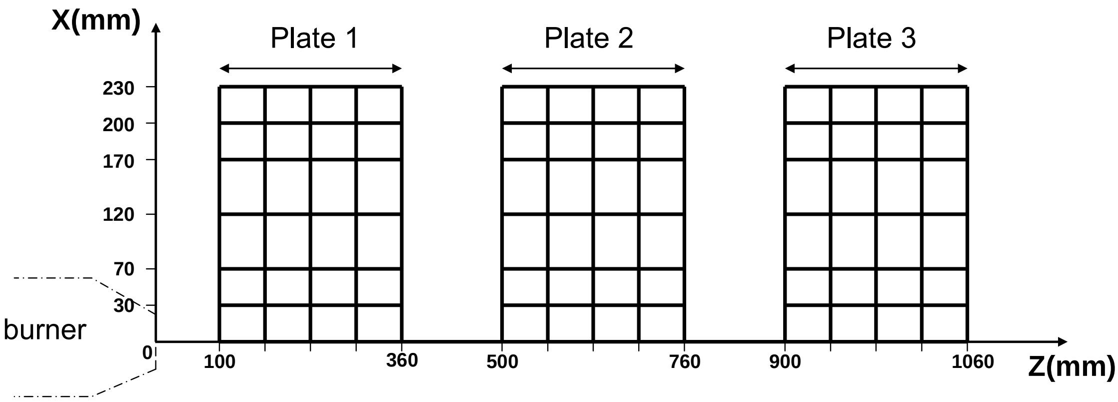


Figure 4: location of the temperature measurement point on the plane XZ

## Experimental study: results and discussion

Series of test runs have been realized. Temperature profiles have been measured along the boiler axis for three cases:
1) firing rate 200 kW, excess air 15 %
2) firing rate 200 kW, excess air 3 %
3) firing rate max (~ 300kW), excess air 3 %

For these three cases, the heat balance of the system has been checked and the species has been measured at the chimney.

The flue gases corrected temperature field corresponding to the case 3 is plotted on the figure 5. This field has been computed with the equation 2 from the values delivered by thermocouples 1 (500 µm) and 2 (350 µm), assuming a wall temperature value of 700 K. On this figure, we can notice that the temperature is above the threshold temperature of 800°C nearly everywhere in the chamber. The coolest zone in the combustion chamber is around the nozzle of the burner.

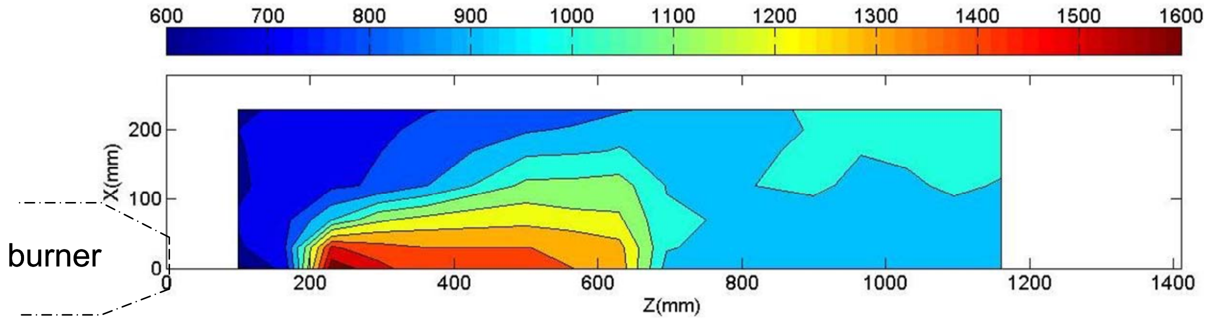

Figure 5: corrected temperature (°C) for a firing rate of 300 kW and an air excess of 3%

## Numerical study

The combustion chamber and the chimney are modelled (Figure 9) using Fluent 6.2 ®.

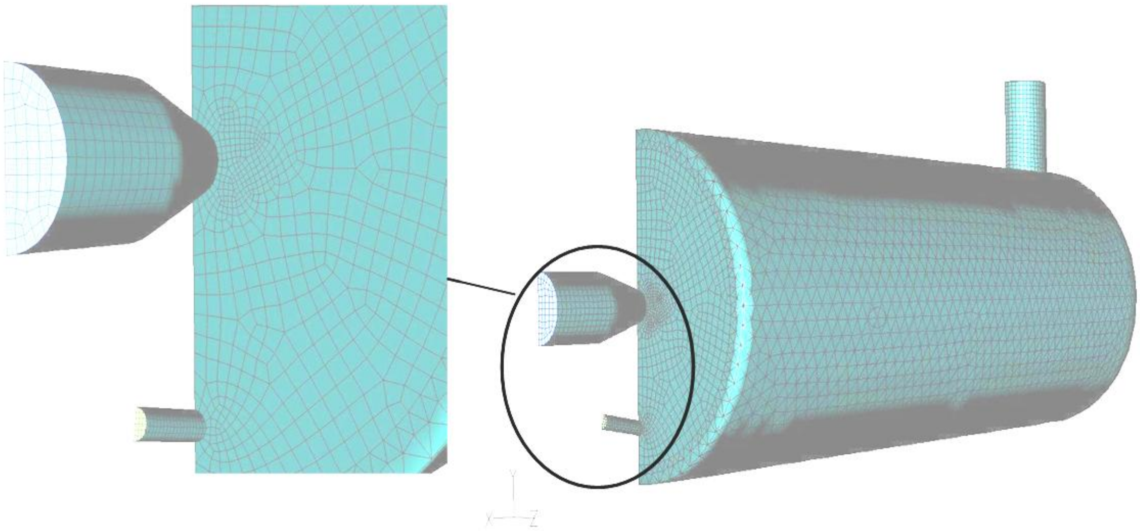

Figure 6: combustion chamber and chimney modelled in Fluent®

Half of the Thermjet 100 (293 kW) Eclipse burner and of the combustion chamber has been modelled with 250,000 cells grid (Figure 6). The grid has been refined in zones with high velocity and temperature gradients, and at the exit of the air and gas injector in order to make the numerical results independent to the meshing.

## Boundary conditions

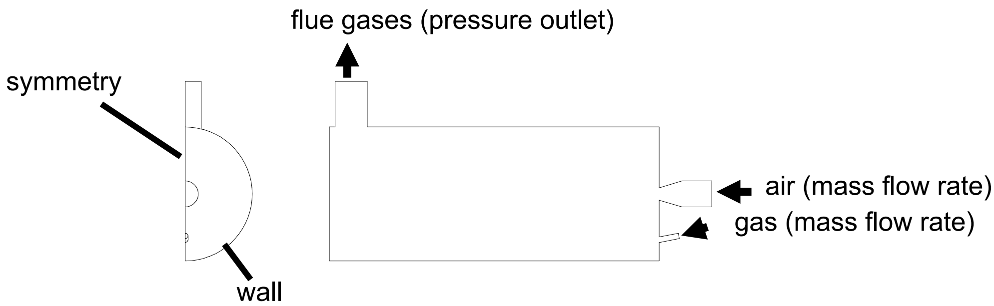


Figure 7: boundary conditions

The boundary conditions are shown on Figure 7:

- For the gas and air inlet, a mass flow rate condition is used, where a constant temperature and the mass flow of each fluid are fixed. The gas mass flow rate is fixed according to the thermal input and then a corresponding air mass flow rate is calculated with a defined excess air.
- A pressure outlet condition is used at the exit of the combustion chamber. Temperature and pressure outside the model are fixed in this condition.
- Choice of the wall temperature has been discussed in [9]. Boiler wall heat losses are imposed by a Fourier boundary condition with a heat transfer coefficient K of 4000 (W/K m²) and a water temperature of 350 K.

## Models

Standard models implemented in FLUENT are used:

- Turbulence is modelled using standard *k-ε* model, with standard wall functions.
- Radiative heat transfer is modelled with the discrete ordinates approach with an angular discretization of 3 Theta and Phi divisions. Absorption coefficient is computed with the weighted sum of gray gases assumption.
- A 2-step mechanism $C_xH_y$-Air with CO as an intermediate species implemented in Fluent® is used.
- A transport equation is solved for each species involved in the combustion reaction mechanism. Fluent proposes several models which differ by the way they compute the average reaction rate. We use the “Eddy-Dissipation Model” which assumes that the reaction rates are fully controlled by turbulent mixing parameters.

In fact, most fuels are fast burning, and the overall rate of reaction is controlled by turbulent mixing. The “Eddy-Dissipation Model” is a turbulence-chemistry interaction model. It is used when the combustion is said to be mixing-limited, and the complex and often unknown, chemical kinetic rates can be safely neglected. In diluted combustion, the turbulence slowly convects/mixes cold reactants and hot products into the reaction zones, where reaction occurs rapidly.The net rate of production of species ***i*** due to reaction ***r***, $R_{i,r}$ , is given by the smaller (i.e., limiting value) of the two expressions below:

$$R_{i,r} = \nu'_{i,r} M_{w,i} A\rho \frac{\varepsilon}{k} \min_R \left( \frac{Y_R}{\nu'_{R,r} M_{w,R}} \right) \qquad \text{(Equation 2)}$$

$$R_{i,r} = \nu'_{i,r} M_{w,i} AB\rho \frac{\varepsilon}{k} \frac{\sum_P Y_P}{\sum_j^N \nu''_{j,r} M_{w,j}} \qquad \text{(Equation 3)}$$

Where
$Y_P$ is the mass fraction of any product species, ***P***
$Y_R$ is the mass fraction of a particular reactant, ***R***
***A*** is an empirical constant equal to 4.0
***B*** is an empirical constant equal to 0.5
$\nu'_{i,r}$ stoichiometric coefficient for reactant ***i*** in reaction ***r***
$\nu''_{j,r}$ stoichiometric coefficient for product ***j*** in reaction ***r***
$\rho$ density
$M_{w,i}$ molecular weight of reactant ***i***
$M_{w,j}$ molecular weight of product ***j***
***k*** turbulence kinetic energy and $\varepsilon$ dissipation rate of ***k***

But the difficulty in studying numerically the diluted combustion with this model is that the standard mixing parameters ***A*** and ***B*** correspond to a classical flame. The works of Lupant [2] and Malfa [10] have show that a modification of the “Eddy-Dissipation Model” mixing parameters better reproduce the furnace temperature profiles measured in pilot-scale furnaces working in diluted combustion. The value of ***A*** and ***B*** have been fixed respectively at 0.6 and $10^{+20}$ (infinite). The result of this modification is that the combustion reaction gets slower in a much larger volume than with the standard mixing parameters. On figure 8, the local volumetric heat of reaction is plotted for the two configurations.

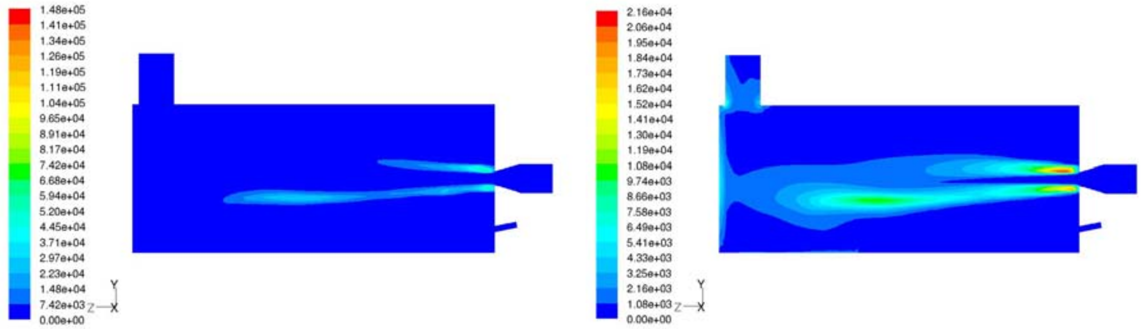


Figure 8: volumetric heat of reaction field (kW/m³) in the median plan YZ of the combustion chamber for at the left, standard mixing parameters (A=4 , B=0.5) and at the right, modified mixing parameters (A=0.6, B=$10^{+20}$)

## Parametric study

A first CFD study has allowed the determination of the gas injector position under the quarl [7]. After this, a parametric study consisting of the optimisation of the gas injector position and diameter has been performed [8]. The position of the gas injection is defined by two parameters: the distance (D) between the injector and the quarl and the angle (α) of the injector axis in the plane YZ (Figure 9).

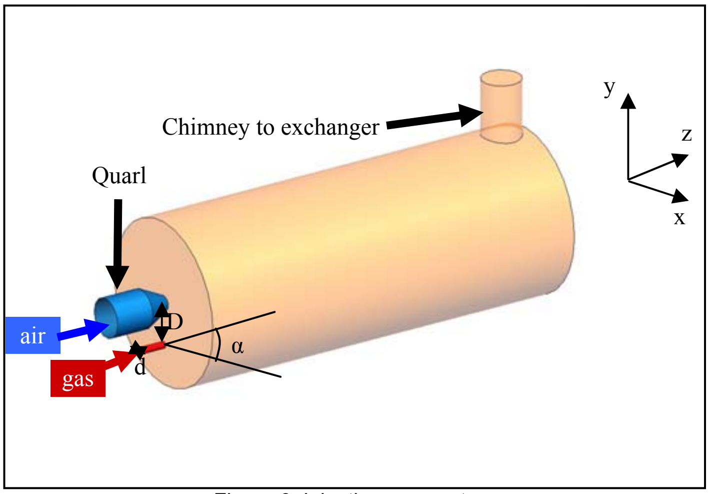


Figure 9: injection parameters

By varying these 2 parameters, we can obtain an intersection point between the 2 jets as far as possible in the combustion chamber. Practically, the distance D has to be limited at 150 mm. The angle α has to be limited to keep a temperature of the recirculation flue gas high enough to reach the auto-ignition threshold. The choice of an angle α of 11° allows a quite good dilution of gas and air before they meet and a mixture temperature above the auto-ignition threshold.

The influence of the secondary gas injector diameter (d) can be characterized by the unburned content at the exit of the combustion chamber and the maximal temperature reached in the chamber. A diameter reduction leads to an increase of the unburned level in the chimney and a decrease of the maximal temperature; this is a consequence of the increasing of the reactants dilution by the acceleration of the gas jet. The gas injection diameter has to be optimized to insure a sufficient dilution of the reactants for maintaining the maximal temperature below a critical level for the NOx formation, while conserving the unburned rate under an acceptable level. Finally, the best compromise between the dilution level and the unburned rate is obtained with a diameter of 24mm [8].

## Influence of the thermal input

By varying the thermal input at a fixed excess air (15%) and with an injector diameter of 24 mm (Figure 10), we observe that the unburned rate at the chimney is constant till 350-400 kW and then increases in a significant way. The capacity of the combustion chamber of the boiler corresponds to 450 kW in classic combustion. In diluted combustion, this capacity is reduced because of the properties of this type of combustion. Actually, the combustion reaction occurs in a much larger volume and is slower than in classical combustion. The volume of the combustion chamber has to be higher to get the same capacity. The maximal temperature in the combustion chamber increases as for the temperature at the chimney when the thermal input increases (Figure 11). But the limitation due to the capacity of the combustion chamber can be seen in the profile of the chimney temperature. In fact, the chimney temperature remains nearly constant when the thermal input is above 350-400 kW.

The influence of the thermal input on the heat release and the Kv is plotted on the figure 12 and 13. The figure 12 corresponds to the linear heat release along the Z axis. The linear heat release corresponds to the integral of the volumetric heat of reaction in planes perpendicular to the Z-axis. By decreasing the thermal input we decrease the specific firing rate (kW/m³) and so the thermal confinement. We get a higher Kv, so a more homogenous linear heat release in the combustion chamber and finally we get a more uniform temperature field. Although the dilution level (Kv) is better for a lower thermal input, the temperature level is to low to answer to the other requirement of the diluted combustion (temperature above the auto-ignition threshold). Finally, the best compromise is a thermal input of 370 kW.

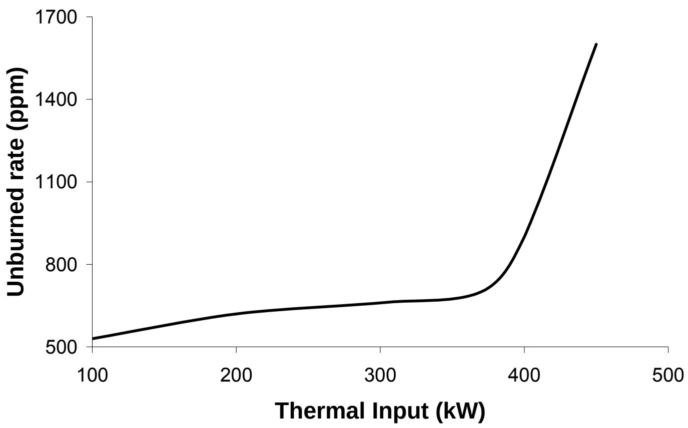


Figure 10: unburned rate at the chimney according to the firing rate

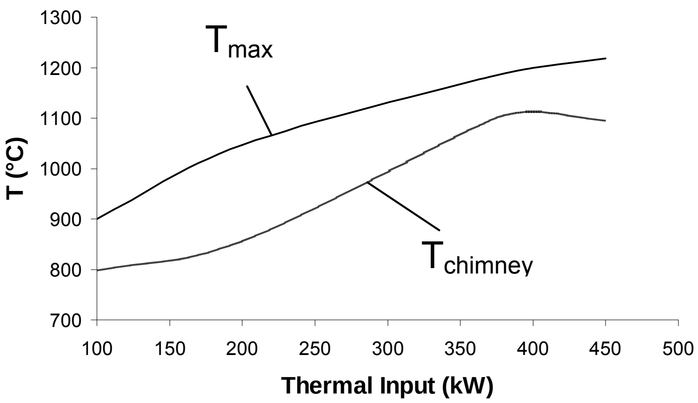


Figure 11: maximal temperature and temperature at the chimney according to the firing rate

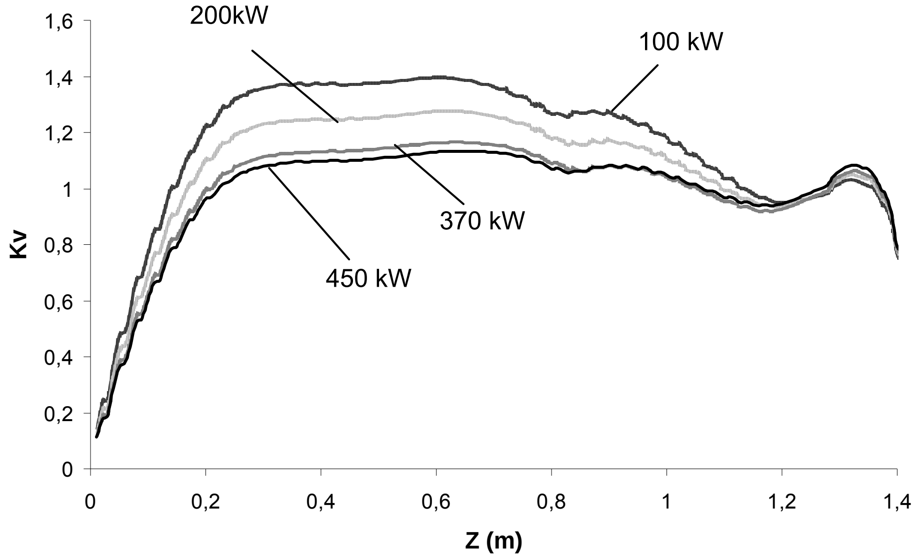


Figure 12: recirculation ration Kv at 15% excess air for different thermal input

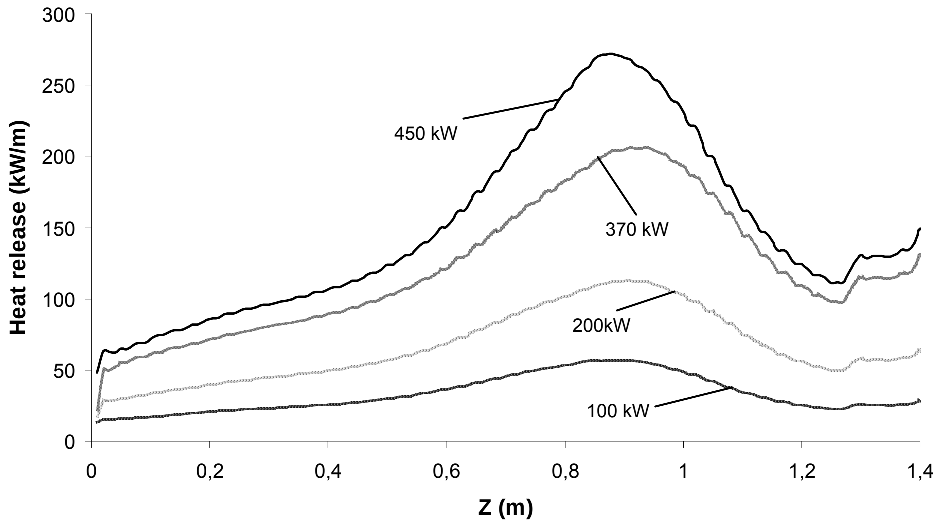


Figure 13: linear heat release at 15% excess air for different thermal input

## Influence of the excess air

The influence of excess air on maximal temperature and on heat release distribution is plotted on figure 13 and 14. As expected when the excess air increases, we observe a decrease of the reactant dilution: the heat of reaction field becomes less homogeneous and the maximum increases and moves to the injector exit. The property of diluted combustion are conserved even at an excess air equal to 30% as it can be seen of the uniform temperature profile of figure 13. However, the excess air has to be high enough to limit the unburned rate at the exit of the combustion chamber (Figure 15). We will fix the excess air to 10% for the rest of the simulations.

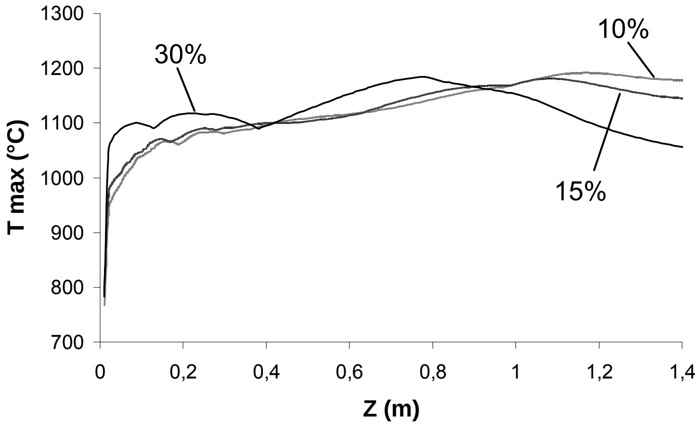


Figure 13: maximal temperature along the Z axis for an excess air of 10%, 15% and 30% and a thermal input of 370 kW

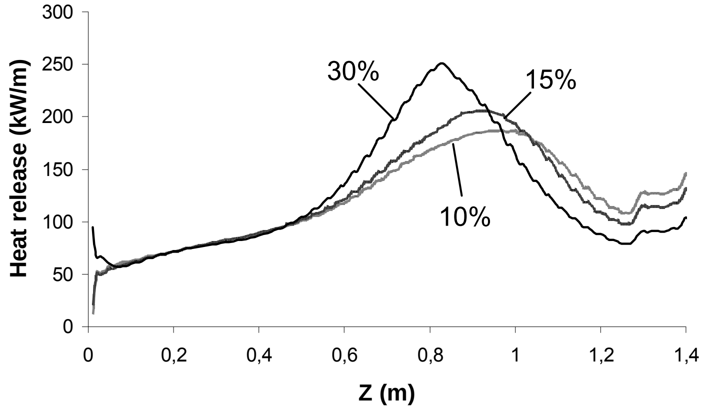


Figure 14: linear heat of reaction along the Z axis for an excess air of 10%, 15% and 30% and a thermal input of 370 kW

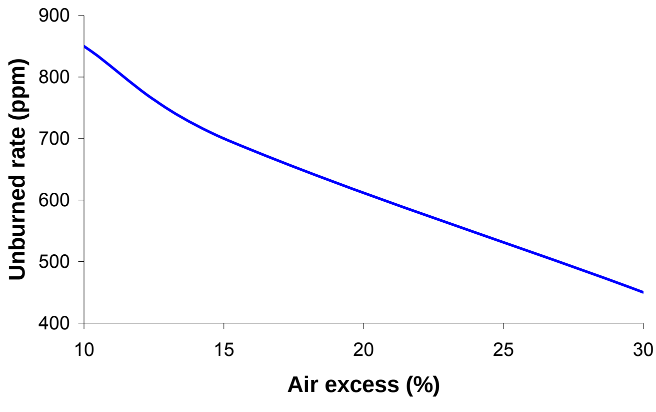


Figure 15: unburned rate in function of the excess air for an injector diameter of 24 mm

## Numerical characterization from classical combustion to diluted combustion

The passage from the classical combustion to the diluted mode has been simulated. All the simulations are in a stationary mode. The starting simulation is the burner at its maximal firing rate (~290 kW) without direct injection of gas. The air injected in the burner is then increased to a mass flow corresponding to a firing rate of 370 kW. Then a mass flow of gas corresponding to 80 kW is injected through the secondary gas injector. At this point, 290 kW are injected through the burner and 80 kW are injected directly under the burner. The distribution of the gas between the burner and the secondary injector will vary from 290 kW by the burner and 80 kW by the secondary injector to 370 kW all by the secondary injector. The figure 16 and 17 represents the evolution of the unburned and the temperature in function of the distribution of gas. The unburned rate at the exit is null for all the distributions but 0/370 distribution (corresponding to the diluted combustion regime) where the unburned rate is equal to 700 ppm. For this distribution the maximal temperature in the chamber is far below the other configurations. Only the 0/370 configuration gives a maximum temperature under the critical level for thermal NOx formation.

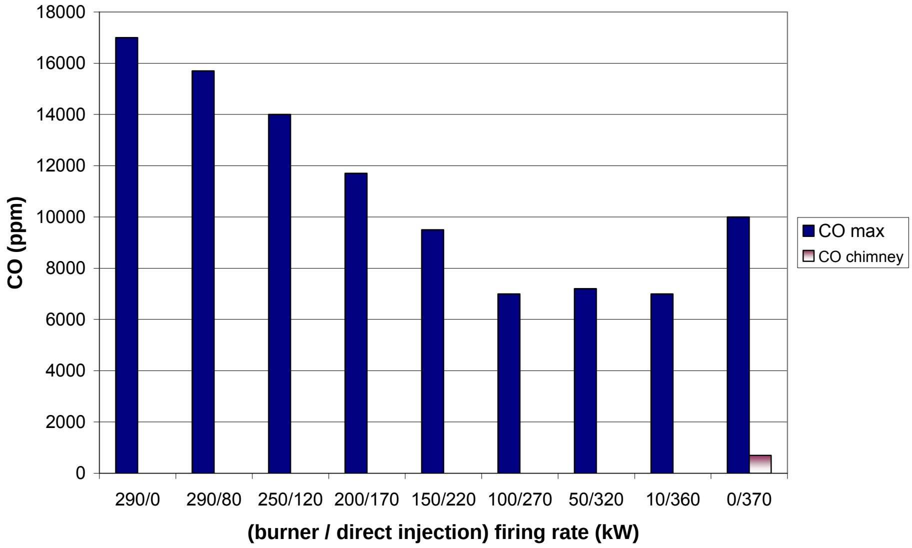


Figure 16: CO max in the chamber and CO at the chimney for variant distributions of the gas

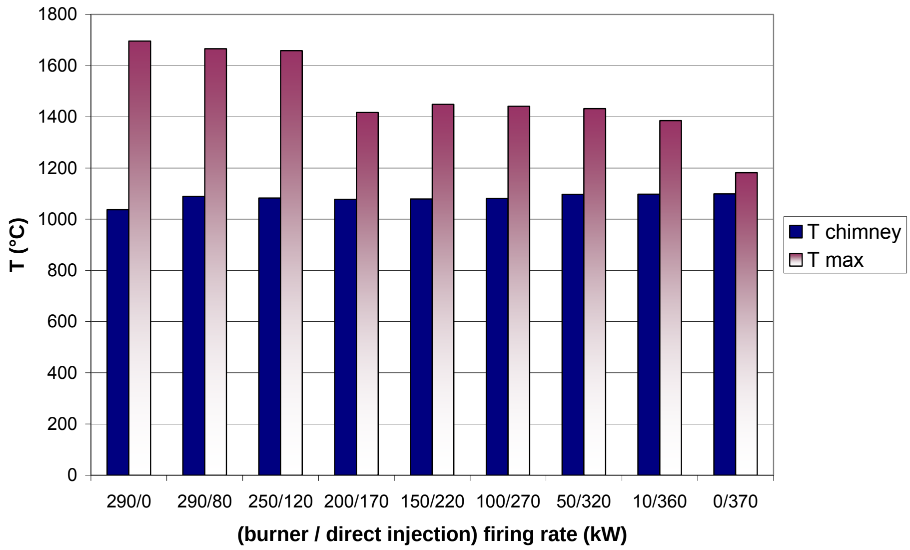


Figure 17: maximal temperature in the chamber and temperature at the chimney for variant distributions of the gas

## Conclusions and perspectives

To assess the feasibility of diluted combustion by direct gas injection in a medium scale boiler at low temperature, a preliminary CFD study has been performed, to select a standard jet burner from the current market, able to generate sufficient internal recirculation for reactants dilution in the boiler. A characterization of the combustion chamber in classic combustion allowed the best determination of the wall boundary condition in Fluent®.

The dependence of the present numerical results to the parameters of the combustion model has been examined. In the meantime, a first parametric study has been performed to determine the optimum location, injection angle and diameter of a secondary gas injector to maximize the dilution of the air and gas jets before they meet. The optimum is obtained with a distance D of 150 mm, an angle α of 11° and an injector diameter of 24 mm. The influence of the thermal input and excess air has been acknowledged numerically. Finally, the evolution of the gas distribution has been studied numerically.

Simultaneously, an experimental study has been started at University of Liège (Belgium) to validate modelling results. Temperature profiles have been measured in the boiler equipped with the Thermjet burner, in classic flame mode. The measurements have shown that the flue gas temperature level is high enough to get conditions for diluted combustion.

At the end of year 2008, the adaptation of the secondary gas injection in the chamber will be finalized and measurements will be performed on the semi-industrial boiler available at the Thermodynamics Laboratory of Liège University to assess the feasibility of the diluted combustion and validate numerical results.

## Acknowledgements

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## Bibliography

[1] Wünning, J.A. and Wünning, J.G., Progress in Energy and Combustion Science 23 n°12, 81-94, (1997).

[2] Lupant D., Pesenti B. and Lybaert P., 27th TLM “Numerical and Experimental Characterization of a Self-Regenerative Flameless Oxidation Burner Operation in a Pilot-Scale Furnace”, Zurich, September 2005

[3] De Joannon, M., Langella, G., Beretta, F., and Noviello, C., Combustion Science and Technology 153, 33-50, (2000).

[4] Plessing, T., Peters, N. and Wünning, J.G., 27th International Symposium on Combustion, University of Colorado at Boulder, USA, (1998).

[5] Mancini, M., PhD. Thesis “Analysis of mild combustion of Natural Gs with preheated air”, Clausthal University of Technology, Germany, (April 2007).

[6] Masson, E., PhD. Thesis “Etude expérimentale des chams dynamique et scalaire de la combustion sans flamme”, Institut National des sciences appliquées de Rouen, France, (2005).

[7] Seggio G., Ngendakumana P., Pesenti B. and Lybaert P., 28th IEA Task Leader Meeting Heidelberg, Germany, (2006).

[8] De D.S., “Measurement of flame temperature with a multi-element thermocouple”, Journal of the Institute of Energy, June 1981

[9] Seggio G., Ngendakumana P., Pesenti B. and Lybaert P., 29th IEA Task Leader Meeting Gembloux, Belgium, (2007).

[10] Malfa, E., Venturino, M, Macchi, E. and Tota, V., 23d IFRF Topic Oriented Technical Meting “Efficiency and Flexibility of Energy Use in the Iron and Steel Industry”, Ijmuiden, Netherlands, March 2003.

POLYTECH.MONS

WORK IN PROGRESS

# Development of stability diagrams of flame in diluted combustion

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RÉGION WALLONNE

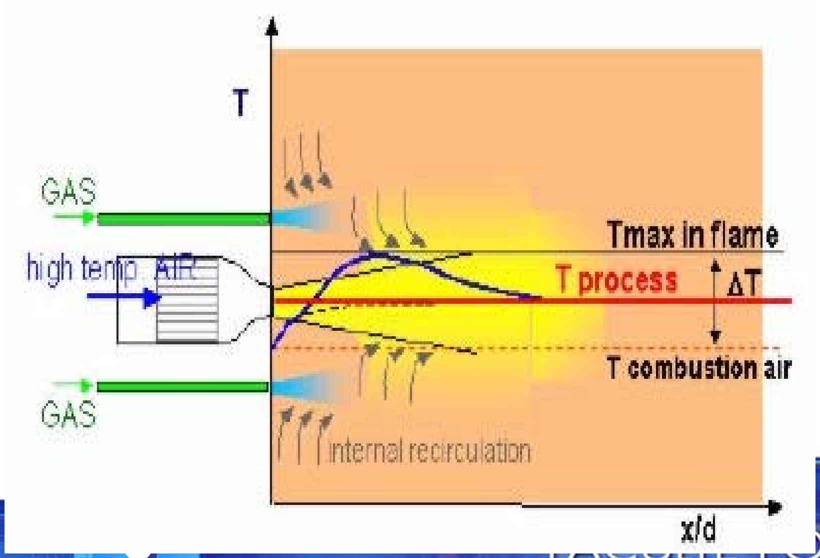
# OUTLINE

- Introduction & Objectives
- Experimental device and measuring equipment
- Experimental study
- Conclusions and perspectives

# INTRODUCTION & OBJECTIVES

The diluted combustion is characterized by a high preheating of the combustion air and a massive recycle of burnt gases. This technique avoids the formation of thermal hot spots in the furnace, thus lowering thermal-$NO_X$ emissions

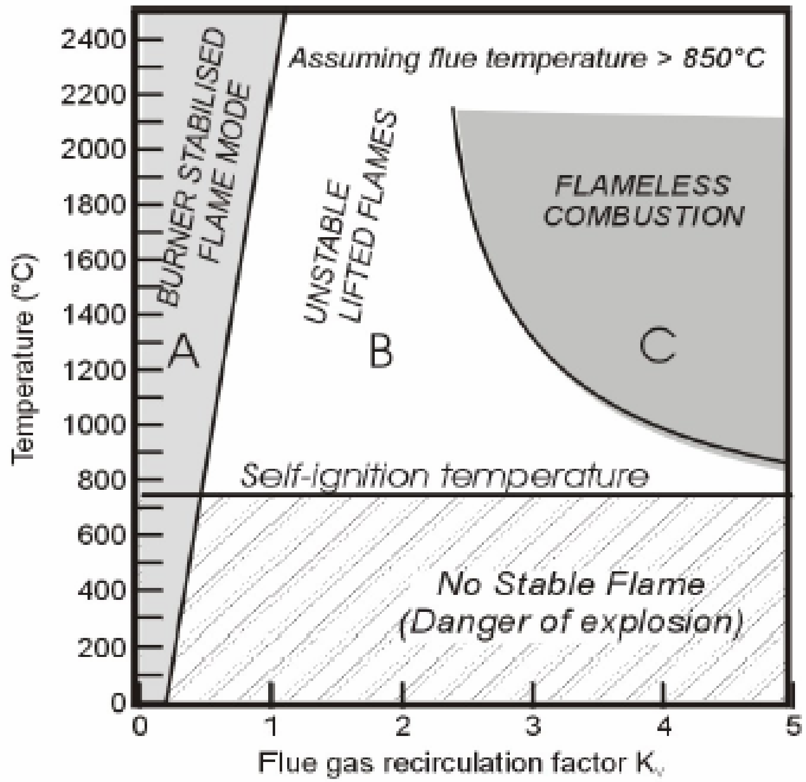
→ So, the essence of this technology is that fuel is oxidized in an environment that contains a substantial amount of inert gases and some, typically not more than 3-5% of oxygen




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

- Literature provides practical information and equipment design guidelines for mild combustion with standard fuels.

BUT few information are available for other fuels than methane




- The temperature to be considered in the diagrams (Y-axis) is not always clearly defined

## Objectives

→ **The aim of this work is to build a diagram of combustion regimes of fuel blends interesting for industry in diluted conditions**

The first step was to design an experimental setup able to supply a range of operating conditions wide enough

In a second step, series of test are performed with methane as fuel and $N_2$ as dilutant; data collected in these series will be compared with information available in literature and used as reference values for the study of other fuel and diluting species

# EXPERIMENTAL DEVICE

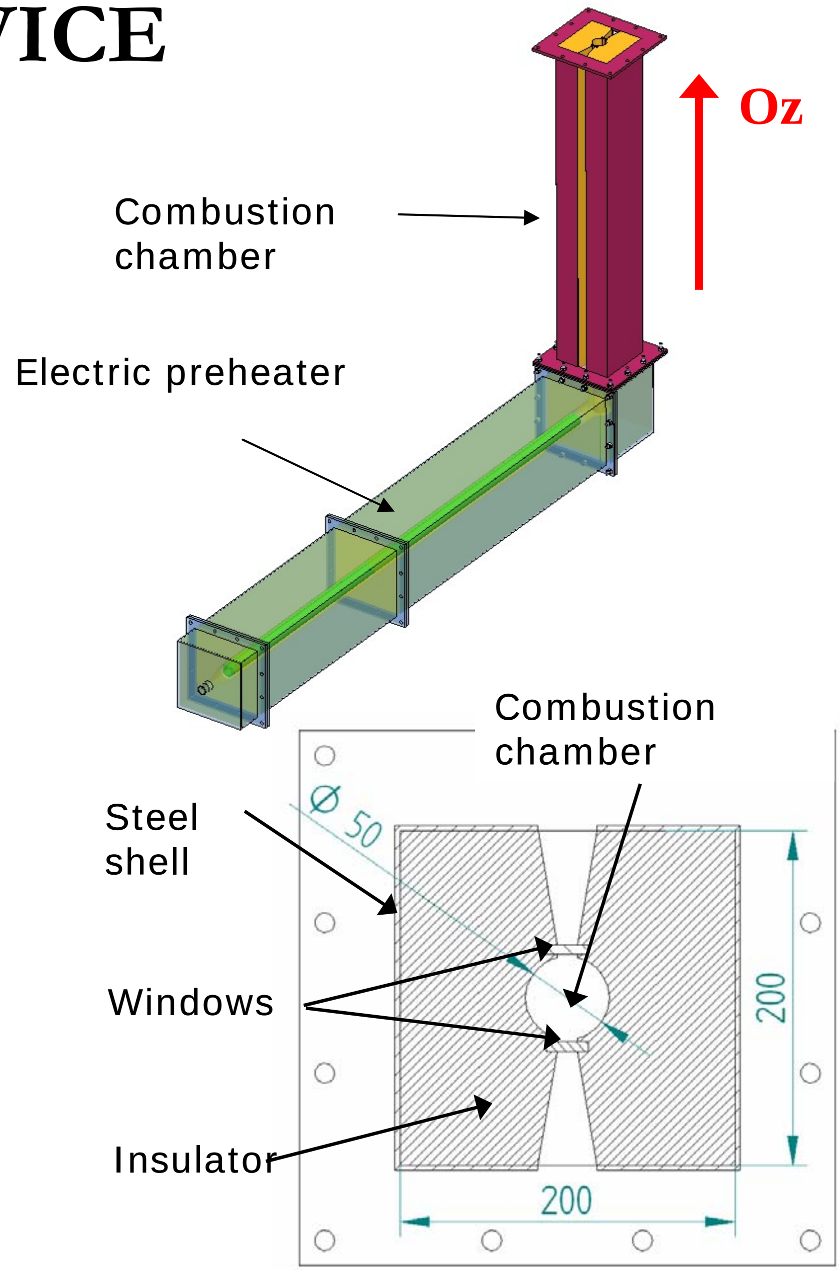
- Cylindrical combustion chamber of 1200mm height and 50 mm diameter

- Insulated

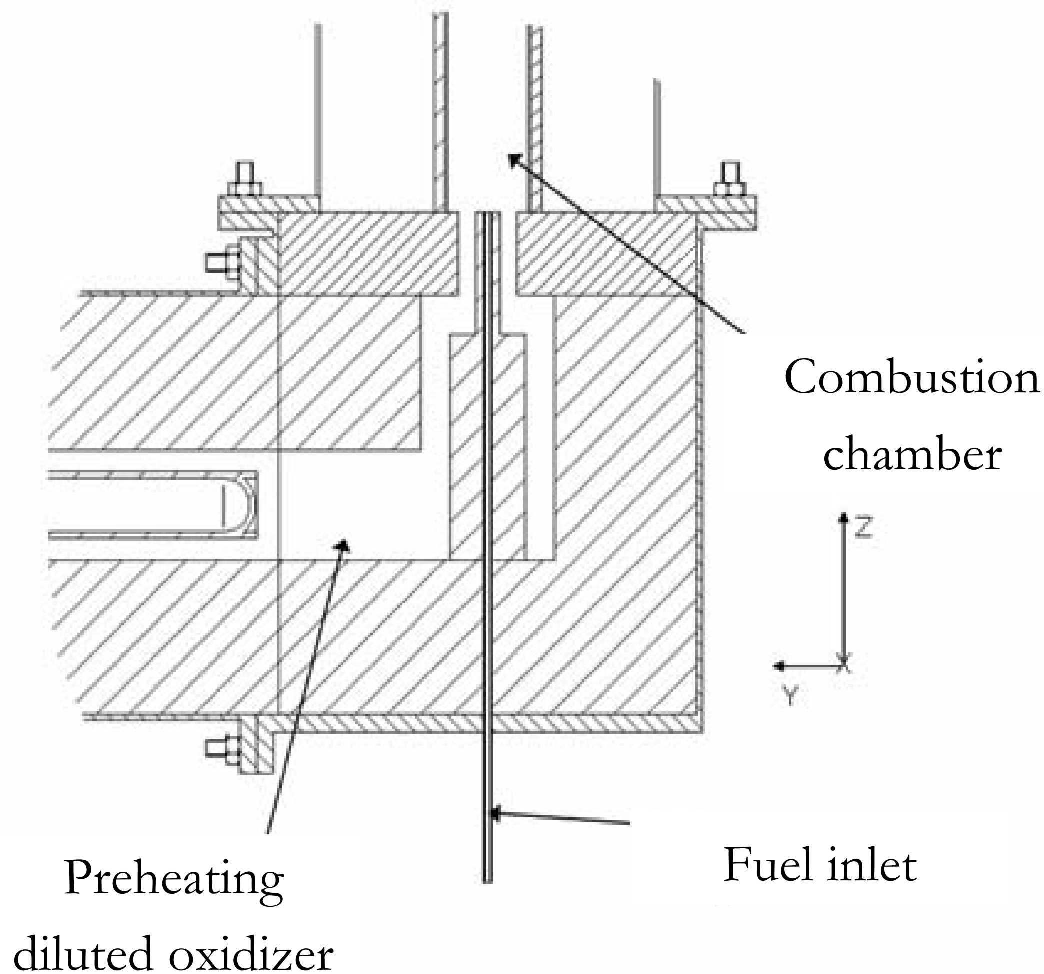
- 2 optical accesses

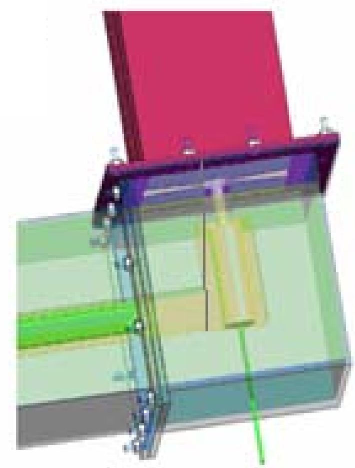
- Electric preheater which allows the heating of the diluted oxidizer up to 1100°C

- Mixing unit



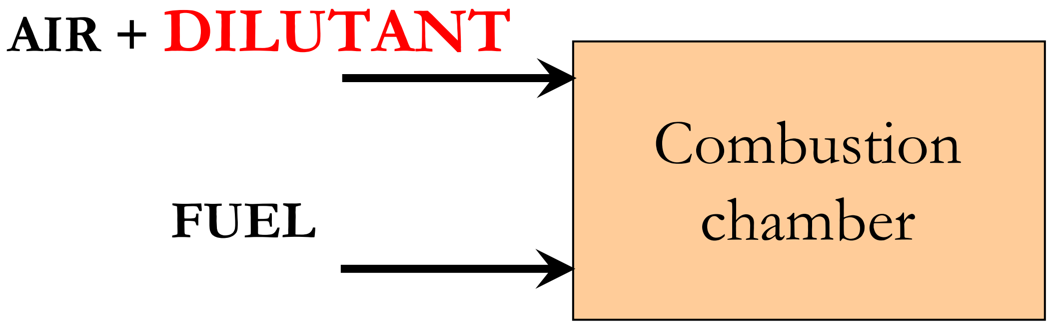
- Coflow configuration has been chosen for the injection of reactants

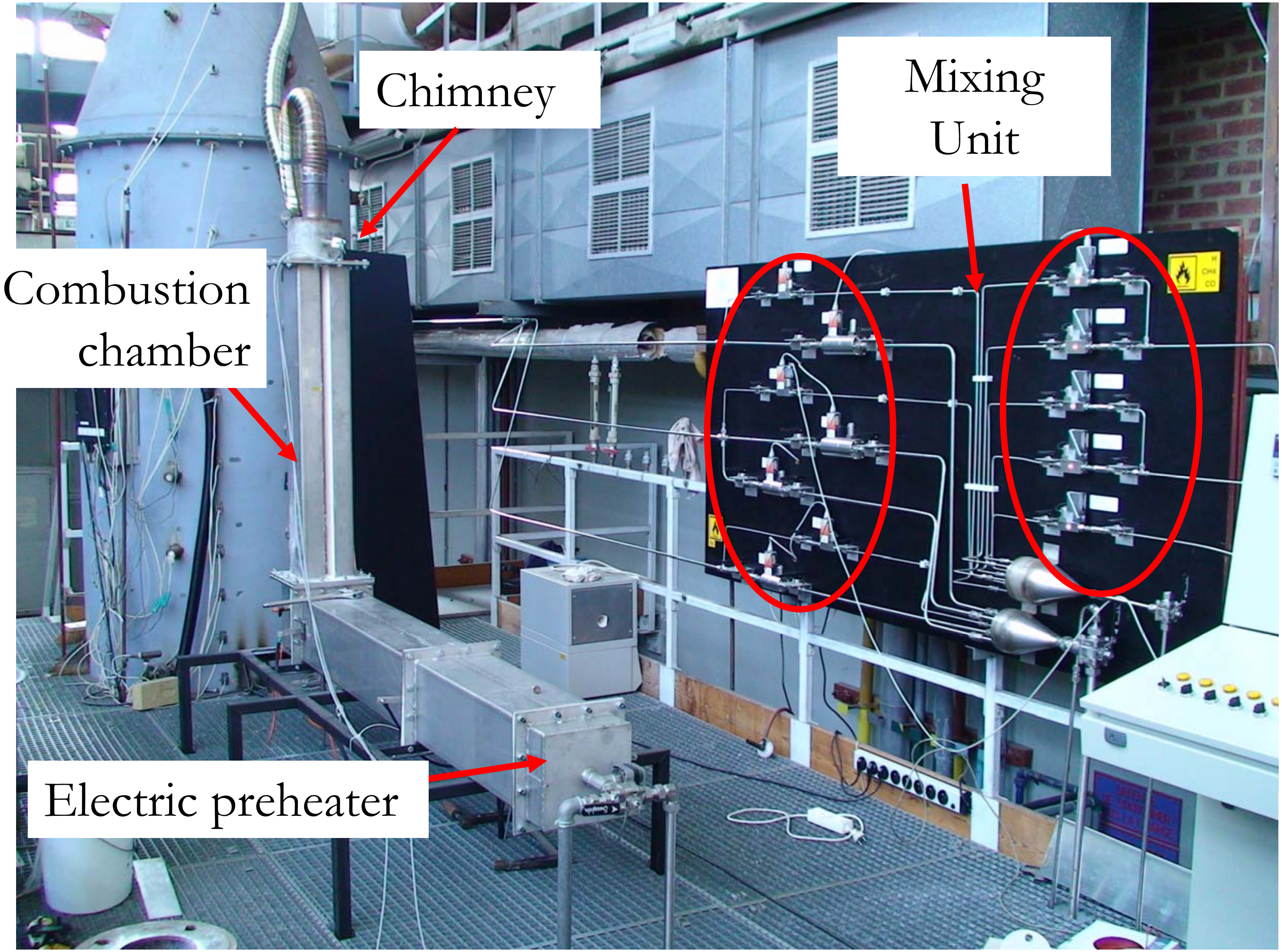


**Real-size burners** achieve diluted condition by feeding the combustion air and the fuel through separated or coflowing high velocity jets into the combustion chamber. The jets of reactants entrain a large amount of burnt gases before mixing and reacting.

**In our experimental setup**, it has been chosen to simulate the effect of recirculation by vitiating the oxidizer by inert gases such $N_2$ at high temperature. The amount of added inert gases (called the dilutant) determines the dilution.




Chimney
Mixing
Unit
Combustion
chamber
Electric preheater

## Measuring equipment

- **Inlet flow rate of reactants** ;Flow rates of reactants ($O_2$, $N_2$ and $CH_4$) are controlled by mass flow meters

- **Temperature of the diluted oxidizer** at the inlet of the combustion chamber via a standard S thermocouple

- **Temperature at the exit** of the combustion chamber via a fine wire thermocouple (Standard B (Pt-30% Rh/Pt-6% Rh))

- **Chemiluminescence emissions** of radical OH, CH and $C_2$ : maps of intensity of spontaneous emission of theses radicals are recorded using an intensified CCD camera and various filters

**- Composition of combustion gases** ; the gases are extracted in the chimney, near the temperature measurement point

# EXPERIMENTAL STUDY

Series of test runs were completed with varying operating parameters like temperature of preheating, amount of diluting gas, excess of oxygen and firing rate. Excess of oxygen is defined as the supplementary oxygen relatively to stoichiometric oxygen. The dilution factor is here defined as the $O_2$ percentage in the oxidizer. **Fuel is $CH_4$ and diluting species of oxidizer is $N_2$.**

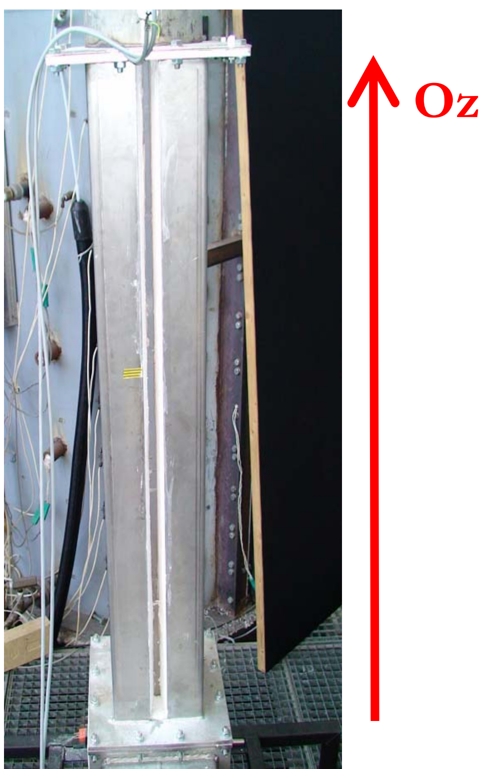
| | Firing rate **[kW]** | Excess of $O_2$ | Dilution | T preheating **[°C]** |
|---|---|---|---|---|
| STEP 1 | 3 | 0% | 2,8% to 7% | 1050 |
| STEP 2 | 3 | 5% | 3% to 10% | 950 -1000 - 1050 |
| STEP 3 | 2 to 5 | 5% | 6% | 1050 |

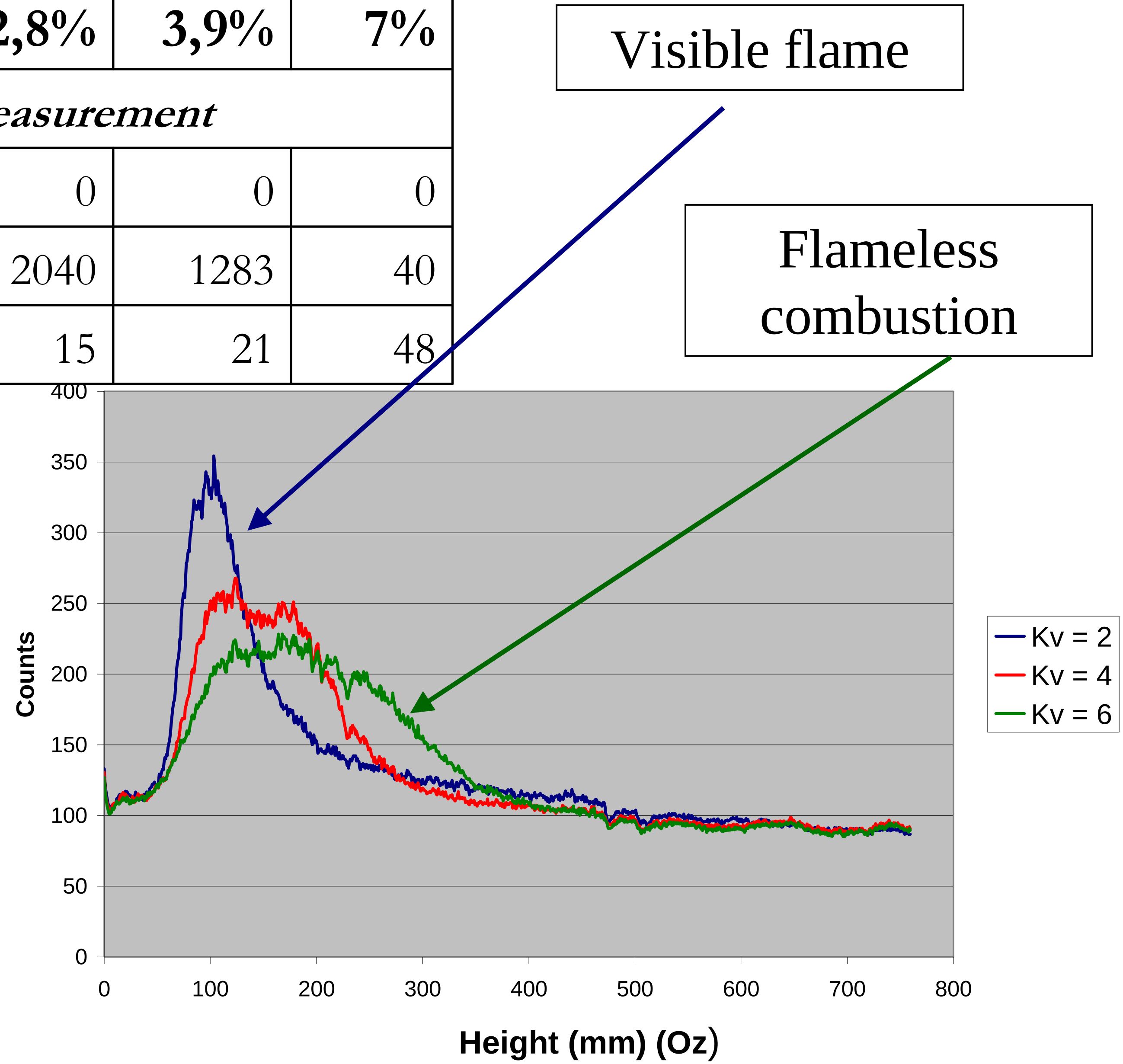
**STEP 1**

- Fuel: $CH_4$
- P = 3kW
- E = 0%
- Preheating temperature : 1050°C
- Dilution: $K_v$ = 2 - 4 – 6
  $[O_2]$ = 7% - 3,9% - 2,8%

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

| Dilution **[Kv]** | **6** | **4** | **2** |
|---|---|---|---|
| Dilution **[%O2]** | **2,8%** | **3,9%** | **7%** |
| ***Flue gas measurement*** | | | |
| CH4 **[%]** | 0 | 0 | 0 |
| CO **[ppm]** | 2040 | 1283 | 40 |
| NO **[ppm]** | 15 | 21 | 48 |



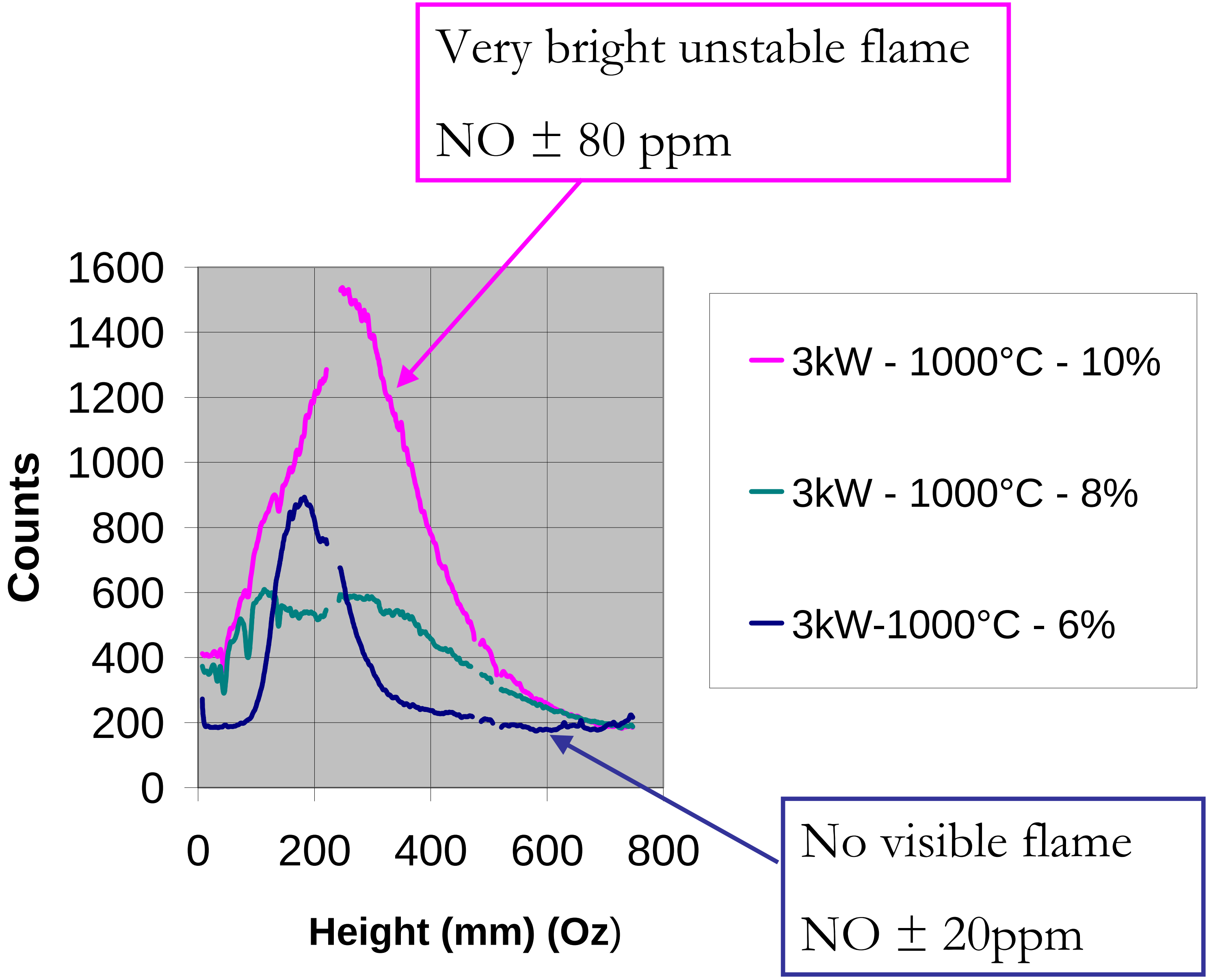



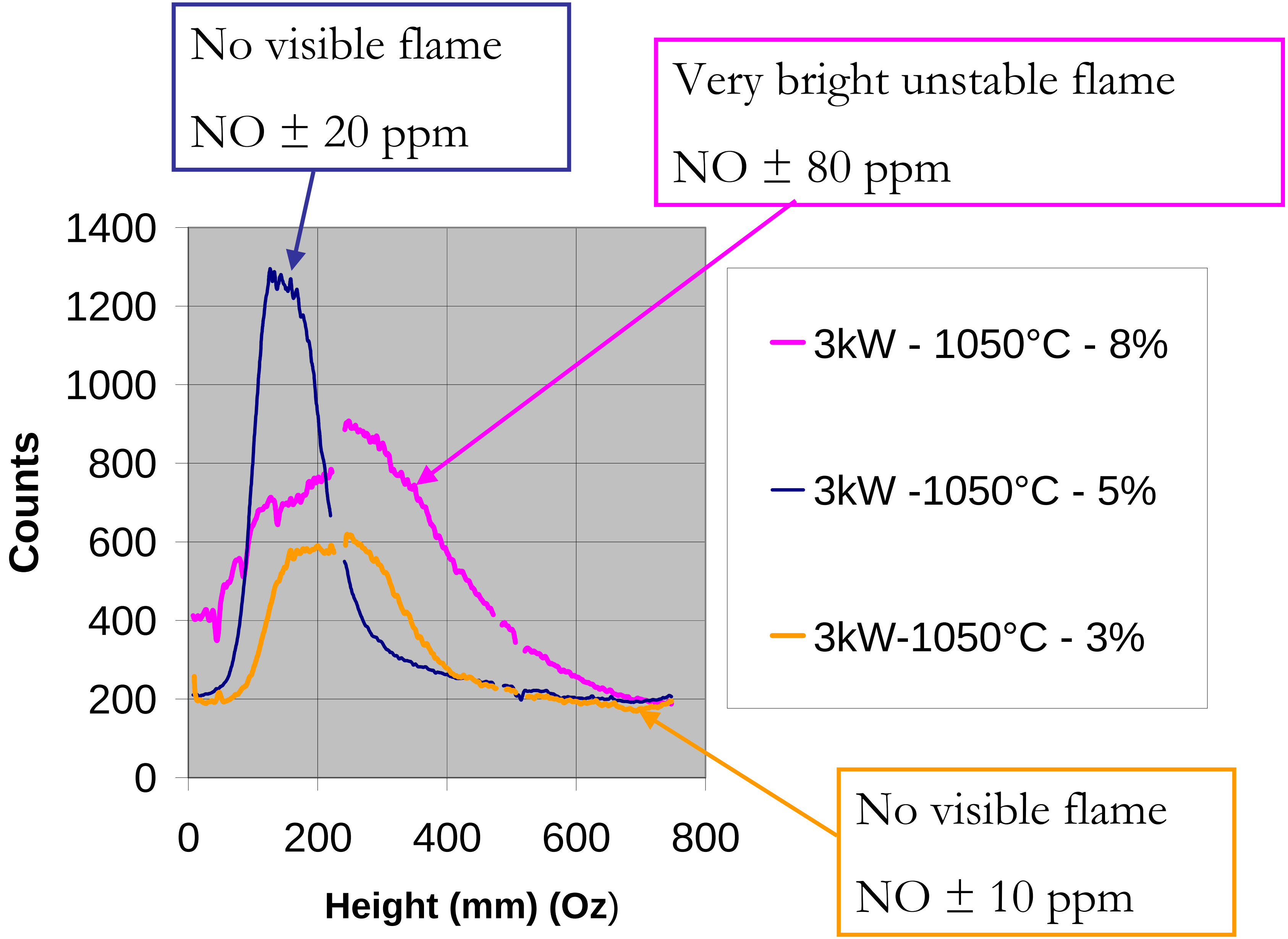
**STEP 2**

- Fuel: $CH_4$
- P = 3kW
- **E = 5 %**
- Preheating temperature : 950°C – 1000°C - 1050°C
- Dilution: from 3% to 10% $O_2$ in the diluted oxidizer

INCOMPLETE COMBUSTION

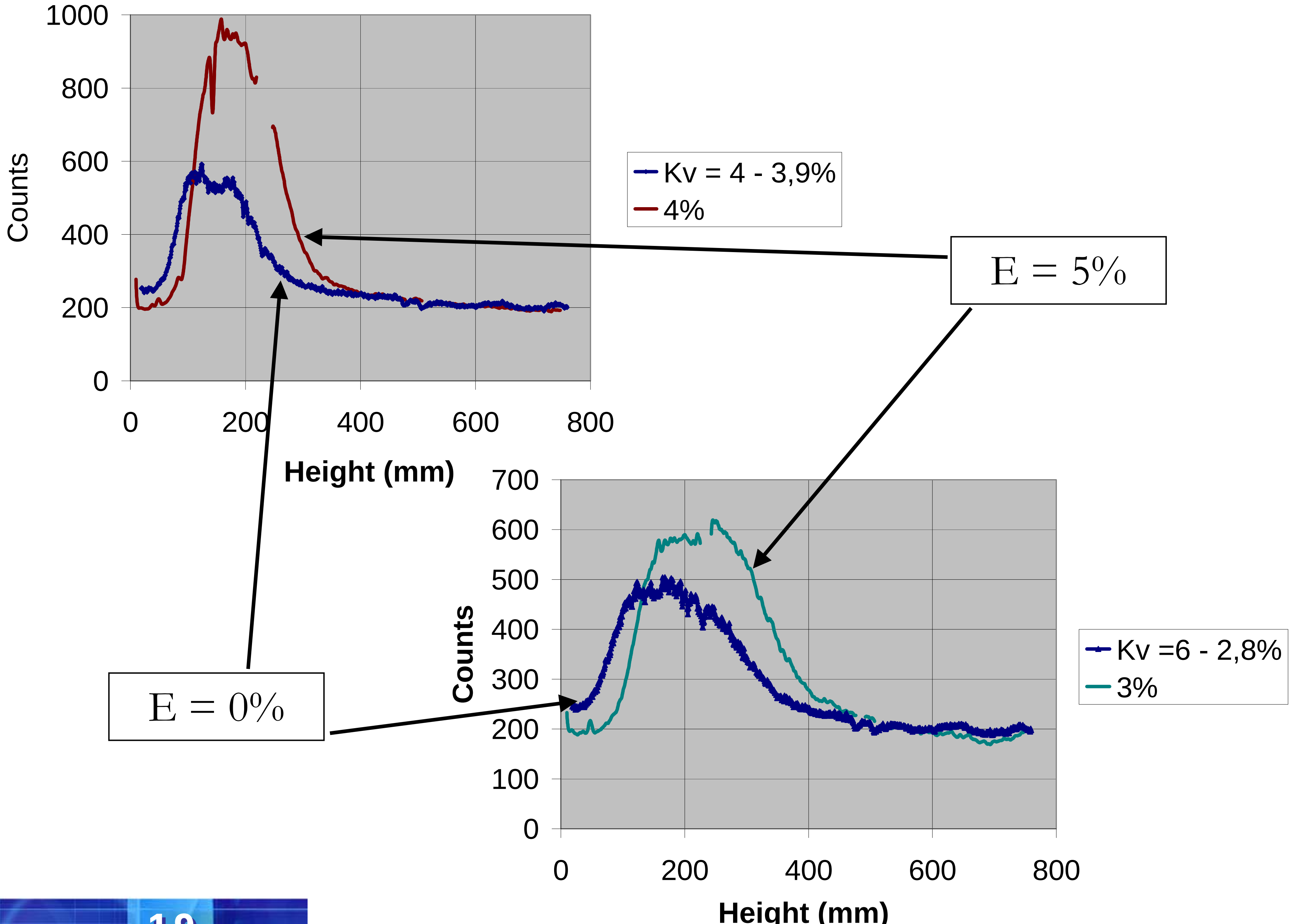
| Dilution [%O2] | 10% | 8% | 10% | 8% | 6% | 5% | 8% | 6% | 5% | 4% | 3% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| T preheating [°C] | 950 | 950 | 1000 | 1000 | 1000 | 1000 | 1050 | 1050 | 1050 | 1050 | 1050 |
| *Flue gas measurement* | | | | | | | | | | | |
| CH4 [%] | 0 | | 0 | 0 | 0 | | 0 | 0 | 0 | 0 | 0 |
| CO [ppm] | 83 | | 79 | 87 | 99 | | 85 | 91 | 109 | 233 | 367 |
| NO [ppm] | 74 | | 87 | 67 | 22 | | 75 | 35 | 25 | 16 | 11 |


Very bright unstable flame
NO ± 80 ppm
1600
1400
1200
1000
800
600
400
200
0
Counts
0
200
400
600
800
Height (mm) (Oz)
3kW - 1000°C - 10%
3kW - 1000°C - 8%
3kW-1000°C - 6%
No visible flame
NO ± 20ppm


No visible flame
NO ± 20 ppm
Very bright unstable flame
NO ± 80 ppm
No visible flame
NO ± 10 ppm
Counts
1400
1200
1000
800
600
400
200
0
0
200
400
600
800
Height (mm) (Oz)
3kW - 1050°C - 8%
3kW -1050°C - 5%
3kW-1050°C - 3%

→ First observation : The excess of $O_2$ with respect to stoichiometric condition is an important parameter. It's necessary to specify the excess in the stability diagram.

| | | |
|---|---|---|
| Dilution **[%O2]** | **4%** | **3,9%** |
| Preheating temperature **[°C]** | **1050** | **1050** |
| Excess of $O_2$ | **5%** | **0%** |
| CH4 **[%]** | **0** | **0** |
| CO **[ppm]** | **233** | **1283** |
| NO **[ppm]** | **16** | **21** |



1000
800
600
400
200
0
Counts
0
200
400
600
800
Height (mm)
Kv = 4 - 3,9%
4%
E = 5%
700
600
500
400
300
200
100
0
Counts
0
200
400
600
800
Height (mm)
Kv =6 - 2,8%
3%
E = 0%

The combustion regime is determined through those parameters:

- aspect of the reaction zone :visible flame or not, flame aspect
- chemilumescence emission of the reaction zone : intensity profile (width and maximum value)
- unburned species at the exit ($CH_4$, CO)
- $NO_X$ emissions at the exit

→ During the series of test, 4 regimes have been distinguished:

1)**Very bright unstable flame**

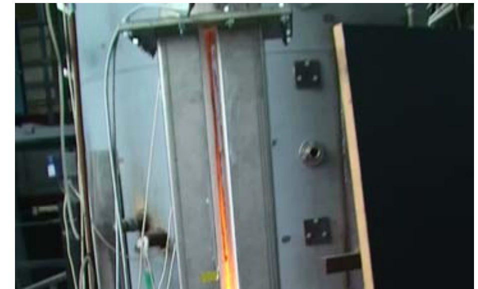
2)**Diluted combustion**

3)**Very diluted combustion**

4)**Incomplete combustion**

## Very bright unstable flame:

- very luminous yellow flame
- high OH, CH and C2 emission intensity
- flame position highly fluctuating
- high level of $NO_X$ (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 (order of magnitude : 20 ppm)
- CO ≤ 100 ppm

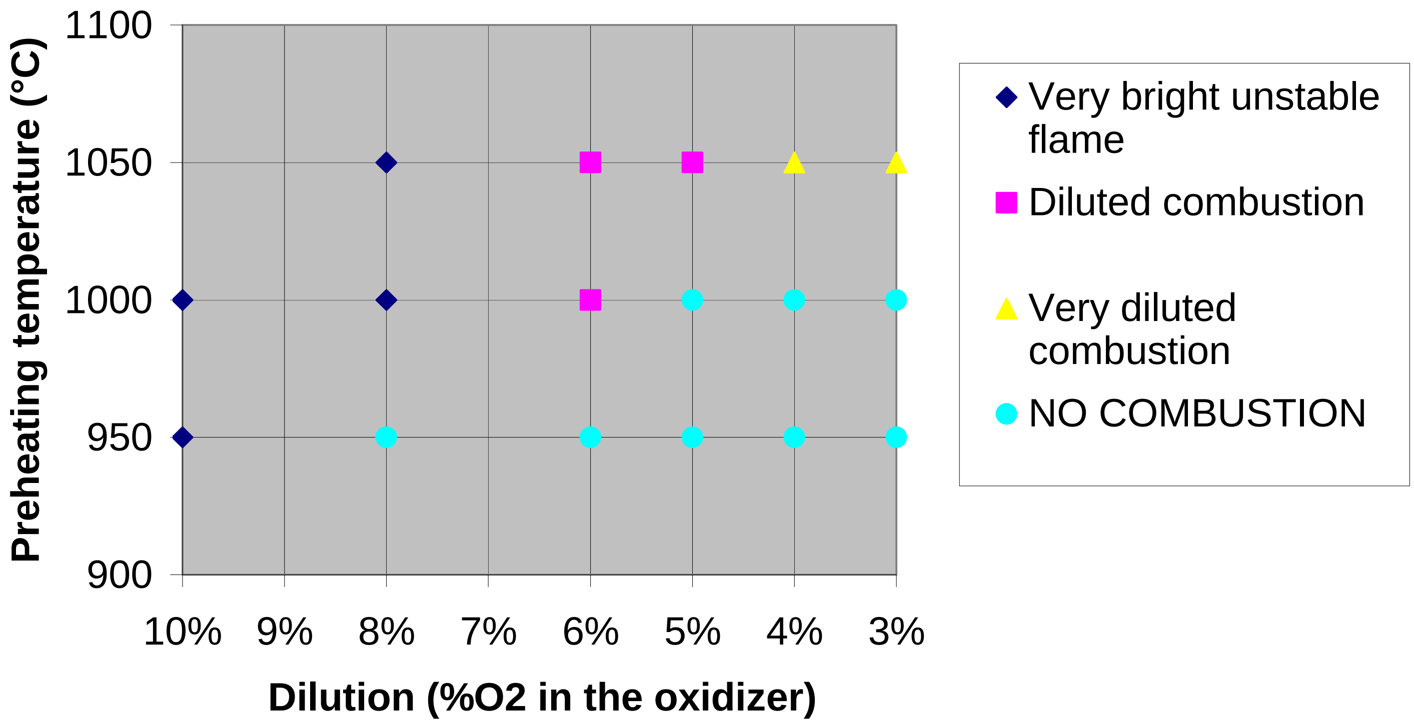
## Very diluted combustion

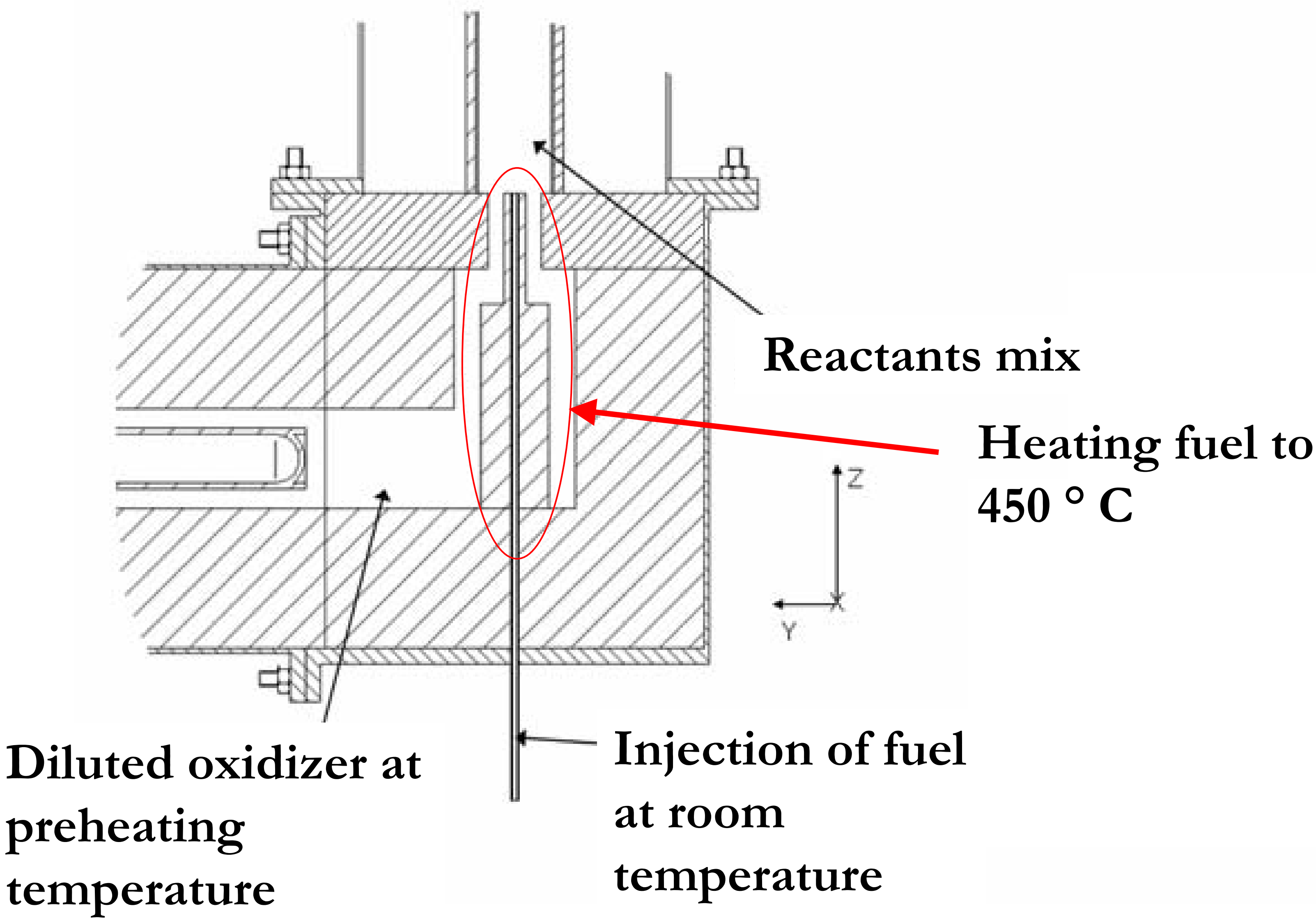
similar to diluted combustion but CO emission increase ( 200ppm<CO<400ppm)

## Incomplete combustion

The evolution of the combustion regime in test series n°2, as a function of preheating temperature and oxidizer dilution. It is important to notice that transitions between these regimes are progressive and not precisely localised.

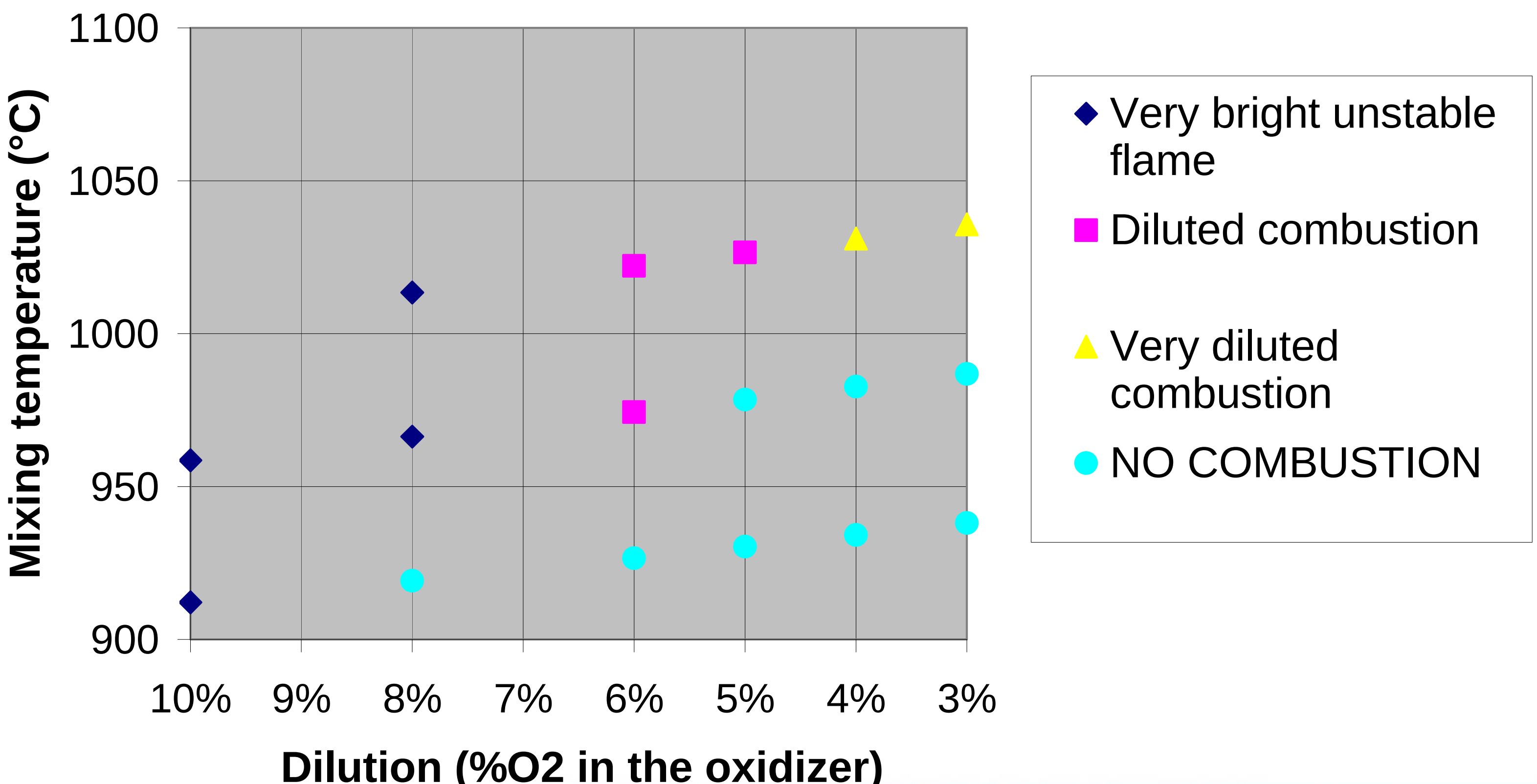
It is possible to locate the flameless combustion zone compared to a conventional combustion





Reactants mix
Heating fuel to
450 ° C
Z
Y
X
Diluted oxidizer at
preheating
temperature
Injection of fuel
at room
temperature

→ Operating map with the mixing temperature. The temperature is the mixing temperature computed as the average value of methane and diluted oxidizer temperature, weighted by mass flows. This temperature is expected to be significant in the operating map

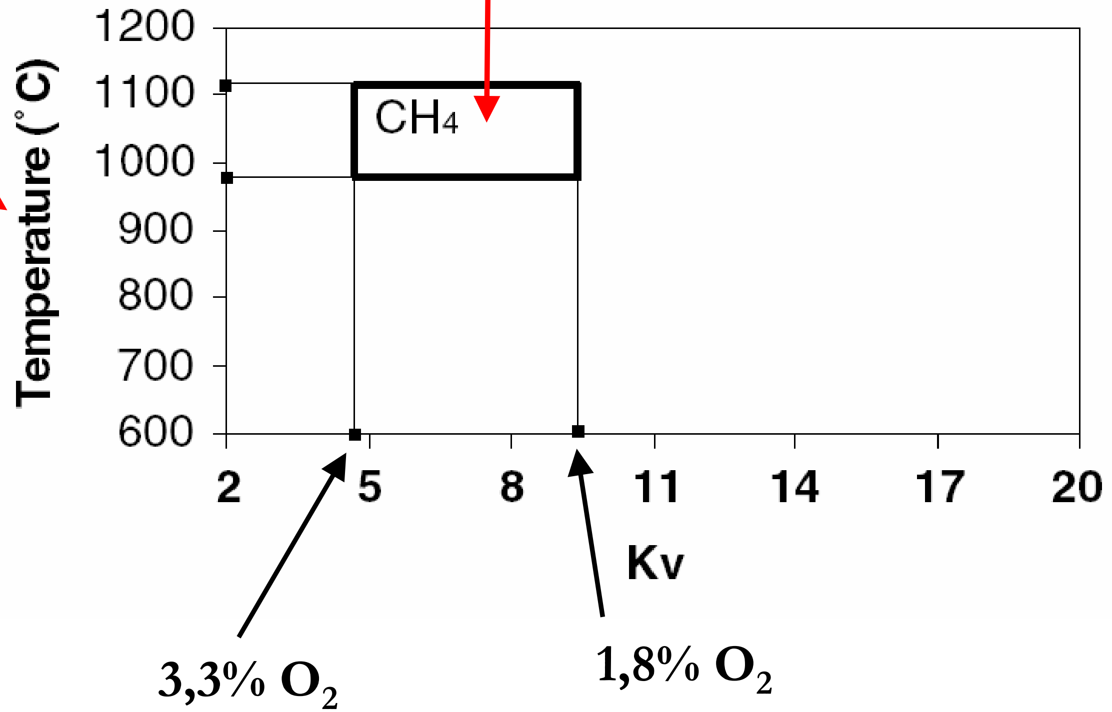


# Comparison with data in scientific literature

Flameless combustion zone is defined:

CO<50ppm – $NO_X$<30ppm – Disappearance of the flame

Average temperature in the furnace




*Excess of oxygen should be define in the operating map*

**STEP 3**

- Fuel: $CH_4$

- **P = 2kW – 3kW – 4kW – 5kW**

- E = 5 %

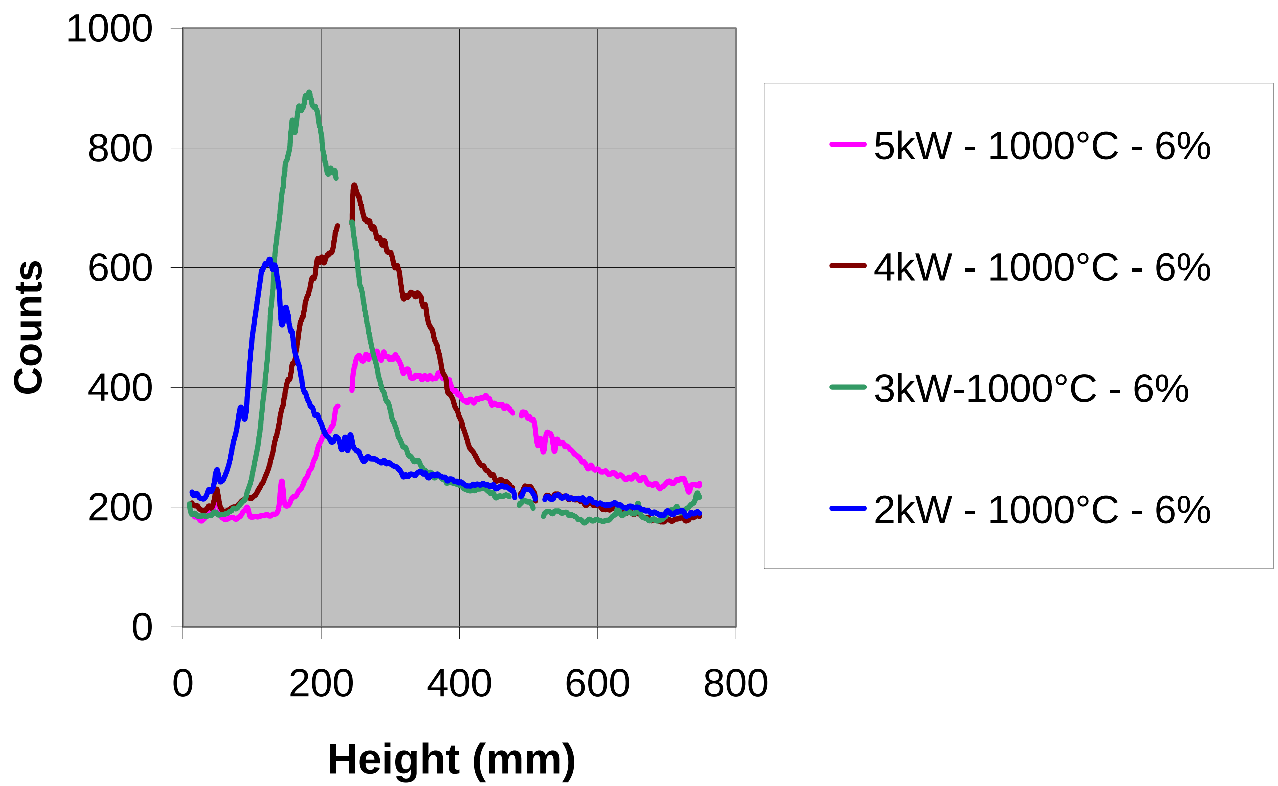
- Preheating temperature: 1000°C

- Dilution: 6% $O_2$ in the diluted oxidizer

Test of STEP 3 have been performed to check the influence of the firing rate.

For each test, the speed ratio between fuel and diluted oxidizer is maintained.

| Firing rate **[kW]** | **5** | **4** | **3** | **2** |
|---|---|---|---|---|
| Dilution **[%O2]** | 6% | 6% | 6% | 6% |
| ***Flue gas measurement*** | | | | |
| CH4 **[%]** | 0 | 0 | 0 | 0 |
| CO **[ppm]** | **547** | **140** | **99** | **68** |
| NO **[ppm]** (at 3% O2, dry basis) | 14 | 19 | 22 | 28 |



# CONCLUSIONS & PERSPECTIVES

• It has been shown that the experimental apparatus is well designed for the study of diluted combustion for a firing rate of 3kW

• The flexibility of experimental installation allows obtaining information on more fundamental aspect of the diluted combustion.

• The excess of oxygen is also appeared as an important parameter

• Other important parameter to study : ratio of reaction jets velocity

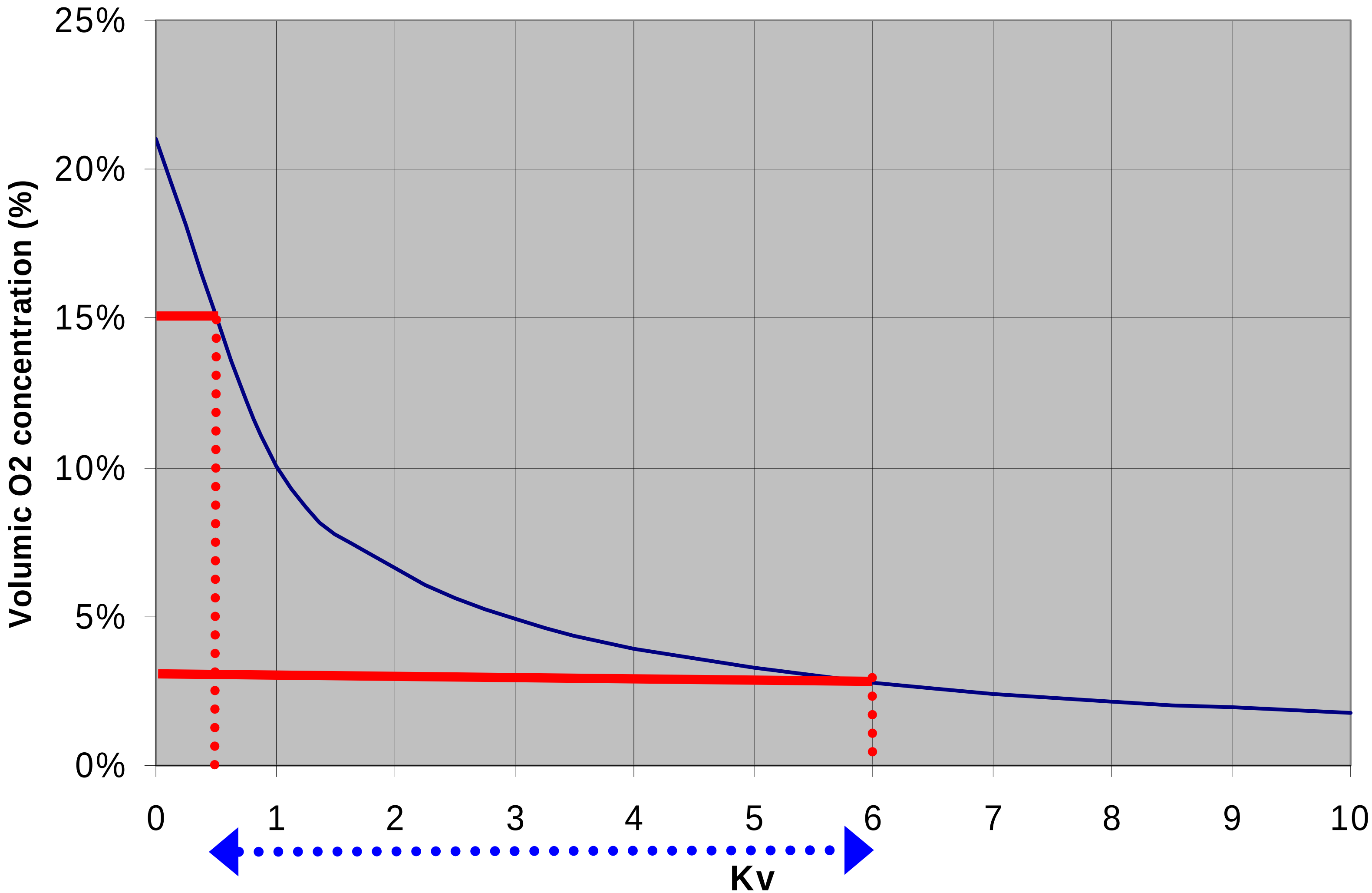
• Series of test to collect data with other fuels (mixture of $CH_4$, $H_2$ and CO)

This work has been performed thanks to the financial support of the Walloon Government

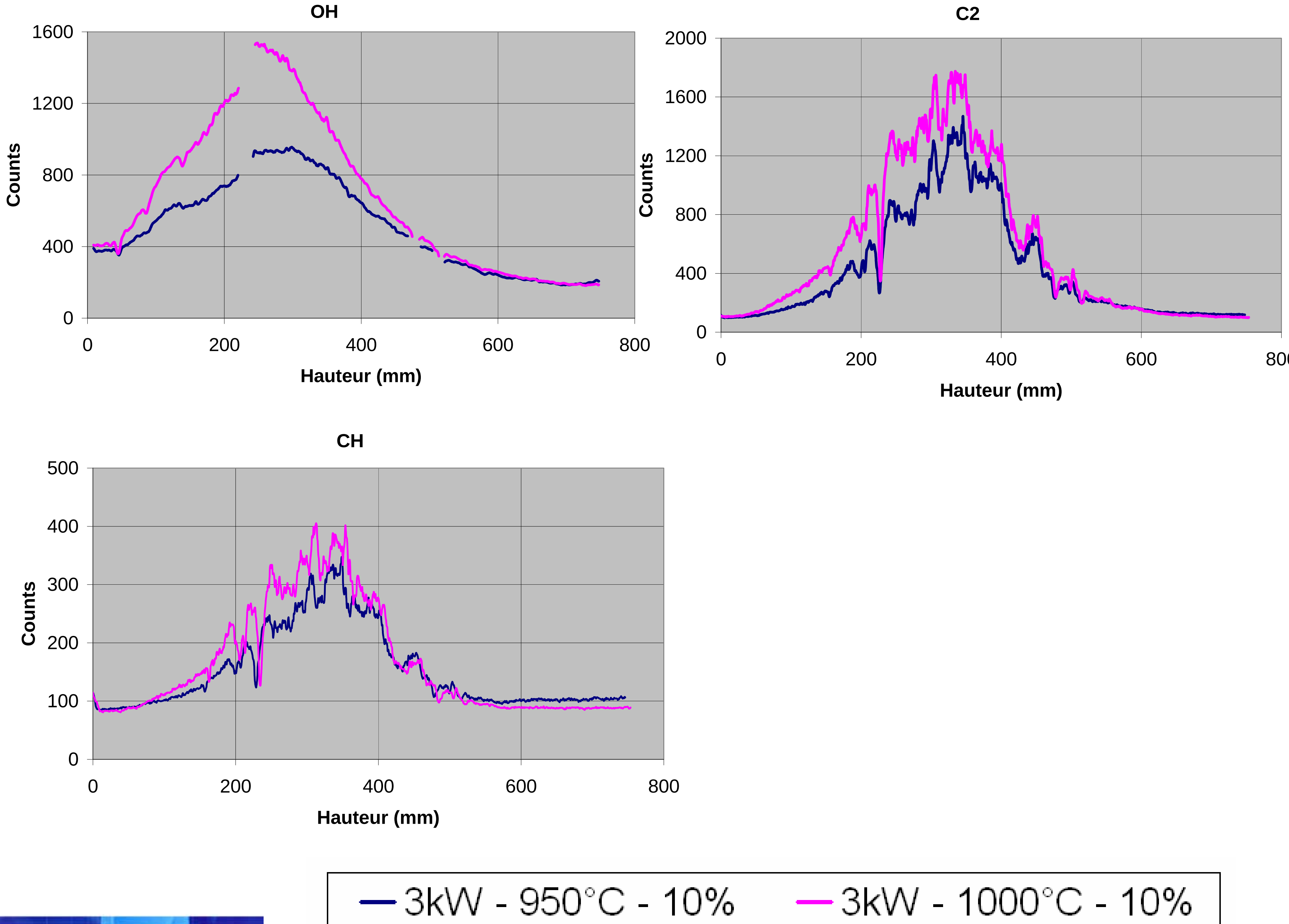
RÉGION WALLONNE

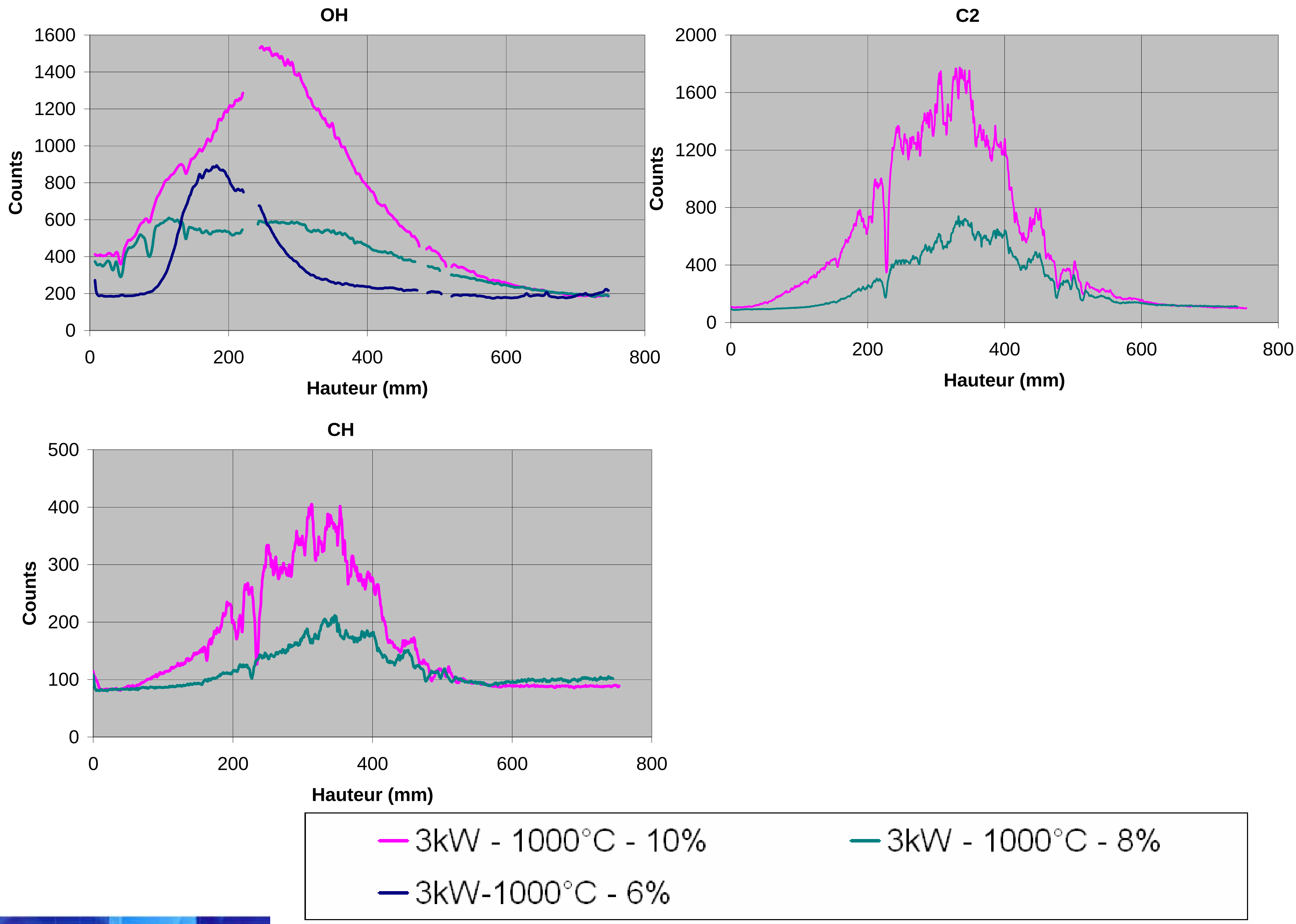
**Thanks for your attention**

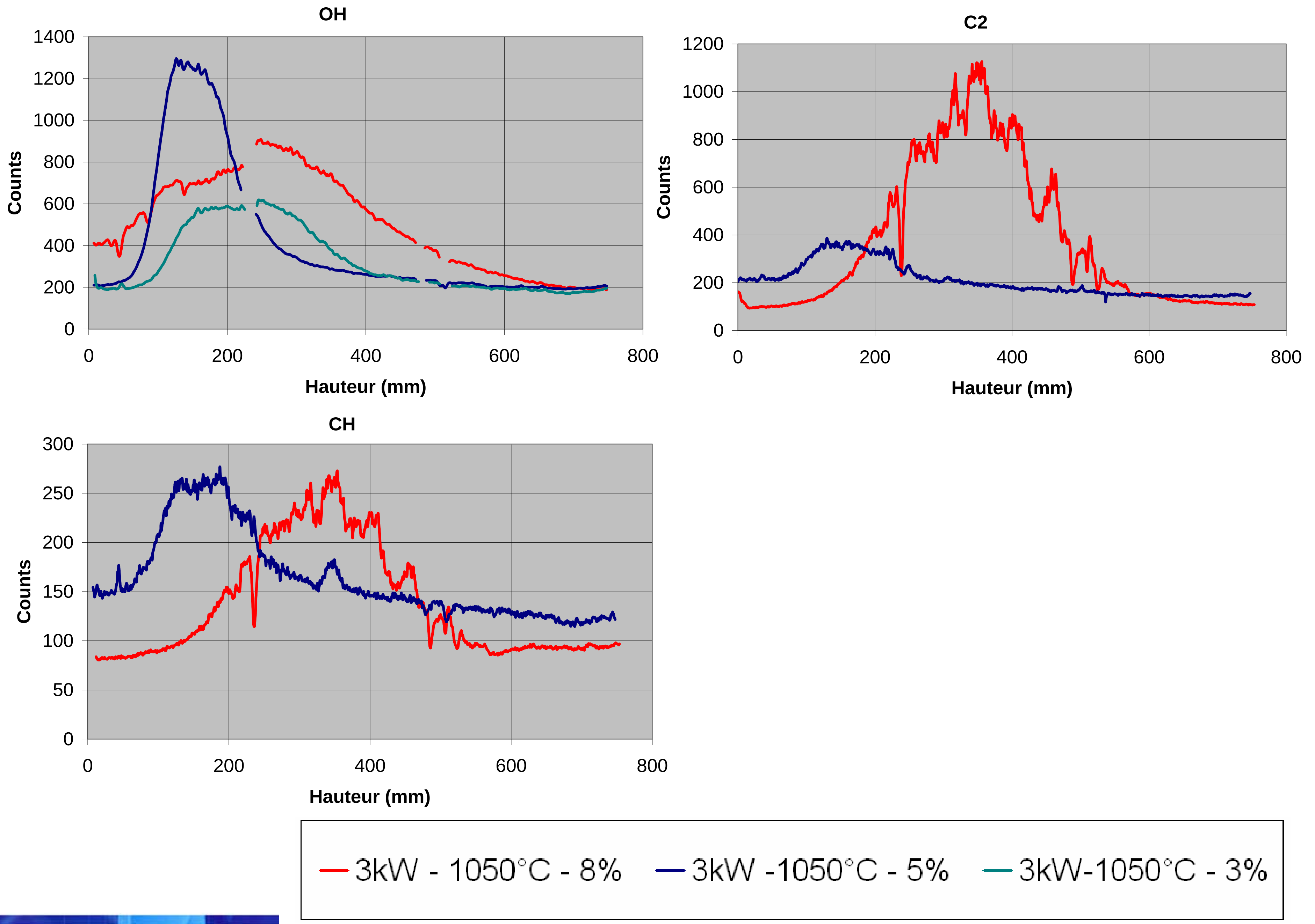
# Correspondence Kv- O2 concentration



- le filtre OH dont la bande passante est centrée à 307 nm
- le filtre CH dont la bande passante est centrée à 430 nm
- le filtre C2 dont la bande passante est centrée à 515 nm


OH
Counts
Hauteur (mm)
C2
Counts
Hauteur (mm)
CH
Counts
Hauteur (mm)
3kW - 950°C - 10%
3kW - 1000°C - 10%


OH
Counts
Hauteur (mm)
C2
Counts
Hauteur (mm)
CH
Counts
Hauteur (mm)
3kW - 1000°C - 10%
3kW - 1000°C - 8%
3kW-1000°C - 6%


OH
Counts
Hauteur (mm)
C2
Counts
Hauteur (mm)
CH
Counts
Hauteur (mm)
3kW - 1050°C - 8%
3kW -1050°C - 5%
3kW-1050°C - 3%

Pas de combustion

| Dilution [%O2] | 10% | 8% | 10% | 8% | 6% | 5% | 8% | 6% | 5% | 4% | 3% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| T préchauf. [°C] | 950 | 950 | 1000 | 1000 | 1000 | 1000 | 1050 | 1050 | 1050 | 1050 | 1050 |
| *Analyse fumées* | | | | | | | | | | | |
| **Rapport $OH_{MAX}/C2_{MAX}$** | 1,54 | | 1,15 | 1,21 | 0,11 | | 1,24 | - | 0,3 | 0,16 | 0,16 |

Pas de combustion

| Dilution [%O2] | 10% | 8% | 10% | 8% | 6% | 5% | 8% | 6% | 5% | 4% | 3% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| T préchauf. [°C] | 950 | 950 | 1000 | 1000 | 1000 | 1000 | 1050 | 1050 | 1050 | 1050 | 1050 |
| ***Analyse fumées*** | | | | | | | | | | | |
| CH4 [%] | 0 | | 0 | 0 | 0 | | 0 | 0 | 0 | 0 | 0 |
| CO [ppm] | 83 | | 79 | 87 | 99 | | 85 | 91 | 109 | 233 | 367 |
| NO [ppm] | 74 | | 87 | 67 | 22 | | 75 | 35 | 25 | 16 | 11 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Rapport des vitesses** | 3,1 | | 3 | 2,4 | 1,8 | | 2,3 | 1,7 | 1,4 | 1,2 | 0,9 |
| **Rapport des impulsions** | 12 | | 12 | 19 | 34 | | 20 | 36 | 51 | 80 | 142 |

# Development of stability diagrams of flame in diluted combustion

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(Sub – Tasks 2.1 H & 2.1 I)

**Abstract**

In order to achieve a reduction in emissions of greenhouse gases and other pollutants like $NO_X$, it is necessary to make effort in the combustion process. In this context, the diluted combustion (also called Flameless or Mild Combustion) offers great advantages in terms of thermal efficiency and pollutant emissions.
This combustion mode is often characterized by

- a high preheating of combustion air by recovering flue gas heat which improves the thermal efficiency
- a specific design of air and fuel jet nozzles to obtain a high dilution which decreases the hot spot and therefore reduces the thermal $NO_X$ formation

However, in the scientific literature, information and design guidelines are available for standard fuels, such as methane or propane, but there is a lack of information for other fuels such as industrial by-products and gasification fuels (mixture of $CH_4$, $H_2$ and CO).
The purpose of this work is to collect experimental data to characterize combustion features of various fuel blends in diluted combustion conditions. The first step was the design of a laboratory scale test bench able to supply a large range of operating conditions. This paper reports the first series of experiments with methane, which serve as a reference fuel.
Furthermore, an evaluation of chemiluminescence of OH*, CH* and $C_2$* in diluted combustion is also presented.

## 1. Introduction

The improvement of combustion efficiency and the reduction of pollutant emissions are the main goals of research in the combustion field. The diluted combustion can achieve these requests. The diluted combustion is usually characterized by a high preheating of the combustion air and a massive recycle of burnt gases. This technique avoids the formation of thermal hot spots in the furnace, thus lowering thermal-$NO_X$ emissions without compromising combustion efficiency [1].
The amount of exhaust gases entrained in the reaction jets is usually quantified through a dilution factor, $K_V$, defined as the ratio between the entrained exhaust gases flow rate and the inlet jet flow rate.

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

with

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

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

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

So, the essence of this technology is that fuel is oxidized in an environment that contains a substantial amount of inert (flue) gases and some, typically not more than 3-5% of oxygen [2].

The achievement of mild combustions requires:
- to heat up the combustion chamber above a threshold temperature
- to design the air et fuel jet nozzles in order to obtain a dilution larger than a threshold value

Literature provides practical information and equipment design guidelines for mild combustion with standard fuels as methane, natural gas and propane. Nowadays, increasing costs of fossil fuels are pushing heavy and manufacturing industry using gasified waste or by-product gases as alternative fuels. These gases are mainly composed of $CH_4$, CO and $H_2$ blends in variable proportions. Generation of a stable flame can be a hard issue with gases with such variable calorific value and ignition characteristics and diluted flameless combustion can provide a safer way to burn these gases. Therefore, operation map and design guidelines have to be suited for such fuels in flames oxidation regime.

## 2. Objectives

The aim of this work is to build a diagram of combustion regimes of fuel blends interesting for industry in diluted conditions. Combustion regime will be characterized by means of content of unburned in flue gas, flue gas temperature, $NO_X$ emissions and intensity of chemiluminescence emission of reaction zone. Operating parameters to be varied are: temperature and $O_2$ content of the diluted reacting mixture, composition of the gaseous fuel ($CH_4$, CO, $H_2$), nature of the dilution gas, residence time.
The first step was therefore to design an experimental setup able to supply a range of operating conditions wide enough in the limits of a laboratory scale installation, and to collect data to characterize the combustion regime.
In a second step, series of test are performed with methane as fuel and $N_2$ as dilutant; data collected in these series will be compared with information available in literature and used as reference values for the study of other fuel and diluting species.

## 3. Experimental device and measuring equipment

The experimental setup has been described in detail [3]. It consists of a cylindrical combustion chamber of 1200 mm height and 50 mm diameter with two optical accesses. A coflow configuration has been chosen for the injection of reactants. The chamber is insulated in order to have a thermally stable environment (figure 1, 2).

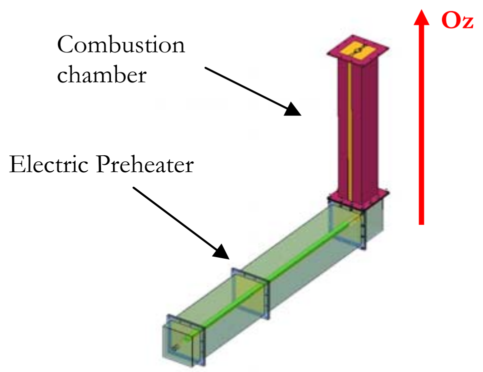


*Figure 1: Design of the experimental apparatus*

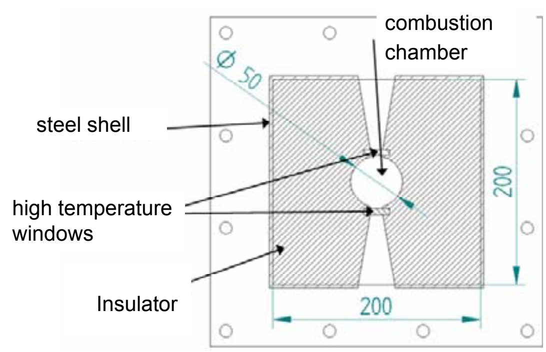


*Figure 2 :cross-section of the combustion chamber*

The fuel is injected by a refractory material pipe (3mm internal diameter) insulated to avoid cracking. The oxidizer is injected by a ring-shaped section of 35mm and 15mm of internal diameter (figure 3).
Real-size burners achieve diluted condition by feeding the combustion air and the fuel through separated or coflowing high velocity jets into the combustion chamber. The jets of reactants entrain a large amount of burned gases before mixing and reacting. Consequently oxygen local concentration in the reacting mixture is much lower than in classical flames [4]. The dilution of the reactant mixture is depending on the amount of entrained burned gases quantified by the "recirculation ratio" (see §1

introduction). As this ratio is strongly related to the geometry of the system, it is difficult to vary it in practice within a large range. Therefore, it has been chosen to simulate the effect of recirculation by vitiating the oxidizer by inert gases such $N_2$ at high temperature. The amount of added inert gases (called the dilutant) determines the dilution.
The installation is equipped with an electric preheater which allows the pre-heating of the diluted oxidizer at a temperature ranging from ambient to a maximum value of 1100°C. A mixing unit supplies the installation with fuel and diluted oxidizer in desired proportions.

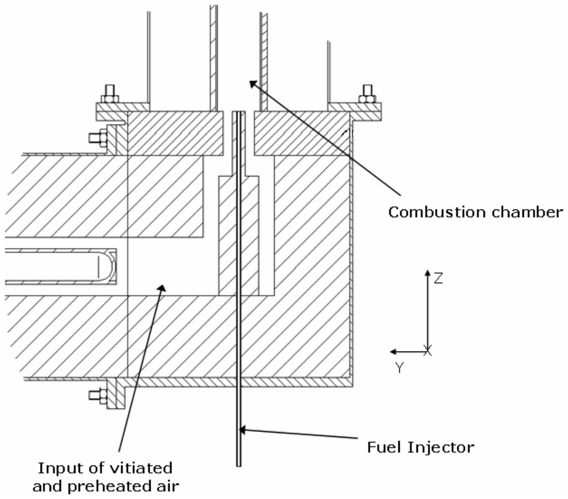



*Figure 3*

Operating conditions and combustion characteristics are determined by measuring:

- inlet flow rate of reactants ;
  Flow rates of reactants ($O_2$, $N_2$ and $CH_4$) are controlled by mass flow meters. Relative error in the tests range is 1%.
- temperature of the diluted oxidizer at the inlet of the combustion chamber via a standard S thermocouple.
- temperature at the exit of the combustion chamber via a fine wire thermocouple (Standard B (Pt-30% Rh/Pt-6% Rh)).
- chemiluminescence emissions of radical OH, CH and $C_2$ : maps of intensity of spontaneous emission of theses radicals are recorded using an intensified CCD camera and various filters
- composition of combustion gases ; the gases are extracted in the chimney, near the temperature measurement point.
  For $O_2$ content measurements, paramagnetic analyzer is used with an error of 1% with full scale. Methane, carbon dioxide and carbon monoxide measurements are performed with infrared analyzer (2% of full scale error). $NO_X$ are measured with chemiluminescence analyzer (5% of full scale error).

## 4. Results and discussion

Series of test runs were completed with varying operating parameters like temperature of preheating, amount of diluting gas, excess of oxygen and firing rate. Excess of oxygen is defined as the supplementary oxygen relatively to stoichiometric oxygen. The dilution factor is here defined as the $O_2$ percentage in the oxidizer.
Three series of test have been performed:

| | Firing rate **[kW]** | Excess of $O_2$ | Dilution | preheating temperature **[°C]** |
|---|---|---|---|---|
| STEP 1 | 3 | 0% | 2,8% to 7% | 1050 |
| STEP 2 | 3 | 5% | 3% to 10% | 950 -1000 - 1050 |
| STEP 3 | 2 to 5 | 5% | 6% | 1050 |

Fuel is $CH_4$ and diluting species of oxidizer is $N_2$.

A recirculation ratio $K_V$ can be related to the dilution by $$K_V = \frac{\dot{M}_{DILUTANT}}{\dot{M}_{fuel} + \dot{M}_{Air}}$$

**STEP 1**

Table 1 shows the experimental results for this step:

| | case n°1 | case n°2 | case n°3 |
|---|---|---|---|
| Dilution **[Kv]** | 6 | 4 | 2 |
| Dilution **[%O2]** | 2,8% | 3,9% | 7% |
| ***Flue gas measurement*** | | | |
| CH4 **[%]** | 0,0 | 0,0 | 0,0 |
| CO **[ppm]** | 2040 | 1282,5 | 40,4 |
| NO **[ppm]** (at 3% O2, dry basis) | 15,48 | 21,43 | 47,71 |

*Table 1*

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 oxidizer
- the dilution decreases the concentrations and also the reaction speed of combustion

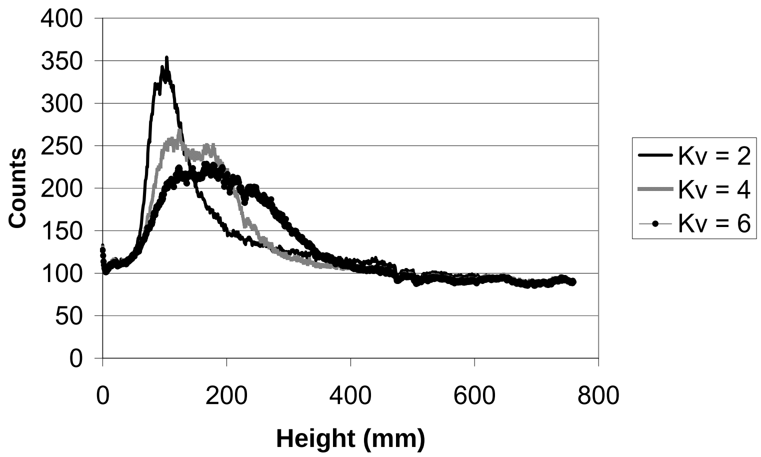



*Figure 4: OH profile*

**STEP 2**

Table 2 shows the experimental results for this step:

| | case n°4 | case n°5 | case n°6 | case n°7 | case n°8 | case n°9 | case n°10 | case n°11 | case n°12 | case n°13 | case n°14 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Dilution **[%O2]** | 10% | 8% | 8% | 6% | 5% | 10% | 8% | 6% | 5% | 4% | 3% |
| T preheating**[°C]** | 950 | 950 | 1000 | 1000 | 1000 | 1000 | 1050 | 1050 | 1050 | 1050 | 1050 |
| ***Flue gas measurement*** | | | | | | | | | | | |
| CH4 **[%]** | 0,1 | | 0,1 | 0,1 | 1,3 | 0,1 | 0,1 | 0,1 | 0,1 | 0,1 | 0,1 |
| CO **[ppm]** | 83,32 | | 87,24 | 99,38 | 540,44 | 78,74 | 84,74 | 91,47 | 109,11 | 232,77 | 367,43 |
| NO **[ppm]** (at 3% O2, dry basis) | 73,82 | | 66,56 | 22,02 | 3,25 | 87,18 | 74,91 | 34,52 | 24,57 | 16,13 | 11,3 |

*Table 2*

| | case n°4 | case n°5 | case n°6 | case n°7 | case n°8 | case n°9 | case n°10 | case n°11 | case n°12 | case n°13 | case n°14 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Dilution **[%O2]** | 10% | 8% | 8% | 6% | 5% | 10% | 8% | 6% | 5% | 4% | 3% |
| T preheating[°C] | 950 | 950 | 1000 | 1000 | 1000 | 1000 | 1050 | 1050 | 1050 | 1050 | 1050 |
| Injection speed of oxidizer **[m/s]** | 10,03 | 12,54 | 13,05 | 17,4 | 20,88 | 10,44 | 13,57 | 18,09 | 21,71 | 27,13 | 36,18 |
| Injection speed of fuel **[m/s]** | 31,35 | 31,35 | 31,35 | 31,35 | 31,35 | 31,35 | 31,35 | 31,35 | 31,35 | 31,35 | 31,35 |
| SPEED RATIO | 3,1 | 2,5 | 2,4 | 1,8 | 1,5 | 3 | 2,3 | 1,7 | 1,4 | 1,2 | 0,9 |
| Ratio of momentum jet | 12 | 19 | 19 | 34 | 49 | 12 | 20 | 36 | 51 | 80 | 142 |

*Table 3*

The following figures represent the intensity profiles of the chemilumescence of OH (figure 6). The discontinuities in graphs can be explained by the presence of joints between quartz glasses and small spot of glues.

The combustion regime is determined through those parameters:

- aspect of the reaction zone :visible flame or not, flame aspect
- chemilumescence emission of the reaction zone : intensity profile (width and maximum value)
- unburned species at the exit ($CH_4$, CO)
- $NO_X$ emissions at the exit

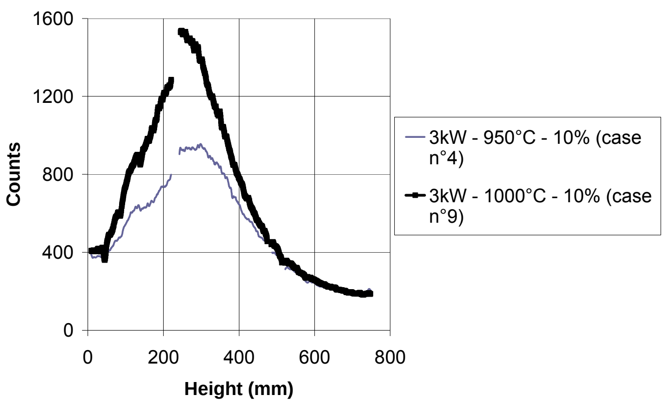
During the series of test of STEP 1&2, four regimes have been distinguished:

1. **Very bright unstable flame:**
   - very luminous yellow flame
   - high OH, CH and $C_2$ emission intensity
   - flame position highly fluctuating
   - high level of $NO_X$ (order of magnitude : 70 ppm)
   - CO and $CH_4 \approx 0$ at the exit

2. **Diluted combustion**
   - no visible flame
   - OH, CH and $C_2$ emission intensity much lower
   - stable position of the reaction zone
   - $NO_X$ emission are low (order of magnitude : 20 ppm)
   - CO ≤ 100 ppm

3. **Very diluted combustion**
   - similar to diluted combustion but with increasing CO emission at the outlet ( 200ppm<CO<400ppm)

4. **Incomplete combustion**
   - Unburned gases > 0,1%. This regime should be avoided.



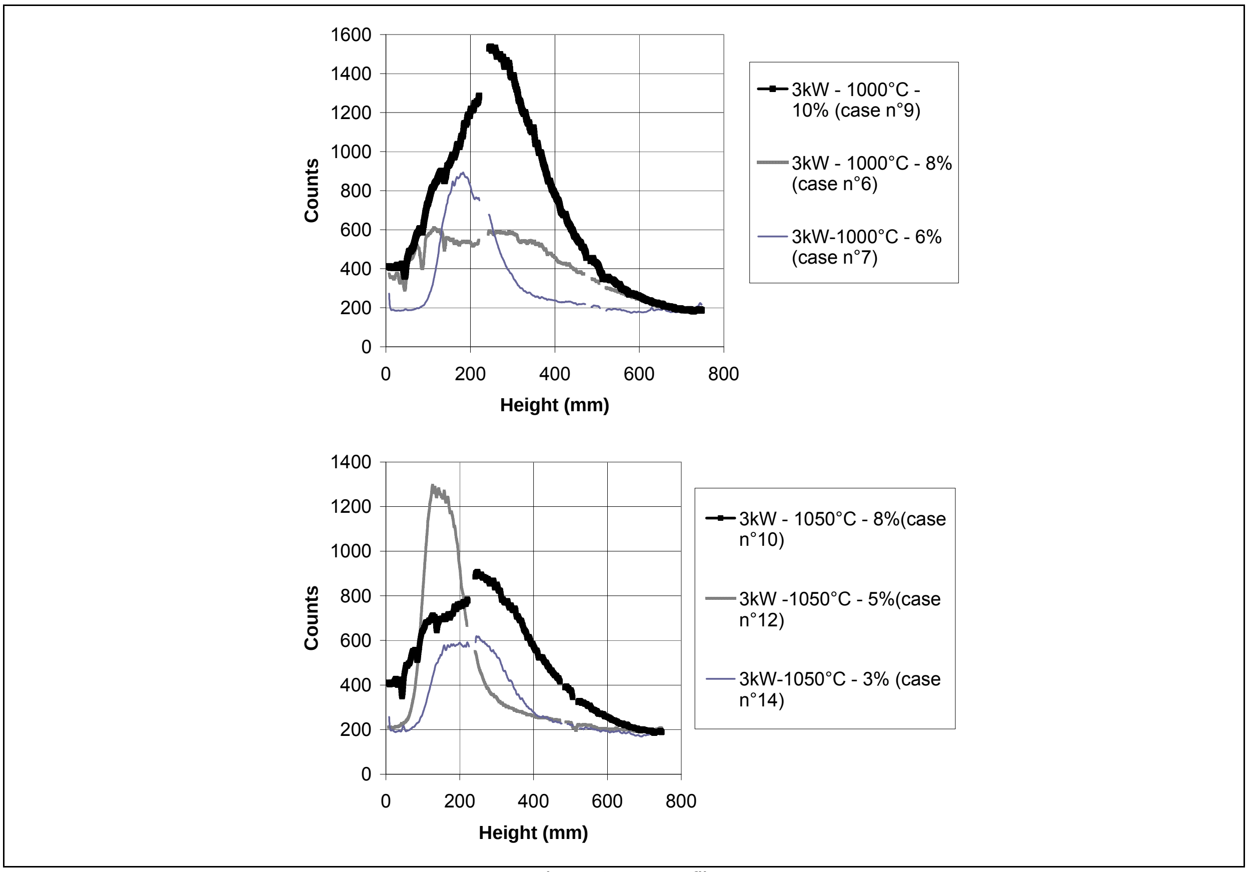



*Figure 6: OH profile*

Figure 7 shows the evolution of the combustion regime in test series n°2, as a function of preheating temperature and oxidizer dilution. It is important to notice that transitions between these regimes are progressive and not precisely localised.
The next figure (figure 8) show operating map with the mixing temperature. So, in this figure, the temperature is the mixing temperature computed as the average value of methane and diluted oxidizer temperature, weighted by mass flows. This temperature is expected to be significant in the operating map. In literature results are generally reported as a function of furnace average temperature. The furnace average temperature is assumed to represent the temperature of the recirculation gases, mixing with reactants before reaction begins.

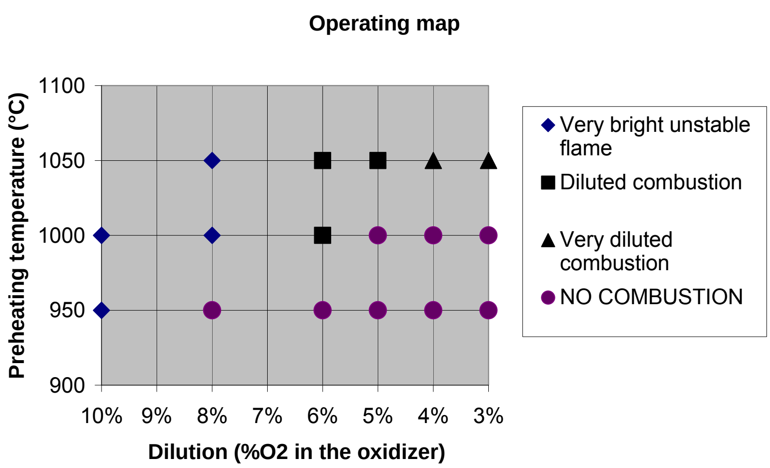



*Figure 7: operating map*

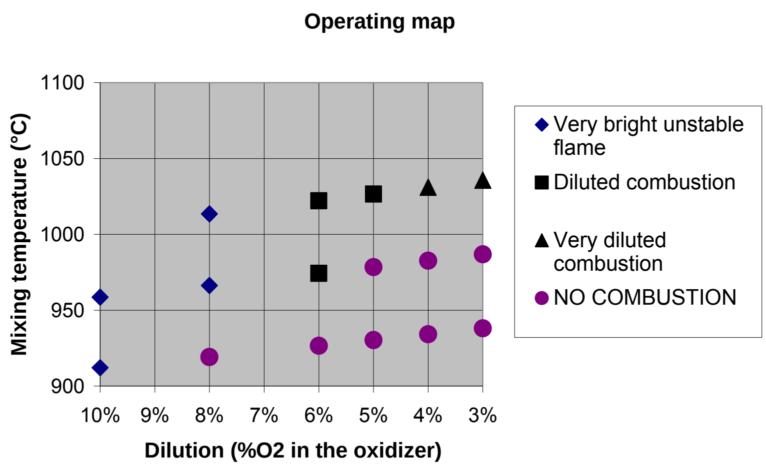



*Figure 8: operating map*

## Comparison with data in scientific literature

In the literature [4] [5], we can find diluted operative parameters maps like figure 9. In these studies, the clean flameless region is defined by disappearance of the flame and by the value of pollutant emission: $NO_X$ below 30 ppm and CO below 50 ppm. The excess of oxygen is between 2 and 3 % with respect to stoichiometric condition. The temperature indicates in the y-axis is an average temperature in the chamber.

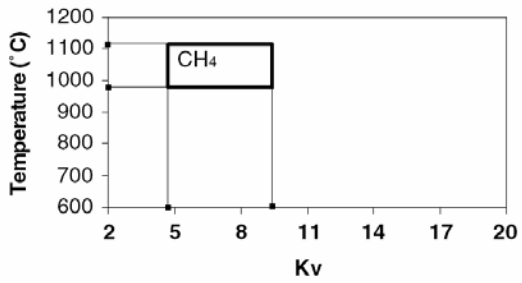



*Figure 9: Clean flameless region for methane [5]*

Comparison of figure 8 with data from literature (figure 9) is strictly not feasible, because the composition of the reacting mixture depends both on the recirculation ratio and on the excess of oxygen with respect to stoichiometric conditions. These parameters and also the mixing temperature should be identical to compare combustion regimes. Despite these different temperatures, we can see that the flameless combustion occurs in the same area.
Two more important parameters to be examined, when comparing data from different sources, are the residence time in the combustion chamber and the ratio of reaction jets velocity. These data are not always available in the literature. The values of these parameters for the present study (speed ratio and momentum ratio) are reported in table 3. Due to the inlets fluid geometry, the speed ratio between fuel and oxidizer jets varies from 1 to 3. Further investigation is planned with variable inlet sections to impose a constant fuel/oxidizer speed ratio.

## STEP 3

The parameters of this study are:
- Firing rate: 5kW – 4kW - 3kW – 2kW
- Temperature of preheating: 1000°C
- Nature of the dilutant: $N_2$
- Dilution: 6% of oxygen in the diluted oxidizer

Test of series n°3 have been performed to check the influence of the firing rate.
For each test, the speed ratio and the jet momentum ratio between fuel and diluted oxidizer is maintained.

| | case n°15 | case n°16 | case n°7 | case n°17 |
|---|---|---|---|---|
| P gaz **[kW]** | 5 | 4 | 3 | 2 |
| Dilution **[%O2]** | 6% | 6% | 6% | 6% |
| T preheating[°C] | 1000 | 1000 | 1000 | 1000 |
| ***Flue gas measurement*** | | | | |
| CH4 **[%]** | 0,1 | 0,0 | 0,1 | 0,0 |
| CO **[ppm]** | 546,9 | 140,03 | 99,38 | 68,42 |
| NO **[ppm]** (at 3% O2, dry basis) | 13,69 | 18,74 | 22,02 | 27,92 |

*Table 4*

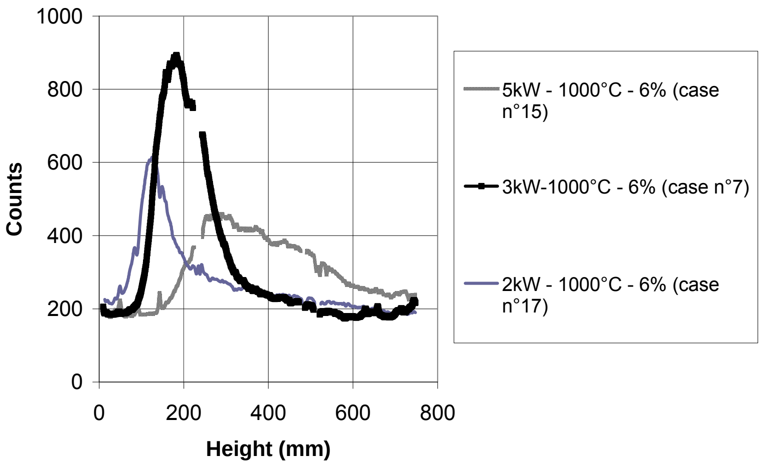



*Figure 10: OH profile*

We can see by observation of OH profiles and also by the result in table 4 that 3kW of firing rate corresponds to the installation. For lower power, it is difficult to have a favourable thermal balance (losses become important) and for bigger power, the residence time in the combustion chamber isn't enough.

## 5. Comparison of chemiluminescence of OH*, CH* and $C_2$*

Spontaneous emission of photon through a reaction D*→D+hv (where the energy of the photon is a signature of the molecule as it is function of electronic states of the excited molecules) is the chemiluminescent emission.
2D images of the emission intensity are recorded with three different filters:
- OH filter (bandwidth is centered at 307 nm)
- CH filter (bandwidth is centered at 430 nm)
- $C_2$ filter (bandwidth is centered at 515 nm)

1D profiles are extracted from the maps. These profiles are plotted on figure 11a&11b as a function of the increasing distance from the combustion chamber base.

We can notice that levels of emissions of CH and $C_2$ radicals decrease very quickly when the combustion mode change from very bright flame to diluted combustion (figure 11a, 11b).

The emission of CH and $C_2$ are in the visible part of the electromagnetic spectrum. In flameless combustion, there isn't emission for those.

The peaks of intensity and the width of emission zone are not very different between OH, CH and $C_2$ for the visible flames; this shows that OH can be considered as a good indicator of the reaction zone, despite that it is expected to be still present in the burned gases in a small zone outside of the main reaction zone.

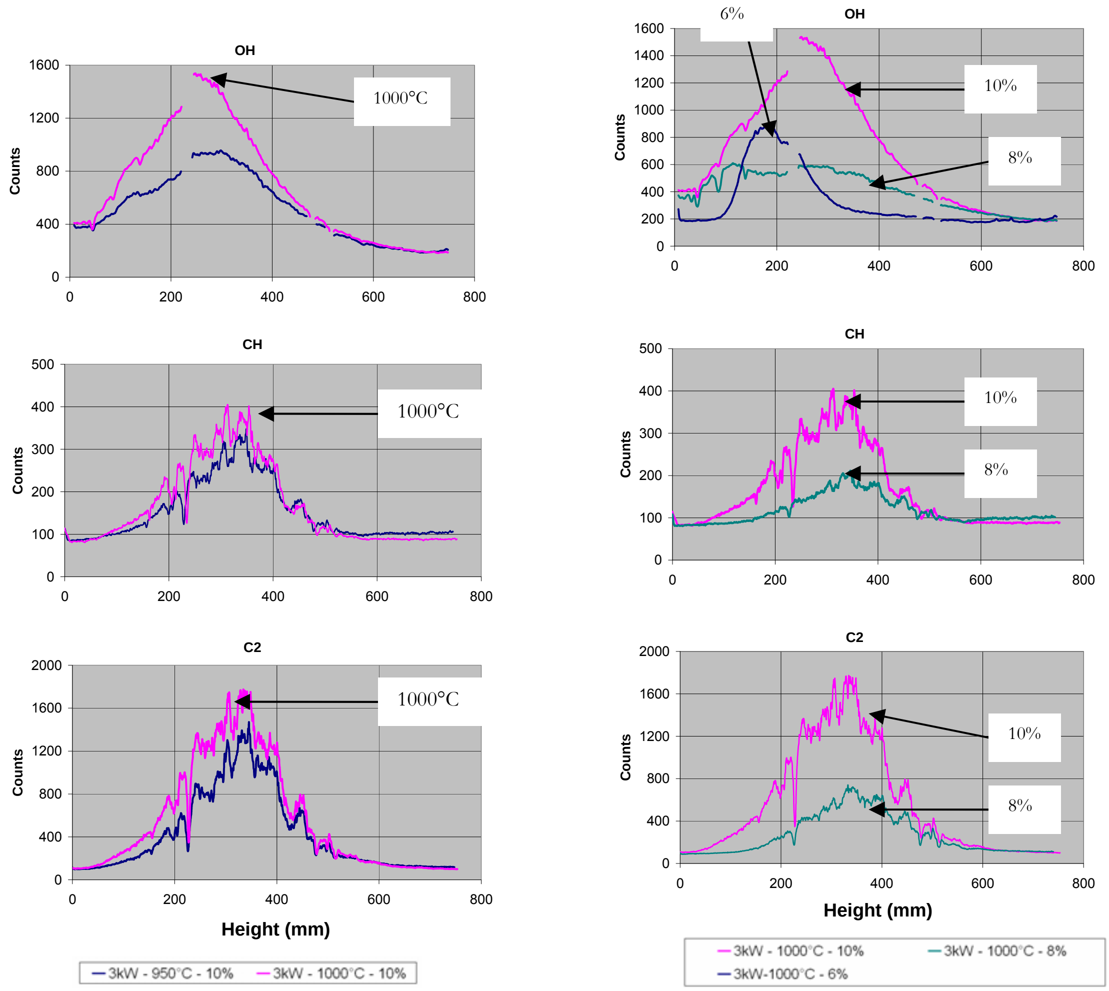



*Figure 11a: Comparison OH, CH and $C_2$ profile*

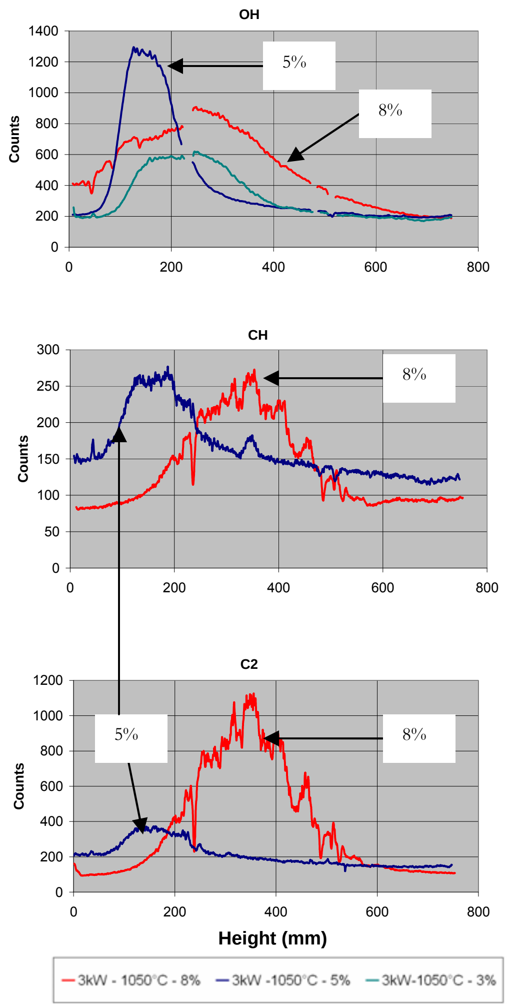


*Figure 11b: Comparison OH, CH and $C_2$ profile*

## 6. Conclusions and perspectives

It has been shown, in this paper, that the experimental apparatus is well designed for the study of diluted combustion for a firing rate of 3kW. The flexibility of experimental installation allows obtaining information on more fundamental aspect of the diluted combustion.
The excess of oxygen is also appeared as an important parameter. It is necessary to specify the excess of oxygen with respect to stoichiometric condition in the operating map.
It has been found (for E=5%) that diluted combustion requires a dilution that corresponds to at least 4% oxygen concentration (very diluted combustion) ($K_V$=4), and requires a temperature where the reactant mixture starts to be consumed at least 1000°C.
We can also note that the reaction zone determined by the emission of radical CH and $C_2$ is not significantly very different than with the OH emission for the visible flames.

### Acknowledgements

This work has been performed thanks to the financial support of the Walloon Government.

### References

[1] Alessandra Effuggi, Davino Gelosa, Marco Derudi and Renato Rota, *Mild Combustion of methane-derived fuel mixtures: Natural gas and biogas,* Combust. Sci. and Tech., 180:481-493, 2008

[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 & 29th Task Leader Meeting

[4] Alessandro Cavigiolo, Mauro A. Galbiati, Alessandro Effugio, Davino Gelosa and Renato Rota, *'Mild Combustion in a laboratory-scale apparatus'* Combust. Sci. and Tech., 175 :1347-1367 (2003)

[5] Marc Derudi, Alessandro Villani, Renato Rota, *Sustainability of mild combustion of hydrogen-containing hybrid fuels,* Proceedings of the Combustion Institute 31 (2007) 3393-3400