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EXPERIMENTAL AND NUMERICAL INVESTIGATION ON THE LAMINAR FLAME SPEED OF CH₄/O₂ MIXTURES DILUTED WITH CO₂ AND H₂O

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ABSTRACT
The effects of CO₂ and H₂O addition on premixed oxy-fuel combustion are investigated with experiments and numerical simulations on the laminar flame speed of CH₄/O₂/CO₂/H₂O(v) and CH₄/O₂/N₂/H₂O(v) mixtures, at atmospheric pressure and for a reactants inlet temperature Tᵤ = 373 K. Experiments are conducted with steady laminar conical premixed flames over a range of operating conditions representative of oxy-fuel combustion with flue gas recirculation. The relative O₂-to-CO₂ and O₂-to-N₂ ratios, respectively defined as O₂/(O₂+CO₂) (mol.) and O₂/(O₂+N₂) (mol.), are varied from 0.21 to 1.0. The equivalence ratio of the mixtures ranges from 0.5 to 1.5, and the steam molar fraction in the reactive mixture is varied from 0 to 0.45. Laminar flame speeds are measured with the flame area method using a Schlieren apparatus. Experiments are completed by simulations with the PREMIX code using the detailed kinetic mechanism GRI-mech 3.0. Numerical predictions are found in good agreement with experimental data for all cases explored. It is shown that the laminar flame speed of weakly (CO₂, H₂O)-diluted CH₄/O₂ mixtures is underestimated by the GRI-mech 3.0 predictions.

NOMENCLATURE
A f  Flame area (m²)
ṁ  Mass flow rate (kg.s⁻¹)
p  Pressure (Pa)
s₀  Laminar flame speed (m.s⁻¹)
şT  Turbulent burning velocity (m.s⁻¹)
T  Temperature (K)
T ad  Adiabatic flame temperature (K)
Xᵢ  Molar fraction of species i
ρ  density (kg.m⁻³)
φ  Equivalence ratio
Ωᵢ  O₂ molar dilution ratio with respect to N₂ (i = N) or CO₂ (i = C)
RFG  Recycled Flue Gas

INTRODUCTION
Oxy-fuel combustion technology has been identified as a promising approach for power generation with CO₂ capture and storage [1]. In this process, the fuel is burned in pure oxygen diluted with a large amount of recycled flue gas (RFG) in order to maintain exhaust temperatures compatible with materials thermal resistance. Carbon dioxide and water vapor are the main
components of the flue gas generated by oxy-combustion processes, thereby reducing significantly the cost of CO₂ separation. The presence of CO₂ and H₂O₂ in the reactive mixture in place of N₂ in traditional air-fuel combustion is likely to affect the combustion properties through thermal, chemical and radiative mechanisms. Additional research is thus required to characterize combustion in O₂/RFG environments [1]. Although many studies on oxy-fuel combustion are dedicated to solid fuels, especially coal (see e.g. the review proposed by Buhre et al. [2]), it is worthwhile investigating the effects of RFG dilution on gaseous fuels, which are also widely used in gas turbines for power generation.

Some effects of CO₂ addition and of H₂O₂ addition on flame characteristics have been separately examined in the last decades. A brief overview is given here on the main results obtained regarding CO₂-diluted and H₂O-diluted flames properties.

The effects of CO₂ addition on premixed flame structure have been examined for CH₄/O₂/N₂/CO₂ and H₂/O₂/N₂/CO₂ mixtures [3, 4]. Species concentrations were measured in a jet-stirred reactor for a wide range of equivalence ratios and temperatures, at p = 1 atm and 10 atm. It was observed that CO₂ inhibits the oxidation of H₂ and CH₄, reacting with H radicals in the reaction CO₂ + H = CO + OH (R1). This chain-carrying reaction competes for H atoms consumption with the chain-branching reactions H + O₂ = OH + H and H + HO₂ = OH + OH. The chemical effect of CO₂ in oxy-fuel combustion of methane was also discussed for high CO₂ concentrations. It was found that CO₂ dilution is likely to yield increased CO concentrations in the near-burner region due to the reaction (R1), having possible consequences for burner corrosion and slagging [5].

Ignition and extinction characteristics of CO₂-diluted reactive mixtures have also been examined. Homogeneous ignition was investigated with OH concentrations LIF-measurements in a catalytic channel-flow reactor for lean CH₄/O₂/N₂/CO₂ mixtures, at pressures p = 4 - 16 bar [6]. Extinction limits were measured as a function of stretch for CH₄/O₂ (resp. CH₄/N₂) and O₂/CO₂ (resp. CH₄/N₂) counterflow non-premixed flames up to 7 bar [7]. While conventional C-shapes extinction behaviors were observed for CH₄/O₂/N₂ mixtures, the extinction limits of CH₄/O₂/CO₂ are broadened at low stretch rates at 5 and 7 bar. This phenomenon was attributed to radiation reabsorption due to the presence of CO₂ in fresh gases. The effects of radiative emission and absorption on the propagation and the extinction of premixed flames have also been studied numerically [8, 9] and experimentally [10]. Results show a significant contribution of non-grey radiation on flammability limits and burning velocities when increasing the pressure and the amount of CO₂ in the unburned gases.

The influence on soot formation of carbon dioxide addition in diffusion flames was studied experimentally [11–13] and numerically [14, 15]. The addition of CO₂ led to a significant decrease of soot volume fraction. It was shown that CO₂ dilution thermally and chemically limits the formation of soot precursors due to the decrease of H radicals consumed in the reaction CO₂ + H = CO + OH.

The effects of CO₂ addition on the burning velocity have been explored to discuss the validity domain of detailed kinetic mechanisms. However, existing studies are limited to highly diluted oxy-fuel mixtures or to air-fuel mixtures in which small CO₂ quantities are added. The chemical effect of CO₂ replacement of N₂ in air on the burning velocity of CH₄ and H₂ flames was examined numerically [16]. Laminar flame speeds of CH₄/(Ar, N₂, CO₂)-air mixtures were measured for a wide range of equivalence ratios, pressure and flame temperatures [17]. Propagation speeds of flat flames were also measured with the heat flux method for different fuels (H₂, CH₄, C₆H₆, C₃H₈) in O₂/CO₂ environments with high CO₂ molar fractions [18–22]. In those studies, the O₂-to-CO₂ molar ratio, defined as O₂/(O₂+CO₂) (mol.), ranges typically between 0.12 and 0.35. Laminar burning velocities were also measured for H₂-air/He/CO₂ mixtures with a constant volume spherical bomb [23].

The effects of CO₂ dilution on turbulent premixed flames were investigated for CH₄/air mixtures, at elevated pressure [24–26]. For small CO₂ concentrations – corresponding to CO₂ molar fractions X₁-X₂ ranging from 0 to 0.05, no difference was observed in the turbulent flame structure for a given pressure [26]. In experiments conducted with preheated mixtures (573 K) with a CO₂-to-air molar ratio CO₂/CO₂+air (mol.) varying between 0 and 0.10, the addition of CO₂ was found to affect the ratio of the turbulent burning velocity ST normalized with the laminar burning velocity s₀, to increase the mean volume of the flame region and to modify the turbulent flame structure [24]. An increase of the bending of ST/s₀ versus u'/s₀ plots was also observed when N₂ was replaced with CO₂ [25].

A few prior studies have also examined some effects of steam addition on premixed and non-premixed flames properties. Steam dilution is however less commonly investigated because of significant experimental difficulties to accurately control the quantity of steam injected in the reactive mixtures. Steam addition has soon been identified as a successful way to lower pollutants emissions – especially NOₓ emissions – in gas turbines operating both in premixed and non-premixed modes [27–33]. This is particularly attractive when considering the continuous developments in Humid Air Turbine (HAT) cycles. In the most recent studies, it was shown that steam addition in various combustible mixtures (natural gas, n-heptane, iso-octane) led to substantial reductions of NOₓ emissions, due to the decrease of the flame temperature and of O-atom concentration [34, 35]. Operating at constant adiabatic flame temperature, water vapor dilution was found to reduce NOₓ levels by more than a factor of two compared to nitrogen dilution [36]. It was also observed that steam
addition had a very limited impact on CO emissions for a fixed flame temperature [34, 35].

The influence of steam as a fire inhibitor in premixed methane-air flames has been investigated. Regarding the thermal suppression effect, water vapor was found to be more effective than other gaseous thermal agents (N2 and CF3) or some chemical agents (CF3Br) but less effective than the same mass of water mist [37]. These studies are however mainly based on numerical simulations and corresponding experiments were limited yet to small concentrations of added water vapor (steam mass fraction \( Y_{H_2O} < 0.02 \)) [37, 38].

The effects of water vapor addition on flame extinction and ignition have also been examined recently. Critical conditions of ignition and extinction for hydrogen and methane flames were measured and calculated as a function of the water mass fraction in the oxidizer [40, 41]. It was observed that steam addition favors extinction and narrows regimes of ignition for premixed and non-premixed flames. Chemical effects of steam addition in hydrogen-air and methane-air flames were mainly attributed to the chaperon efficiency of water in three body reactions. This hydrogen-air and methane-air flames were mainly attributed to the chaperon efficiency of water in three body reactions. This analysis shows that the chemical effect of steam results from high third body efficiency in the reaction \( H + O_2 + M \) which delays and species concentrations measurements that were compared with computed species profiles. Kinetic modelling analysis shows that the chemical effect of steam results from high third body efficiency in the reaction \( H + O_2 + M \) which delays and species concentrations measurements that were compared with computed species profiles.

Finally, the effects of steam addition on the laminar burning velocity were examined in different experiments. Burning velocities of hydrogen-air-steam and hydrogen-oxygen-steam mixtures were measured with laminar conical flames, for a wide range of steam molar fractions [43, 44]. Results show a significant decrease of the flame speed when water vapor is added. Laminar burning velocities of methane-air-steam were also measured using spherically expanding flames in a constant volume vessel filled with CH4/air/H2O mixtures [45]. Measurements were carried out for stoichiometric mixtures over a wide range of initial pressures and for a constant unburned gas temperature \( T_u = 473 K \), with a water vapor molar fraction varying from 0 to 0.20. Burning velocities were deduced from direct photographs of the early stage of the flame propagation. Results at atmospheric pressure show a quasi-linear decrease of the burning velocity when the water vapor molar fraction is increased, but data were not reported yet for non-stoichiometric or oxygen-enriched mixtures.

It is worthwhile noting that, regarding the effects of steam and carbon dioxide addition in flames, experimental and numerical results have been almost exclusively obtained for weakly diluted air-fuel mixtures or for highly diluted oxy-fuel mixtures, i.e. for mixtures whose flame temperatures are typically lower than 2250 K. In this work, experiments and numerical simulations are conducted to examine the simultaneous effects of CO2 and H2O addition on the laminar burning velocity of oxygen-enriched methane flames, at atmospheric pressure. Carbon dioxide and water vapor concentrations are chosen in order to explore a large domain of flame temperatures, from about 2000 to 3000 K.

**EXPERIMENTAL SET-UP**

Experiments are conducted on an oxycombustion-dedicated setup, including heated gas feeding lines, a steam production apparatus and an axisymetric burner on which steady conical laminar premixed flames are stabilized.

An overview of the experimental setup is shown in Fig. 1. Methane (CH4), oxygen (O2), nitrogen (N2) and carbon dioxide (CO2) gases (purity \( > 99.99 \% \)) are supplied from an internal network of tanks. The flow rates of CH4, O2 and CO2 (respectively N2) are regulated with mass flow controllers (Bronkhorst F-Series) calibrated with the related gas. The accuracy of the mass flow controllers is \( \pm 2 \% \) of the set operating condition. Water vapor is produced with a custom-built apparatus derived from Cellkraft P-50 humidifier. Oxygen and carbon dioxide (respectively oxygen and nitrogen) are premixed before being introduced as a carrier gas in the humidifier. Steam production is based on the humidification of the carrier gas by transfer of water vapor through specific membranes (Nafion® membranes, DuPont). The carrier gas flows in membrane tubes, which are immersed in demineralized liquid water heated with electrical resistances. At the tubes exit, the carrier gas is saturated with steam. The dew point temperature \( T_{dew} \) of the humidified mixture is then measured with a humidity sensor (Vaisala Humicap Series HMT 330). A closed loop control of humidity based on the measured dew point temperature \( T_{dew} \) is used to regulate the humidity of the liquid water in which the membrane tubes are immersed. This temperature \( T_{lw} \) is varied to control the dew point of O2/CO2/H2O (resp. O2/N2/H2O) mixtures obtained at the humidifier outlet. The steam molar fraction \( X_{H_2O}^{\\text{sat}} \) in the humidified carrier gas can then be inferred from the steam partial pressure \( p_{H_2O} \), equal to the saturation vapor pressure at the dew-point temperature \( p_{sat}(T_{dew}) \), and from the humidifier inner pressure \( p_h \), measured with a high temperature pressure transducer (Huba Control) placed at the humidifier outlet:

\[
X_{H_2O} = \frac{p_{H_2O}}{p_h} = \frac{p_{sat}(T_{dew})}{p_h}
\]  

Experimental steam mass flow rates were measured and compared with theoretical predictions obtained with Eq. 1, as shown in Tab. 1. Experimental results are in good agreement with theoretical predictions, within 1% accuracy. It can be concluded from
Honeycomb
$N_2$
coflow
$CH_4/O_2/CO_2/(N_2)/H_2O(v)$

Profiled nozzle

Heating tape

Burner

MFC

N$_2$ or CO$_2$

CH$_4$

O$_2$

Humidifier

N$_2$ or CO$_2$

Liquid water

Figure 1: Schematic of the experimental set-up. a) Overview of the global set-up. b) Detailed view of the burner.

The humidifier linear operation and from the excellent repeatability of these tests that the steam concentration is remarkably stable and accurately controlled.

The O$_2$/CO$_2$/H$_2$O (resp. O$_2$/N$_2$/H$_2$O) mixtures coming from the humidifier and methane flow are premixed before being introduced in an axisymmetric burner. A detailed view of the burner is shown in Fig. 1. Gases are injected in the lower part of the burner, which is filled with glass beads (1 to 5 mm diameter) to further reduce possible mixture non-homogeneities. The reactive mixture then flows successively through a perforated plate, a honeycomb structure and a refined metallic grid to obtain a laminar flow entering the inlet of a profiled converging nozzle. The burner can be equipped with three different converging nozzles of outlet diameter $d = 10$, 7 or 4 mm, with respective contraction ratios $\sigma = (D/d)^2 = 41$, 86 and 256. The converging nozzle is used to reduce the boundary layer thickness by accelerating the flow and to obtain a top hat velocity profile at the burner outlet. A small co-flow of nitrogen surrounding the inner main nozzle is used to prevent potential outer perturbations. The velocity profile at the burner outlet was characterized using a hot wire anemometry system (Dantec). It was checked that the velocity profile remains flat over 80% of the burner diameter and the RMS fluctuations were found to be less than 1.0 % of the mean velocity.

The temperature of all the components downstream the humidifier is controlled and set at the unburned gas temperature $T_u$ to prevent water condensation. The burner temperature is regulated with an electrical heating tape (Vulcanic) and the temperature field homogeneity is simultaneously controlled with a J-type thermocouple TC1 inserted in the burner body and with a K-type thermocouple TC2 inserted in the bottom plate of the burner. A K-type thermocouple TC3 located immediately upstream the perforated plate is used to measure the mixture temperature $T_u$.

Schlieren images are obtained using a classical Z-arrangement with lenses (diameter 100 mm, focal length 1000 mm) and vertical knives (Ealing) to highlight horizontal density gradients. Pictures are recorded with a video CCD camera (768x576 square pixels, Pulnix), equipped with a variable speed shutter and a 100-300 mm lens (Cosina) to zoom in the flame region.

**EXPERIMENTAL METHOD AND CALCULATIONS**

The laminar burning velocity $s_{uo}$ is defined as the velocity at which a laminar, steady, plane, unstretched, adiabatic flame moves relative to the unburned premixed gas in a direction normal to the flame surface [46]. However, a flame fulfilling all the pre-cited requirements cannot be easily obtained experimentally and different experimental configurations can be employed, depending on the range of burning velocities explored and on the humidifier linear operation and from the excellent repeatability of these tests that the steam concentration is remarkably stable and accurately controlled.

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nature of the reactive mixtures [47, 48]. In this study, it was chosen to work with steady conical CH$_4$/O$_2$/CO$_2$/N$_2$/H$_2$O$_{(w)}$ flames stabilized on the burner outlet. The conical flame method is easy to implement, provides reliable results and has been successfully used in the past for oxy-fuel flame speeds measurements [44, 49]. Assuming the whole reactive mixture is burned, one can define an area-weighted average laminar flame speed $\bar{u}_f$ that can be calculated from the mass conservation equation $\dot{m} = \rho_u \bar{u}_f A_f$, where $\dot{m}$ is the reactants mass flow rate, $\rho_u$ is the unburned gas density and $A_f$ is the flame area. Since the laminar burning velocity $s'_u$ is defined relative to the unburned gases, the most appropriated area is the upstream boundary of the preheat zone that can be determined with a Schlieren technique. When using a Schlieren imaging set-up, the light deflection due to optical index gradients is proportional to $|\nabla T|/T^2$, where $T$ is the gas temperature [50]. As the maximum of light deflection occurs close to the upstream boundary of the preheat zone, the Schlieren technique is an efficient diagnostic to measure laminar burning velocities [51, 52]. The main disadvantages of conical flames are the heat losses at the burner rim and the effects of stretch and curvature that are known to affect the burning velocity [53]. Nevertheless, the high temperatures of oxygen-enriched flames induce limited heat losses compared to the total heat released by the flame and it is established that the hydrodynamic stretch is low for conical flames, since velocity gradients along the flame are small for conical flames stabilized in uniform flows [54]. The top-hat velocity profile at the burner outlet ensures that the flame speed is constant along the flame front, except near the flame tip and in the near-burner area [49]. Pictures of typical chemiluminescence and Schlieren images obtained in this work are shown in Fig. 2.

![Schlieren images](image)

**Figure 2:** Left: direct photograph of CH$_4$/O$_2$/N$_2$ flame, with O$_2$/(O$_2$+N$_2$) (mol.) = 0.50 and $\phi = 1.50$, at $T_u = 373$ K and atmospheric pressure. Right: corresponding Schlieren image. The Schlieren front is located close to the upstream boundary of the preheat zone.

Experiments are completed by simulations of one-dimensional, freely propagating, unstretched, adiabatic, laminar, premixed flames using the PREMIX code of the CHEMKIN package [55]. This one-dimensional flame solver is employed with the detailed kinetic mechanism GRI mech. 3.0 [56].

**RESULTS AND DISCUSSION**

As it is discussed in the introduction, this work aims at providing new experimental data on the laminar flame speed of CH$_4$/O$_2$/N$_2$/H$_2$O and CH$_4$/O$_2$/CO$_2$/H$_2$O mixtures, with flame temperatures ranging from 2000 to 3000 K. The parameters examined in this work are: (a) the oxygen-enrichment ratios in the oxidizer $\Omega_N = X_{O_2}/(X_{O_2} + X_{N_2})$ and $\Omega_C = X_{O_2}/(X_{O_2} + X_{CO_2})$ where $X_k$ is the molar fraction of the species $k$; (b) the steam molar fraction $X_{H_2O}$ in the whole reactive mixture; (c) the mixture equivalence ratio $\phi = (m_{CH_4}/m_{O_2})/(m_{CH_4}/m_{O_2})_s$ where $(m_{CH_4}/m_{O_2})_s$ is the fuel-to-oxygen mass ratio in stoichiometric conditions. All the experiments are carried out at a constant unburned gas temperature $T_u = 373$ K ± 1 K, except for the case of CH$_4$/Air/H$_2$O$_{(w)}$ mixtures where the gas inlet temperature is set to $T_u = 473$ K ± 2 K so that the results can be compared to existing experimental data [45].

Typical operating conditions explored in this work are shown for stoichiometric mixtures in Tab. 2. In a first set of experiments, the oxygen concentration in the oxidizer is progressively increased, with $\Omega_N$ varying from 0.21 (air) to 1.0 (pure oxygen). Corresponding flame temperatures vary from 2260 K to 3060 K and computed laminar flame speeds vary from 55 cm/s to 409 cm/s. For each value of $\Omega_N$, the corresponding ratio $\Omega_C$ is chosen in order to keep the same burning velocity. The flame temperatures for corresponding $\Omega_N$ and $\Omega_C$ ratios are found to be close. This allows to delineate four flame temperature ranges: $T_{ad} \sim 2250$ K, 2500 K, 2800 K and 3000 K, for which the burning velocities of CH$_4$/O$_2$/N$_2$/H$_2$O and CH$_4$/O$_2$/CO$_2$/H$_2$O mixtures are measured, in lean ($\phi < 1$), stoichiometric ($\phi = 1$) and rich conditions ($\phi > 1$).

<table>
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<th>$T_{ad}(\Omega_N)$ (K)</th>
<th>$s'_u$ (cm/s)</th>
<th>$\Omega_C$</th>
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</tbody>
</table>

Table 2: Computed adiabatic flame temperatures and burning velocities of stoichiometric CH$_4$/O$_2$/N$_2$ and CH$_4$/O$_2$/CO$_2$ mixtures, at $T_u = 373$ K and $p_u = 1$ atm.

The present experimental procedure for the determination of the flame speed in wet environments is first validated with available experimental data. Results are compared for a stoichiomet-
ric methane/air flame at atmospheric pressure and preheated to \( T_e = 473 \) K with those obtained by Babkin et al. [45] with a spherical vessel. The evolution of the flame speed is plotted in Fig. 3 for \( \text{H}_2\text{O} \) molar fraction ranging from 0 to 0.20. It is found that the results obtained with different techniques match well and follow closely numerical predictions using the GRI-mech 3.0 kinetic mechanism. It is worth noting that the flame speed decreases almost linearly when the steam concentration is increased. Other tests, not shown here, were also conducted with dry methane/air mixtures and showed a good agreement with flame speed data obtained from the literature. This validates the methodology for the determination of the laminar burning velocity with a relative uncertainty of 5%.

All the remaining experiments are conducted at atmospheric pressure for preheated mixtures at \( T_e = 373 \) K and numerical simulations are performed with the GRI-mech 3.0 mechanism. The evolution of the flame speed is now examined in oxycombustion conditions for dry mixtures corresponding to an adiabatic flame temperature of about \( T_{\text{ad}} \sim 2600 \) K obtained with a nitrogen dilution ratio \( \Omega_N = 0.30 \) or a carbon dioxide dilution ratio \( \Omega_C = 0.52 \). Results are plotted in Figs. 4, 5 and 6 for stoichiometric \( (\phi = 1) \), lean \( (\phi = 0.7) \) and rich \( (\phi = 1.4) \) mixtures respectively, as a function of the steam molar fraction. It is worth noting that the flame speed measurements of dry stoichiometric mixtures diluted either with \( \text{N}_2 \) or \( \text{CO}_2 \) are equal as expected and reach about \( \bar{s}_u = 1.1 \) m.s\(^{-1}\) (Tab. 2). When increasing the steam molar fraction from 0 to 0.30, the flame speed features a larger decrease for a stoichiometric mixture diluted with nitrogen \( \Omega_N = 0.30 \) than with carbon dioxide \( \Omega_C = 0.52 \) (Fig. 4). Data are found in good agreement with numerical predictions in both cases. These observations can also be made for lean and rich mixtures presented in Figs. 5 and 6 where experimental data closely match numerical simulations, even for high steam concentrations. The evolution of the flame speed of \( \text{CO}_2 \) diluted wet oxy-flames has however a slightly different concavity than that found for \( \text{N}_2 \) diluted wet oxy-flames.
flame speeds of CH\textsubscript{4} and CH\textsubscript{4}/O\textsubscript{2}/N\textsubscript{2}/H\textsubscript{2}O mixtures, for $\Omega_N = X_{O_2}/(X_{O_2} + X_{N_2}) = 0.30$ and $\Omega_C = X_{O_2}/(X_{O_2} + X_{CO_2}) = 0.52$ respectively, $\phi = 1.40$, at $T_u = 373$ K and atmospheric pressure.

Figure 7: Experimental (symbols) and computed (lines) laminar flame speeds of CH\textsubscript{4}/O\textsubscript{2}/N\textsubscript{2}/H\textsubscript{2}O and CH\textsubscript{4}/O\textsubscript{2}/CO\textsubscript{2}/H\textsubscript{2}O mixtures, for $\Omega_N = X_{O_2}/(X_{O_2} + X_{N_2}) = 0.50$ and $\Omega_C = X_{O_2}/(X_{O_2} + X_{CO_2}) = 0.72$ respectively, $\phi = 1.0$, at $T_u = 373$ K and atmospheric pressure.

Figure 8: Experimental (symbols) and computed (lines) laminar flame speeds of CH\textsubscript{4}/O\textsubscript{2}/N\textsubscript{2}/H\textsubscript{2}O and CH\textsubscript{4}/O\textsubscript{2}/CO\textsubscript{2}/H\textsubscript{2}O mixtures, for $\Omega_N = X_{O_2}/(X_{O_2} + X_{N_2}) = 0.50$ and $\Omega_C = X_{O_2}/(X_{O_2} + X_{CO_2}) = 0.72$ respectively, $\phi = 0.60$, at $T_u = 373$ K and atmospheric pressure.

Figure 9: Experimental (symbols) and computed (lines) laminar flame speeds of CH\textsubscript{4}/O\textsubscript{2}/N\textsubscript{2}/H\textsubscript{2}O and CH\textsubscript{4}/O\textsubscript{2}/CO\textsubscript{2}/H\textsubscript{2}O mixtures, for $\Omega_N = X_{O_2}/(X_{O_2} + X_{N_2}) = 0.50$ and $\Omega_C = X_{O_2}/(X_{O_2} + X_{CO_2}) = 0.72$ respectively, $\phi = 1.50$, at $T_u = 373$ K and atmospheric pressure.

Data are now reported for a higher concentration of oxygen in Figs. 7, 8 and 9. The same observations can be made for dry oxy-flames diluted with N\textsubscript{2} ($\Omega_N = 0.50$) and CO\textsubscript{2} ($\Omega_C = 0.72$). The flame speed of the dry stoichiometric mixture $s_u = 2.2$ m.s\textsuperscript{-1} is now twice the value found in the previous case and corresponds to mixtures with a flame temperature of about $T_{ad} \sim 2800$ K. In stoichiometric conditions, the flame speed decrease is still more pronounced for N\textsubscript{2}-diluted wet flames than for CO\textsubscript{2}-diluted wet flames, but the difference is reduced because the oxygen ratio in the mixture has been increased. Numerical predictions still match closely the experimental data for stoichiometric ($\phi = 1$), lean ($\phi = 0.6$) or rich conditions ($\phi = 1.5$), up to high steam conditions.
molar fractions $X_{H_2O} \sim 0.4$. The agreement between measurements and numerical predictions is observed to improve for results obtained at $T_{ad} = 2800$ K compared to those obtained at $T_{ad} = 2600$ K. This database is completed in Fig. 10 where the burning velocities of CH$_4$/O$_2$/N$_2$/H$_2$O flames are plotted as a function of the equivalence ratio of the mixture. It is still found a good agreement between predictions and measurements of the flame speed for the three values of the steam molar fraction investigated $X_{H_2O} = 0, 0.10$ and 0.20 in the range $\phi = 0.60$ to 1.50.

Effects of dilution by H$_2$O or CO$_2$ are now examined for oxy-fuel CH$_4$/O$_2$ flames. Results are plotted in Figs. 11, 12 and 13 for lean ($\phi = 0.50$), stoichiometric ($\phi = 1.0$) and rich ($\phi = 1.5$) mixtures respectively. When the laminar flame speed evolution is plotted as a function of the diluent molar fraction, a more pronounced decrease is observed for CO$_2$ dilution than for H$_2$O dilution. This is mainly due to the molar weight difference between H$_2$O (18 g/mol) and CO$_2$ (44 g/mol), although CO$_2$ features a slightly lower heat capacity than H$_2$O. For a same molar fraction of H$_2$O or CO$_2$ in the mixture, the flame temperature is lower for
CO₂ addition than for H₂O addition. Consequently, the decrease rate of the flame speed is higher for CO₂-diluted flames than for H₂O-diluted flames. The general trend observed in these figures is correctly predicted by the simulations for all cases explored, but large differences are observed at low dilution rates for lean and stoichiometric flames. For dry CH₄/O₂ flames, simulations yield \( \phi \Omega = 3.1 \text{ m s}^{-1} \) and 4.0 m s\(^{-1}\) for a lean (\( \phi = 0.5 \)) and a stoichiometric mixture (\( \phi = 1.0 \)). These predictions should be compared with the measurements yielding \( \phi \ Omega \) = 3.5 m s\(^{-1}\) and 4.5 m s\(^{-1}\) in the same conditions. One can note that the GRI-mech 3.0 mechanism slightly underestimates the flame speed of CH₄/O₂ mixtures diluted with H₂O or CO₂, and that these differences reduce for higher dilution rates. The largest differences between experimental data and numerical predictions are observed for CO₂ dilution. These differences cancel for a rich mixture at \( \phi = 1.5 \). It is therefore interesting to examine the effects of equivalence ratio. The flame speed of methane/oxygen mixtures is plotted versus the equivalence ratio for two carbon dioxide molar fractions \( X_{\text{CO}_2} \) = 0.20 and 0.40 in Fig. 14. This figure clearly confirms that the predictions of the flame speed of CH₄/O₂ mixtures diluted with CO₂ are underestimated for equivalence ratios ranging from \( \phi = 0.5 \) to 1.50 for carbon dioxide molar fractions lower than \( X_{\text{CO}_2} < 0.40 \). The relative difference reaches about 10% for stoichiometric mixtures and reduces in lean and particularly in rich conditions. These differences between numerical predictions and measurements also cancel for highly CO₂-diluted oxy-fuel flames.

**CONCLUSION**

An experimental and numerical investigation on the laminar flame speed of CH₄/O₂ mixtures diluted with N₂, CO₂ and H₂O was conducted in this work. Laminar flame speeds were measured for a wide range of equivalence ratios (0.50 < \( \phi < 1.50 \)), O₂-to-N₂ and O₂-to-CO₂ molar ratios (0.21 < \( \Delta \Omega \), \( \Delta \Omega \) < 1.0) and steam molar fractions in the mixture (0 < \( X_{\text{H}_2\text{O}} < 0.45 \)). It was observed that the laminar burning velocity of CH₄/O₂/N₂/H₂O and CH₄/O₂/CO₂/H₂O mixtures features a quasi-linear decrease when the steam molar fraction is increased. This decrease was found to be more pronounced for N₂-diluted than for CO₂-diluted wet mixtures. In these conditions, the flame speed is well predicted by the GRI-mech 3.0 mechanism. The effects of CO₂ and H₂O dilution were also investigated for oxy-fuel CH₄/O₂ flames. Experimental results show that GRI-mech 3.0 predictions underestimate the flame speeds at low H₂O (\( X_{\text{H}_2\text{O}} < 0.10 \)) and CO₂ (\( X_{\text{CO}_2} < 0.30 \)) dilution rates in lean and near-stoichiometric conditions, while differences reduce in rich conditions.

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