Premixed CH$_4$/O$_2$-enriched air combustion: Identification of thermal, chemical and aerodynamic effects

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Abstract. This work contributes to the evaluation of a new innovative process focused on the reduction of the cost of a post-combustion capture of CO$_2$ in a Carbon Capture and Storage system (CCS). The process based on the separation of dried fumes composed mainly by CO$_2$ and N$_2$ by using membranes, which should lead to a lower energetic separation cost than amines. But the membranes become efficient if the upstream CO$_2$ concentration is higher than 30% at their entrance that requires enriching the oxidizer flow by O$_2$. To maintain the exhaust temperature compatible with materials thermal resistance, the reactants are diluted by a recirculation of a part of the flue gases (like N$_2$/O$_2$/CO$_2$). But, the chemical kinetic, the energetic efficiencies, the radiation transfer, the transport and thermal properties of the flow can be affected by CO$_2$. The objective of this work will be to identify the behaviour of the combustion of premixed CH$_4$/O$_2$-enriched air, both diluted in N$_2$ and CO$_2$ and to determine the combustion parameters. This allows to recover the CH$_4$/air conditions in terms of CO$_2$ concentration in reactants, O$_2$ excess, dilution rate, temperature of the reactants, etc. Experiments are performed on the laminar premixed flame using counterflow burner. To characterize the combustion behaviour, the flammability limits are determined and flame thickness and position are measured from PLIF-OH diagnostic. Further, CHEM Kin simulations are performed to check the validity of the GRI3.0 chemical kinetic mechanism for premixed CH$_4$/air synthetic combustion and identify the leading phenomena.

1. Introduction

Concerns over greenhouse gas emissions have sparked many ideas on the removal of CO$_2$ from stationary power generation systems and its long-term sequestration by Carbon dioxide Capture and Storage (CCS). Although tested CCS technologies can remove CO$_2$ from the exhaust of existing power plants, but the CO$_2$ capturing and compressing increases the energy by 25%-40% for the N$_2$/CO$_2$ separation. Thus, more promising options involve novel power plant designs that make CO$_2$ removal simpler and more energy-efficient [1]. One such option is the oxy-fuel combustion power plant [2]. In oxy-fuel combustion, fuel is burned in pure O$_2$ with recycled combustion products’ yielding a CO$_2$-rich exhaust stream, after drying that is readily prepared for sequestration [2-3]. The energy for N$_2$/CO$_2$ separation is then shifted to produce O$_2$ by an air separation unit. However, the potential value in terms of improved energy efficiency, reductions in soot and NOx can offset the cost penalty of burning a fuel in an oxidizer other than air [3-4]. Furthermore, the cost of oxygen is coming down due to partial air separation and recently the DOE has proposed O$_2$-enriched combustion with carbon sequestration by CCS [5].
This work will contribute to the evaluation of an alternative CCS process between air combustion and oxy-combustion (discussed with details in [6] applied to a diffusion flame). The global CCS cost, which should be minimized, corresponds to the sum of energies for a partial air separation to get from 40 to 80% of O\(_2\) and a CO\(_2\) separation by membranes (CO\(_2\) concentration from 30 to 80%). This hybrid system is based on a carbon capture realized by membrane, which, to be efficient, requires a volume CO\(_2\) concentration over 30% in the flue gases imposing air enriched with O\(_2\) in the reactants.

But, it must be clarified the N\(_2\) replacement by CO\(_2\) which modifies the flame behaviour through chemical [7-8], thermal [6, 9-11] or physical [6, 9] effects. It is observed that exhaust gas, as well as temperature of reactants, play a significant role not only in the stabilization mechanisms, but also in the transitions between the various combustion regimes [6, 9-11]. For example, bibliography shows that it is necessary to increase the O\(_2\) fraction in the oxidizer flow to conserve the combustion behaviour with the same thermodynamic efficiency than with air. In these conditions, the O\(_2\) and fuel concentrations diluted in CO\(_2\) can have an effect on flame structure and consequently on soot formation [12]. The present work will be focused on the characterisation of O\(_2\)-enriched air combustion in order to identify the phenomena, which are responsible of the combustion behaviour modification in a counterflow burner configuration.

Many studies on oxy-fuel combustion are dedicated to solid fuels, especially coal [13], it is worthwhile investigating the effects of CO\(_2\) dilution on gaseous fuels i.e. like natural gas also used in boilers.

In the literature, very few experimental studies have been reported on the oxy-fuel counterflow premixed flame [10-11]. Some researchers reported detailed numerical studies with the effect of CO\(_2\) on combustion behaviour [6-7]. Complementary to experimentation some researchers [6, 14] have made an attempt to combine the experimental and computational approaches to study the CO\(_2\) dilution effects. Their hybrid approaches are genuine to tackle the problem in order to to optimize the chemical process and chemical kinetic scheme for combustion diluted in CO\(_2\)(flame stabilization and pollutant formation). As reported in [6-11, 14], the main effects due to the presence of CO\(_2\) in the diluents are: a pure dilution, which reduces the O\(_2\) concentration in local reaction zones and affects the combustion reaction rate, the temperature rises and extinction limit; thermal and transport contributions, which are linked to the specific heat capacity and the diffusivity coefficient; aerodynamic effects, through the modification of the local gas density and radiation transfers enhanced by CO\(_2\). Further, [15-16] showed, experimentally and numerically, the effect of diluents on the laminar and turbulent combustion conditions. In addition [6, 9 and 11] experimentally and numerically studied the flame extinction with the effects of diluents and illustrated that it is essentially related to their heat capacities. Moreover [6, 9 and 14] experimentally and numerically found that CO\(_2\) addition reduced the flame temperature by diminishing the reactant concentration in the reaction zone. On the other hand, [9, 14 and 16] experimentally and [6-7, 9 and 16], always experimentally and numerically, revealed the importance of chemical contribution on flame stabilization as well as [7] on soot formation, by introducing a new species FCO\(_2\) which was chemically inert but held the same physical properties as those of CO\(_2\).

In this work, our interest points towards the increase of knowledge on the behaviour of a premixed flame between CH\(_4\) and O\(_2\)-enriched air using a counterflow burner, the premixed reactants are diluted in a mixing of N\(_2\)/CO\(_2\) simulating an external recirculation of flue gases mixed in O\(_2\)-enriched air. Does CO\(_2\) in the reactants influence the combustion stability and does standard chemical kinetics scheme (GRI 3.0) for the modelling stay valid? In this work, it will be to determine the flame behaviour modifications and identify the involved phenomena where reactants are diluted in CO\(_2\) and to select the working conditions allowing an efficient combustion. The fed information will be expressed in terms of flammability limit and the flame characteristics i.e. flame thickness δ\(_0\) and position P between the counterflow burners.

2. Experimental setup

2.1. Counterflow burner system

A counterflow burner is used and illustrated in Figure 1. It consists of two identical vertically opposed nozzles: the premixed mixture (CH\(_4\)/O\(_2\)/N\(_2\)/CO\(_2\)) is injected in the bottom burner and the diluents (N\(_2\)/CO\(_2\)) in the top burner. The separation distance between the nozzles H is fixed to 0.024m and the
internal injection diameter D is 0.035m. An annular co-flow of nitrogen (N\textsubscript{2}) provides a flow curtain to isolate the premixed mixture from reaction with surrounding air. The flow characteristics are kept constant to those of the cold stream velocity of \(u_c=0.5\text{m/s}\) corresponding to a constant volumetric flow rate of \(Q_c=4.82\times10^{-4}\text{m}^3\text{/s}\) and a thermal output of 16.1kW. The two laminar opposed flows are electrically preheated from ambient temperature to 750K corresponding to the exit temperature from compressor, and pass through an aluminium or stainless steel honeycomb ring, positioned 25mm upstream the nozzle exits, to ensure the uniformity of the flows. As the two reactant flows are heated up, the average exit velocities of the hot reactants \(u_h\) at the exit follow the law: \(u_h=[(u_c/T_c)\times T_{pr}]\text{m/s}\), \(u_c\) being the inlet cold flow velocity, \(T_c\) the cold temperature (298 K) and \(T_{pr}\) the preheat temperature (298-750K). The preheat temperature is close to the exit temperature of a standard compressor. Unfortunately, as during all combustion experiments, parameters are not all independent and \(T_{pr}\) affects the flow strain rate \(\sigma\). In this study the equivalence ratio \(\phi\) was varied from 0.9 to 1.1 i.e. from lean to rich condition. The composition of the diluents, a mixture of N\textsubscript{2} and CO\textsubscript{2}, is represented by the dimensionless \(X^*=X_{CO2}/(X_{CO2}+X_{N2})\); it varies in the range 0 to 1, and is equal on the two burners sides. The O\textsubscript{2} volume fraction in the oxidizer stream, \(X_{O2}\), varies in the range from 0.21 to 0.23. Thermocouples and flow meters are used to fix the operating conditions of the experiments.

\[ \text{Figure 1. Experimental setup.} \]

\[ \text{Figure 2. Counterflow premixed flame with the } \sigma = 20.83\text{s}^{-1}; X^*=0.33; T_{pr} = 573 \text{ K}; H=0.024\text{m}. \]

A photo of the spontaneous flame emission is represented on Figure 2. It was supposed that the variations of the flame thickness \(\delta_0\) and position P (distance from the bottom burner) can be representative of the behaviour of the flame and are linked to the transport, thermal, chemical, aerodynamical and physical phenomena involved in the O\textsubscript{2}-enriched air combustion with CO\textsubscript{2} dilution.

2.2. Diagnostic methods
To characterize the behaviour of the reaction, Planar Laser Induced Fluorescence on the OH radical (PLIF-OH) is used to determine the reaction zone characteristics through the measurement of the flame thickness \(\delta_0\) and position P along the axial distribution of the intensity of the OH radical induced emission. To excite the fluorescence of OH radical, a second harmonic of a Q-switched infrared pulsed Nd: YAG laser at 532nm is used to pump a tuneable dye laser (ND6000, Continuum). The frequency doubled beam is tuned at 282.910nm to excite the Q1(6) transition of the A–X(1–0) band of OH radical in this experiment. The beam is spread into a vertical sheet with the help of a series of sheet-forming optics, and the sheet of light traverse the centreline of counterflow burners. An ICCD camera (PI-MAX2, Princeton Instruments) equipped with a UV lens (Cerro 2017 UV-VIS-NIR, 45mm, f/1.8) is used to detect the two-dimensional fluorescence from the excited molecule OH.
combination of Scott glass UG11 and WG305 filters is placed in front of the camera to avoid detection of flame luminosity and spurious light scattering. Images are collected in the direction orthogonal to the laser sheet, providing black-and-white measurement on a 581x591 pixels matrix. The spatial resolution was 133μm per pixel. To provide a sound basis for analysis, a minimum of 200 single-shot OH distributions is taken for each experimental flame condition. The processing is performed with the SLIP platform developed at the laboratory. It consists to calibrate the position of the burner mouths, to determine the OH emission zone in order to reduce the processing time, to spatially filter the image, to identify the maximum of the OH emission, to threshold the image before to extract the OH zone thickness assimilated to the reaction zone. The threshold is accurately determined from the method of least squares to fit the experimental OH emission profile with a Gaussian distribution. The reaction zone outline is then extracted as the wideness at the inflexion point level of the normal distribution.

The quenching effect in the PLIF-OH signal due to CO₂ has not been taking into account in the image processing, the signal attenuation was supposed to be negligible because of small size flame.

3. Numerical validation
The Sandia National Laboratories Code OPPDIF which is a part of the CHEMKIN package was combined with GRI-MECH 3.0 reaction mechanism [17] to solve for velocity, temperature and species concentrations along the centreline of premixed counterflow flames. The flame is modelled by the OPPDIF, but with premixed reactants. The radiation effects and the heat losses are not considered (combustion is assumed adiabatic). Details of the OPPDIF similarity solutions (counterflow flames) are widely described in the literature [18-19]. The calculated flame thickness is determined as the full width of the maximum of the temperature or OH peak [18].

4. Results and discussion
4.1. Flammability study
Flammability limits are determined from extinction tests. The premixed flame between the opposed reactants (CH₄/O₂/N₂/CO₂ injected in the bottom burner) and diluents (N₂/CO₂ injected in the top one) flows is first established for a given values of φ, Tᵦ, X⁺ and σ (flow strain rate σ = ∂uᵦ/∂x), then, the extinction limit is searched by decreasing the X₀₂ volume fraction by keeping constant Y Chung. Figures 3 and 4 reports the minimum X₀₂ required for sustaining the flame for various preheat temperatures Tᵦ, strain rates σ and X⁺ dilution rates. The strain rate for the cold condition is kept constant. The results (Figures 3 and 4) show that a higher O₂ concentration X₀₂ is required to hold the flame for an increase of X⁺ or a decrease of the preheat temperature Tᵦ. These raw observations must be attentively discussed because the variation of a certain parameter induces modifications in to the other ones. For example, all the parameters Tᵦ, X₀₂, φ, X⁺ modify the fluid density which affects the flow strain rate σ. The σ effect shows, in the studied parameters range, a weak influence on the extinction limit value (Figure 4). So, we will consider that the test parameters Tᵦ, X₀₂, φ, X⁺ act nearly independently on the combustion behaviour.

In first approximation of the experimental trends, on Figure 3, it can be supposed that, for a given Tᵦ preheat temperature, the same extinction limit can be found as if X₀₂ is correlated to X⁺, for example if Tᵦ= 723K, for air [X⁺=0] the flame is sustained for X₀₂=0.17, for pure CO₂ diluent where [X⁺=1], X₀₂ must be increased to 0.19 corresponding to a linearized equation X₀₂= 0.02X⁺ + 0.17 which can be similarly extrapolated to all Tᵦ values. The same development can be made to evaluate the temperature effect for a given (X₀₂, X CO₂) pair. These results show that a rise of the preheating or X₀₂ is beneficial for flame stability over the whole studied spectrum of the parameters. It is clear that the beneficial effect of the high reactant temperature more than compensates for the detrimental effect of the reduced O₂ content. To conclude, an X⁺ increase reduces the flammability limit, which can be counter balanced either by higher oxygen concentrations in the reactants (or equivalent ratios) or a higher preheating.
4.2. Flame colour
It is observed from flame observations that the soot production, linked to the flame colour, is yellowish when $T_{pr}$, $X_{O2}$ are increasing or $X^*$ decreasing. Moreover, when CO$_2$ is added both in the fuel and oxidizer streams, the flame luminosity decreased until near extinction and the radical emission turns to blue (CH* emission) and soot formation decreases. These observations do not confirm, for the studied conditions, the enhancement of the radiation transfer by CO$_2$, which is counter-balanced by the local temperature effect.

4.3. Flame thickness ($\delta_0$)
The thickness of OH radical emission zone got from PLIF-OH image processing is assumed to be correlated to the reaction zone thickness $\delta_0$, representative of the transport, thermal and chemical behaviour of the combustion. Figures 5 to 7 present respectively the reaction zone thickness $\delta_0$ variation vs. $T_{pr}$, $X_{O2}$ and $\phi$ for various $X^*$ values. An increasing trend observed for $\delta_0$ with $T_{pr}$, $X_{O2}$ or $\phi$ while an inverse trend with $X^*$.

Figure 3. Variation of the flammability limit with the preheat temperature $T_{pr}$ for 4 diluent compositions $X^*$, $\sigma = 20.83$ s$^{-1}$; H=0.024 m.

Figure 4. Variation of the flammability limit with the strain rate $\sigma$ for 4 diluent compositions $X^*$; $T_{pr} = 573$ K; H=0.024 m.

Figure 5. Reaction zone thickness $\delta_0$ (mm) and flame position vs. $X_{O2}$ for various $X^*$, $T_{pr} = 573$ K; H=0.032 m; $\phi=1$; $\sigma = 20.83$ s$^{-1}$.

Figure 6. Reaction zone thickness $\delta_0$ (mm) and flame position vs. $T_{pr}$ for various $X^*$, $X_{O2} = 0.23$; H=0.032 m; $\phi=1$; $\sigma = 20.83$ s$^{-1}$.
The effect of an increase of $T_{pr}$, $X_{O2}$ and $\phi$ on $\delta_0$, for constant $X^*$ values, can be interpreted as i) a higher heat released in the reaction zone which increases the temperature maximum in the flame and ii) a larger mixing molecular transport coefficient $D_{mix}$, which induces preferential diffusion of the reactants with an enlargement of the quasi-Gaussian temperature, species and radical distributions [9].

The second effect is related to $X^*$ ($\delta_0 \downarrow$ when $X^* \uparrow$), which thermally modifies the fluid density and specific heat capacity $C_{p_{mix}}$ in the flame zone, in turn inducing a modification of the OH emission signal. For example, CO$_2$ and N$_2$ have a specific heat of 1.235kJ/kg·K and 1.170kJ/kg·K, a density of 0.5438kg/m$^3$ and 0.3388kg/m$^3$ at 1000K respectively. $C_{p_{mix}}$ increases with the local temperature $T$ and $C_{p_{CO2}} > C_{p_{N2}}$ if $T>400K$, an increase in $X^*$ narrows $\delta_0$ and reduces the flame temperature (the maximum temperature peak falls down from 2000K to 1500K when $X^*$ varies from 0 to 1 [6]). The $C_{p_{mix}}$ effect is particularly important because the CO$_2$ concentration and the temperature must be considered in the combustion products, not in the reactants (the mass of CO$_2$ in the fumes is approximately the sum of the mass of CO$_2$ in the reactants and the mass of CO$_2$ from the CH$_4$/O$_2$ combustion). Transport phenomena must be also need to take into account, but it seems marginal to control the global behaviour. Moreover, according to the analysis of [7, 20] for a mild combustion, the CO$_2$ content in diluents can also contribute in the chemical reaction and cannot be considered as inert. It directly participates in chemical reactions primarily through CO + OH $\Leftrightarrow$ CO$_2$ + H. Then, a competition of CO$_2$ for H radical through the reverse previous reaction with the single most important chain branching reaction H + O$_2$ $\Leftrightarrow$ O + OH significantly reduces the concentrations of important radicals, i.e. O, H, and OH lead to significant reduction of the fuel burning rate. The present experimental results confirm this chemical interpretation; this effect is counter-balanced by an increase either of $T_{pr}$, $X_{O2}$ or $\phi$ and reflects that, in the diluted combustion systems, where both dilution and preheating exist, the reaction rate is dominated by these three parameters together. This is agreeing well with the results of literature [6, 9 and 21] fore-mentioned, in which reactants are highly preheated and diffusion of reactants increased.

![Figure 7. Reaction zone thickness $\delta_0$ (mm) and flame position vs. $\phi$ for various $X^*$, $\sigma = 20.83s^{-1}$; $T_{pr}$ =573 K; $X_{O2}$ =0.23; H=0.024m.](image)

Figures 5 to 7 also reported the flame thickness $\delta_0$ obtained from experiments (PLIF-OH) and CHEMKIN II simulation (defined as the full width at half maximum (FWHM) of the temperature or OH distribution [18]). Very good agreement between the experimental data and the numerical predictions are obtained with the GRI 3.0 kinetic scheme. Consequently, it can be concluded that the CH$_4$ combustion behaviour with pure air, O$_2$-enriched air, or with synthetic air by a replacement of N$_2$ by CO$_2$, are well reproduced and simulated by the used kinetic scheme for a counterflow configuration. Similar numerical results than Figures 5 to 7 were obtained for other working parameters.

To conclude on the behaviour of CH$_4$/O$_2$-enriched air combustion with flue gas recirculation, the chemical reactivity is reduced by CO$_2$ dilution in the reactants due to a chemical effect (competition
between reactions which decreases the maximum flame temperature) and an increase of specific heat capacity $C_{p_{mix}}$ of the flow. This trend can be counted balanced by an increase of the preheat temperature $T_{pr}$ or/and the oxygen concentration $X_{O2}$ or/and fuel concentration $X_{CH4}$ (i.e. equivalence ratio $\phi$).

4.4. Flame position ($P$)
The dimensionless flame position $P/H$ represents the flame distance from the bottom burner (premix reactant side) normalised by the distance $H$ between the burners. It reports the flame behaviour in regards of the stagnation plan of the counterflows for the same working conditions as those for the flame thickness. $P$ is reported on Figures 5 to 7, which show respectively the influence of $X_{O2}$ and $X^*$, $T_{pr}$ and $X^*$, and $\phi$ and $X^*$. The results show a shifting of $P$ towards the diluent side (away from the premixed reactant (bottom) burner) of counterflow with the increase of $X^*$ and a reverse trend observed with $T_{pr}$, $X_{O2}$ and $\phi$. These experimental results are well predicted by the numerical simulations.

This conclusion allows again a practical extrapolation to premix CH$_4$/O$_2$-enriched air combustion with flue gas recirculation in industrial burners. To reproduce the behaviour of CH$_4$/air combustion in synthetic air (CO$_2$/N$_2$ mixtures), the O$_2$ concentration should be slightly increased in the reactants. Moreover, this utilisation would permit a reduction of the burner and furnace size.

4.5. Design variables
The present experimental and numerical effort seeks also to provide burner design variables in terms of information on $T_{pr}$, $X_{O2}$ and $\phi$ ($X_{CH4}$) fed and CO$_2$ recirculation from flammability limit study and flame thicknesses and positions. Therefore, the combustion behaviour will be determined in terms of flame structure i.e. from an estimation of $\delta_0$ as a function of $X^*$, $T_{pr}$, $X_{O2}$ and $\phi$. The results show that the flame moves away from burner (i.e. from the premixed reactant side) when the chemical reactivity decreases ($X^*\uparrow$) and stays near the burner exit (i.e. to the premixed reactant side) when $T_{pr}$, $X_{O2}$ or $\phi \uparrow$, therefore, to conserve the same flame behaviour, $X_{O2}$ injected in the industrial burner should be increased.

5. Conclusions
This paper reports the effects of fuel and oxidizer dilution rates in N$_2$/CO$_2$ mixtures characterised with $X^*= [X_{CO2}/(X_{CO2}+X_{N2})]$ on the behaviour of O$_2$-enriched air/methane combustion under various preheat temperatures $T_{pr}$ and equivalence ratios ($X_{CH4}$, $X_{O2}$) operating in a counterflow burner. The PLIF-OH diagnostic method is used to determine the reaction zone thickness and position in the diluted combustion. The conclusions can be summarized as following in Table 1.

| Parameters                      | Trends | With variables |
|---------------------------------|--------|----------------|
| Extinction limits               | ↑      | $X_{O2}$ ↑ $T_{pr}$ ↓ $X^*$ ↓ |
| Flame thickness $\delta_0$      | ↑      | $T_{pr}$ ↑ $X^*$ ↓ |
| Flame position $P/H$ (away from reactant side) | ↑ | $X_{O2}$ ↓ $T_{pr}$ ↓ |

1. Although the reactants dilution makes flame less stable, the preheating of reactant broadens the flammability domain. Compare with pure N$_2$ ($X^*$=0), much CO$_2$ ($X^*$=1) in the diluents decrease the flammability limits (flame stability).
2. The replacement of N$_2$ by CO$_2$ into the reactants decreases the flame thickness (chemical reactivity). CO$_2$ does not act as a passive diluent in the fuel, but interacts kinetically. The kinetic effects of CO$_2$ dilution are manifested primarily in the main CO oxidation reaction, CO+OH ⇌ CO$_2$+H. Higher CO$_2$ levels lead to enhanced back reaction rates and, hence, reduced CO oxidation and enhanced consumption of H atoms. Since CO$_2$ dilution alters the H atom concentration, CO$_2$ can have profound
effects on flame characteristics i.e. flame thickness $\delta_0$ and position $P$, resulting in lower flammability limits. This trend can be counted balanced by an increase of the preheat temperature $T_{pr}$ or/and the oxygen concentration $X_{O2}$ or/and fuel concentration $X_{CH4}$ (i.e. equivalence ratio $\phi$).

3. This study contributes to the prediction of the optimised $X_{O2}$, for constant equivalence ratio, to fit an existing combustor to an advanced CH$_4$/O$_2$-enriched air system coupled to a CCS process using membranes as CO$_2$ capture process.

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References
[1] Bolland O and Saether S 1992 New concepts for natural gas fired power plants which simplify the recovery of carbon dioxide Energy Convers. Mgmt. 33 467
[2] Singh D J, Croiset E, Douglas P L and Douglas M A 2001 CO2 capture options for an existing coal fired power plant: O2/CO2 recycle combustion vs. amine scrubbing Presented at the First National Conference on Carbon Sequestration.
[3] Wall T F 2007 Combustion processes for carbon capture Proc. Combust. Inst. 31, 47
[4] Pillier L, de Persis S, Cabot G, Bounaireau R, Liu Y, Boukhalfa M, Most J M, Gökalp I and Favre E 2009 Coupling of oxygen-enriched combustion and CO2 capture by membrane processes Proc. Euro. Combust. Meet.
[5] NETL Report, Carbon Sequestration: Technology Roadmap and Program Plan – 2004, April 2004
[6] Most J M, Dahikar S, Piller L, de Persis S 2012 Influence of thermochemical conditions on the behaviour of CH4/O2-enriched air diffusion flame methane submitted to a Journal.
[7] Liu F, Guo H and Smallwood G 2003 The chemical effect of CO2 replacement of N2 in air on the burning velocity of CH4 and H2 premixed flames Combust. Flame. 133, 495
[8] Glarborg P and Bentzen L L B 2008 Chemical effects of a high CO2 concentration in oxy-fuel combustion of methane Energy & Fuels. 22 291
[9] Liu Y and Most J M 2009 Effects of diluents on the behaviour of the diluted combustion regime Proc. Euro. Combust. Meet.
[10] Mastorakos E, Taylor A M K P, Whitelaw J H 1995 Extinction of turbulent counterflow flames with reactants diluted by hot products Combust. Flame. 102 101
[11] Guo H, Smallwood J G, Gulder O L 2007 The effect of reformate gas enrichment on extinction limits and NOX formation in counterflow CH4/air premixed flames Proc. Combust. Instit. 31 1197
[12] Phillips M F, Harper P S, Kang K T, Hwang J Y, Chung S H, Lee W 1997 Soot zone structure and sooting limit in diffusion flames: comparison of counterflow and co-Flow flames Combust. Flame. 109 266
[13] Buhre B J P, Elliott L K, Sheng C D, Gupta R P and Wall T F 2005 Oxy-fuel combustion technology for coal-fired power generation Prog. Energy Combust. Sci. 31 283
[14] Mazas A N, Lacoste D A and Schuller T 2010 experimental and numerical investigation on the laminar flame speed of CH4/O2 mixtures dilution with CO2 and H2O Proc ASME Turbo Expo: Power for Land, Sea and Air
[15] Cohé C, Chauveau C, Gokalp I and Kurtulus D F 2009 CO2 addition and pressure effects on laminar and turbulent lean premixed CH4 air flames Proc. Combust. Instit. 32 1803
[16] Kobayashi H, Hagiwara H, Kaneko H and Ogami Y 2007 Effects of CO2 dilution on turbulent premixed flames at high pressure and high temperature Proc. Combust. Instit. 31 1451
[17] Williams F A 2003 San Diego Mechanism http://maewing.ucsd.edu/~combustion=cermech (2003=08=30)
[18] Sung C J, Liu J B and Law C K 1995 Structural response of counterflow diffusion flames to strain rate variations Combust. Flame. 102, 481
[19] Wehrmeyer J A, Cheng Z, Mosbacher D M, Pitz R W, Osborne R 2002 Opposed jet flames of lean or rich premixed propane-air reactants versus hot products Combust. Flame. 128 232
[20] Cavaliere A, de Joannon M 2004 MILD combustion Prog. Energy Combust. Sci. 30 329
[21] Gupta A K, Bolz S, Hasegawa T 1999 Effect of air preheat temperature and oxygen concentration on flame structure and emissions ASME J. Energy Resour. Technol. 121 20