

1 **Methane Combustion in MILD Oxyfuel Regime: Influences of Dilu-**
2 **tion Atmosphere in Co-flow Configuration**

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15 **Abstract:** MILD (moderate or intense low oxygen dilution) oxyfuel com-
16 bustion is a recently proposed clean combustion mode which can remedy
17 the shortcomings of the standard oxyfuel combustion technology. Nowadays
18 most available studies on MILD oxyfuel combustion focus on how to realize
19 this new combustion regime in O₂/CO₂ atmosphere. The open research on
20 methane MILD oxyfuel combustion in O₂/H₂O atmosphere is quite sparse. In
21 the present work, we carry out a comprehensive comparison study on methane
22 MILD oxyfuel combustion in different dilution atmosphere for the first time.

23 The JHC (jet in hot co-flow) burner is adopted as a research prototype. The
24 investigation is based on numerical simulation, so firstly the adopted numer-
25 ical approach is validated by some experimental data in open literature. The
26 numerical comparison is conducted by varying the mass fraction of oxygen
27 in the co-flow and the temperature of the hot co-flow, two key parameters
28 affecting fine reaction structures in JHC. Through the present investigation,
29 a number of findings are reported for the first time and some conclusions pre-
30 sented in previous publications are checked with analyses, especially on some
31 conflicted claims between the previous publications. In addition, several new
32 questions are raised, which may inspire further research activities in future.

33 Keywords: MILD combustion; Oxyfuel combustion; Methane; CO₂-dilution;
34 H₂O-dilution; oxy-steam

35

36 **1 Introduction**

37 MILD oxyfuel combustion [1,2] is a recently emerging term which can be re-
38 garded as an organic combination of two promising clean combustion technolo-
39 gies, MILD (moderate or intense low oxygen dilution) combustion and oxyfuel
40 combustion. Originally, some of the present authors proposed this new idea in
41 order to utilize biogas with a higher efficiency [3]. Soon after, it was extended
42 to various fuels [2,4–8]. Through these preliminary studies, it was found that

43 the MILD combustion regime could be established more easily in oxyfuel con-
44 dition [1,3,7] and meanwhile a number of shortcomings of the standard oxyfuel
45 combustion technology could be remedied straightforwardly by the introduc-
46 tion of MILD combustion regime [4]. Especially, the experimental efforts [4,7]
47 further demonstrated there was no obvious technical difficulty to establish
48 and to sustain MILD oxyfuel combustion in industrial furnaces. Consequent-
49 ly, MILD oxyfuel combustion may become one of the next generation clean
50 combustion technologies for carbon capture which is crucial to the sustainable
51 development of human society [9]. For this purpose, consecutive research on
52 MILD oxyfuel combustion is essential as our knowledge, as well as available
53 open literature, on it is quite limited [1,2].

54 Originally, the research on MILD oxyfuel combustion focused on how to realize
55 this new combustion regime in O_2/CO_2 atmosphere, namely oxygen in oxidan-
56 t flow being diluted by carbon dioxide rather than nitrogen in conventional
57 air-firing mode [2,4–8]. Recently, the present authors discussed the possibility
58 to establish and to sustain MILD oxyfuel combustion in O_2/H_2O atmosphere
59 where oxygen in oxidant flow is diluted by steam rather than carbon dioxide
60 [1]. As shown in Ref.[1], compared with its O_2/CO_2 counterpart, there are
61 at least three advantages to realize MILD oxyfuel combustion in O_2/H_2O at-
62 mosphere, such as simpler plant configuration, lower operation cost and high
63 power-generation efficiency. In the oxyfuel combustion research community,
64 the approach to realize oxyfuel combustion in O_2/H_2O atmosphere is named

65 as steam-moderated oxyfuel combustion or oxy-steam combustion [1,10]. As
66 the chemical and physical properties of steam are quite different from those of
67 CO_2 , inevitably, compared with its O_2/CO_2 counterpart, combustion behavior
68 may be significantly altered in the steam-moderated oxyfuel scenario. Conse-
69 quently, comprehensive comparison of combustion characteristics between in
70 O_2/CO_2 and in $\text{O}_2/\text{H}_2\text{O}$ atmosphere is necessary, as it has done between in
71 O_2/CO_2 (standard oxyfuel combustion) and in O_2/N_2 (air-firing mode) con-
72 dition [11]. Unfortunately, nowadays the essential studies on this critical topic
73 are extremely sparse. Some of the present authors compared the effects of
74 CO_2 - and H_2O -dilution on combustion temperature and reaction kinetics of
75 methane [12]. It was observed that the chemical and thermal effects of CO_2
76 and of H_2O on combustion behavior of methane are quite different and conse-
77 quently they will alter combustion temperature and reaction paths of methane
78 in the oxyfuel combustion regime by different ways. Zou et al. investigated
79 steam's effect on temperature distribution in methane oxy-steam combustion
80 [13]. With the aid of numerical simulation, they found out the key elementary
81 reaction step which determined the combustion temperature. In Refs.[14–16],
82 wet recycle of oxy-coal combustion was investigated, not only by numerical
83 simulation but also by experimental approaches. As steam is rich in wet re-
84 cycle of oxyfuel combustion, it was observed that high concentration H_2O in
85 recycled flue gas could influence combustion characteristics of pulverized coal
86 significantly [14–16]. However, these studies [12–16] all are limited in the so-
87 called "feed-back" combustion regime rather than MILD combustion regime

88 [1], so whether the conclusions made in these studies are tenable in the MILD
89 oxyfuel combustion regime is still an open question. To the best knowledge of
90 the present authors, on comparison study between CO₂ and H₂O on estab-
91 lishing and sustaining MILD oxyfuel regime, until now perhaps there are only
92 three open publications [1,16,17]. In Ref.[1], the present authors compared
93 the effects of CO₂ and of H₂O on establishing biogas MILD oxyfuel combus-
94 tion with the aid of a counter-flow configuration. It was found that biogas
95 MILD oxy-fuel combustion would be established more easily in O₂/H₂O at-
96 mosphere but meanwhile the reaction zone would become more complicated.
97 Sabia et al. discussed propane auto-ignition delay time in MILD combustion
98 regime, where reactants were diluted by CO₂ and H₂O, respectively [16]. In
99 Ref.[16], a cross-flow configuration was adopted. The authors claimed that in
100 the O₂/H₂O option the auto-ignition delay time would be a little shorter than
101 its O₂/CO₂ counterpart. Recently, some of the present authors conducted a
102 numerical investigation about the influence of H₂O addition on MILD oxy-coal
103 combustion [17]. The concentration of H₂O in oxidant flow varied from 0% (s-
104 tandard O₂/CO₂ condition) to 70% (oxy-steam atmosphere). It was observed
105 that NO emission could be suppressed and heat transfer would be enhanced
106 in O₂/H₂O atmosphere. As the IFRF (International Flame Research Founda-
107 tion) semi-industrial scale co-flow furnace adopted in Ref.[17] is not an ideal
108 MILD oxyfuel combustion research prototype and the extreme complication
109 of coal combustion, Ref.[17] failed to reveal the influence of different types of
110 dilution gases (H₂O or CO₂) on fine reaction structures. In our latest work

111 [1], it has been underlined that further research on this topic is necessary as
112 co-flow is more popularly found in practical combustion systems. Especially,
113 through our recent research [12,19], it was observed that the effect of dilution
114 gas on combustion performance in a co-flow configuration may differ from its
115 counter-flow counterpart because flow-reaction interaction, which is exclud-
116 ed in a one-dimension model (e.g. a counter-flow configuration), will play an
117 important role in a co-flow configuration. Consequently, in order to deepen
118 our knowledge in this emerging area so to advance its application in energy
119 industry, a systematic comparison between the performance of co-flow MILD
120 oxyfuel combustion in O_2/H_2O condition and that in O_2/CO_2 atmosphere, is
121 essential.

122 In order to bridge the aforementioned gap, in this work we numerically investi-
123 gate methane combustion in MILD oxyfuel regime, diluted by carbon dioxide
124 and steam, respectively. The JHC (jet in hot co-flow) burner developed in
125 Ref.[20] is adopted in the present study as the research prototype. Besides the
126 JHC burner proposed by Dally's group[20], there is another popularly used
127 JHC burner developed by the researchers in Delft[21,22]. Within a JHC burn-
128 er the influence of surrounding atmosphere on fine reaction structures can
129 be prevented, so it is an ideal benchmark for a comparison study on MILD
130 oxyfuel combustion in various dilution gases. The investigation is based on
131 numerical simulation, so firstly the adopted numerical approach is validated
132 by the experimental data [20]. In the present work, besides the influences of

133 various dilution atmospheres, the effects of temperature of co-flow on MILD
134 oxyfuel combustion are also investigated as until now no open effort report-
135 ed on this important issue. Through the present study, a number of findings
136 are reported for the first time and some conclusions presented in previous
137 publications are checked with analyses on the differences, especially on some
138 conflicted claims. In addition, several new questions are raised, which may
139 inspire future research activities.

140 **2 Computational Details**

141 *2.1 Configuration of the JHC burner and numerical conditions*

142 The configuration of the JHC burner is illustrated by Fig.1 and the detailed
143 description on it please refer to Ref.[20]. As the JHC burner is axisymmetric,
144 in order to reduce numerical simulation cost, the investigated domain can be
145 simplified as a two-dimensional case, as shown by Fig. 2. In the JHC burner,
146 fuel is injected through the central jet pipe whose inner diameter reads 4.25
147 mm. The fuel jet pipe is surrounded by an annulus oxidant co-flow pipe with
148 an inner diameter 77.75 mm. The whole JHC burner is operated inside a wind
149 tunnel filled by environmental gas. The velocity boundary condition is adopt-
150 ed for all jet flows and at the downstream exit the pressure outlet boundary
151 condition is assumed. In addition, a zero-shear stress wall boundary condition
152 is employed as the tunnel flow is much wider than the jet flows. Because the

153 JHC burner is originally designed for air MILD combustion research rather
154 than MILD oxyfuel combustion, in the present simulation, we replace air in
155 tunnel flow by steam or carbon dioxide, respectively. Furthermore, the tem-
156 perature of tunnel flow is set as 400 K to guarantee H₂O at its steam status
157 in tunnel flow. Finally, to reduce the complication induced by variation of fuel
158 mixture, in the present work it is assumed that the fuel jet flow consists of
159 pure methane, instead of the mixture of methane and hydrogen used in Re-
160 f.[20]. Table 1 lists the detailed information of investigated cases covered by
161 the present simulation. In Table 1, \mathbf{u} and T represent jet flow velocity and
162 temperature, respectively. The mass fraction of reactants is also listed in the
163 Table. As the present study aims at the effects of temperature and oxygen
164 concentration of co-flow on methane MILD oxyfuel combustion in different
165 dilution atmosphere, these two parameters vary over a wider range (the tem-
166 perature of the co-flow $1500 \leq T_{cof} \leq 2100$ and the oxygen mass fraction
167 in the co-flow $6\% \leq f_{o2} \leq 18\%$). Through a numerical test, it is found that
168 reactants can not be ignited successfully if oxygen mass fraction in the co-flow
169 is lower than 6% or the temperature of the co-flow is less than 1500 K. It is an
170 obvious difference from the air MILD combustion [20] and it may result from
171 two aspects: (1) there is no hydrogen addition in the present fuel flow while
172 hydrogen is more active than methane to establish and to sustain combustion;
173 (2) the specific heat capacity of H₂O, as well as that of CO₂, is larger than
174 air.

176 The present numerical simulation is conducted with the aid of the commercial
177 CFD software FLUENT (version 6.3) to solve the Reynolds Averaged Navier-
178 Stokes (RANS) equations for turbulence [23]. For heat radiation calculation,
179 the discrete ordinate (DO) model is used [23]. In addition, a modified weighted
180 sum of gray gas (WSGG) model is adopted to calculate the gas mixture total
181 emissivity [19]. Finally, the eddy dissipation concept (EDC) model [23] with
182 detailed chemical kinetic mechanisms (GRI-Mech 3.0, excluding the reactions
183 relevant to Nitrogen) [24] is employed for turbulence-reaction interaction and
184 reaction kinetics. In the present numerical research, 46560 cells are employed,
185 as illustrated by Fig.2, which is the same as that used in Ref.[19]. As demon-
186 strated by our recent work [19], such grid resolution is fine enough to obtain
187 grid-independent numerical prediction. The detailed information about grid
188 discretization and numerical convergence please refer to our previous work
189 [19].

190 Because there is no open experimental data on the JHC oxyfuel MILD com-
191 bustion cases investigated in the present work, we validate the reliability and
192 accuracy of the present numerical approach by the JHC air MILD combustion
193 experiments conducted in Ref.[20]. Fig. 3 illustrates the comparison of temper-
194 ature and species, along the radial direction, between the present numerical
195 prediction and the experimental measurements of JHC air MILD combustion

196 with 3%, 6%, and 9% oxygen mass fraction in the co-flow at the axial location
197 $x = 30$ mm [20]. For the measured CO hump in the co-flow stream, it was
198 explained to be the result of cooling and extinction of the secondary flame
199 near the burner outer wall [19,20]. The present prediction agrees well with the
200 experimental data for these three JHC MILD flames, which demonstrates the
201 present numerical approach is adequate for modeling JHC combustion.

202 **3 Results and Discussion**

203 As shown in previous research[2,6,19], for JHC combustion, the temperature of
204 the co-flow (T_{cof}) and the oxygen mass fraction in the co-flow (f_{o2}) are the key
205 parameters that affect fine reaction structures. Therefore, in the present work
206 we compare the MILD oxyfuel combustion characteristics in different dilution
207 atmosphere by adjusting these two parameters, respectively. Firstly we try
208 to reveal the MILD oxyfuel combustion characteristics in different dilution
209 atmosphere with a changeable f_{o2} and a fixed T_{cof} . In succession, T_{cof} varies
210 with a constant f_{o2} .

211 *3.1 Comparison against various oxygen concentration f_{o2} in co-flow*

212 In order to compare the effects of oxygen mass fraction in the co-flow (f_{o2}) on
213 combustion behavior in different dilution conditions, the cases at $T_{cof} = 1800$
214 K and $6\% \leq f_{o2} \leq 18\%$ are chosen as the representatives in this section.

215 Figure 4 illustrates the temperature distribution in O_2/H_2O or O_2/CO_2 atmo-
216 sphere, respectively. According to this figure, it can be observed that there are
217 two common features between H_2O - and CO_2 -dilution condition: (1) the max-
218 imum temperature of the reactants will increase when more oxygen is added
219 into the co-flow; (2) the zone with high temperature will expand towards the
220 exit as f_{o_2} increases. These phenomena are expected as combustion will be
221 enhanced with more oxygen. Meanwhile, the differences between them are al-
222 so obvious: (1) their maximum temperatures are not identical; and (2) their
223 temperature profiles are quite different. The details are discussed below.

224 Figure 5 plots the maximum temperature (T_{max}) and temperature rise (ΔT) of
225 the reactants in O_2/H_2O or O_2/CO_2 condition, respectively. In both dilution
226 atmosphere, T_{max} , as well as ΔT , is almost a linear increasing function of
227 f_{o_2} . As shown by Fig. 5(b), the temperature rise of the reactants is lower
228 than the ignition temperature of methane and the temperature of co-flow is
229 above the ignition temperature of methane, so the reactants react in the MILD
230 oxyfuel regime [1,25]. The peak temperature in O_2/CO_2 condition is always
231 higher than its steam counterpart. In addition, the increasing rate of T_{max}
232 in O_2/CO_2 condition is faster, so the gap between T_{max} in different dilution
233 atmosphere becomes wider with f_{o_2} growing up. It mainly results from that
234 the mass specific heat capacity of H_2O is larger than CO_2 . Furthermore, the
235 dilution gas may alter reaction paths by different ways, especially in relation
236 to dissociation reactions, which also will influence heat release in combustion,

237 as discussed in our previous studies [1,12,19]. As shown in our latest work[1],
238 the exothermic reaction chain of methane will be suppressed in oxy-steam
239 atmosphere, depending on local temperature.

240 It has been reported that compared with its air-firing counterpart, in MILD
241 oxyfuel combustion oxidization of fuels will take place within a larger area
242 [2,6]. As shown in Refs. [2,6], in O_2/CO_2 condition, the zone with intensive
243 heat release will expand toward the exit of JHC. In our simulation, this phe-
244 nomenon is observed, too. According to Fig. 4, it can be observed that the
245 zone with high temperature will expand towards the exit in both O_2/CO_2
246 and O_2/H_2O condition. Especially, we find that in O_2/CO_2 atmosphere the
247 zone will expand more quickly. However, in its steam dilution counterpart,
248 the zone with high temperature will expand obviously not only axially but
249 also radially. In other words, in oxy-steam condition, most heat is released in
250 the area closer to the fuel jet nozzle. It is another discovery reported by the
251 present work for the first time. In all available open literature on MILD oxyfu-
252 el combustion [1,2,4-8,16,17], few pay attention to compare reaction structure
253 alteration between in CO_2 - and in H_2O -dilution condition until the present
254 work. This new finding is very crucial for burner and chamber design as they
255 both depend closely on temperature distribution. It is clearer with the aid of
256 the distribution of hydroxyl radical (OH), as depicted by Fig. 6. Usually in the
257 MILD combustion research community OH is used as a kind of marker for
258 "flame" front region as MILD combustion is flameless [26]. As illustrated by

259 Fig. 6, in both dilution atmosphere the OH contours will expand with more
260 oxygen being added, but their shape are completely different. The shape of
261 OH contours in O_2/CO_2 condition looks like dragonflies' wings (namely long
262 and slender), which is similar with its air MILD combustion counterpart [27].
263 However, the shape of OH contours in O_2/H_2O atmosphere looks like but-
264 terflies' wings (namely relative wider but shorter), quite different from its air
265 MILD combustion [27] and CO_2 -dilution counterpart [6]. In the "feedback"
266 oxy-steam combustion [14–16], whether there exists a similar feature is still
267 an open question and we will try to answer it in our future work. As in the
268 oxy-steam condition the "flame" front is closer to the fuel jet nozzle, it is eas-
269 ier to establish the MILD oxyfuel regime in H_2O -dilution atmosphere. This
270 conclusion agrees with that drawn from its counterflow counterpart [1]. Figure
271 7 plots the maximum of OH concentration at various f_{O_2} . In both dilution at-
272 mosphere, the maximum of OH concentration will ascend nearly linearly with
273 f_{O_2} . It is in the expectation that the maximum of OH in O_2/H_2O condition
274 is larger than its O_2/CO_2 counterpart since the production of OH will be en-
275 hanced by H_2O addition, as explained in detail in our previous work [12]. In
276 Ref. [12], a counter-flow combustion prototype was adopted and the research
277 objective is "feed-back" oxyfuel combustion. The present work demonstrates
278 that the conclusion for "feed-back" oxyfuel combustion can be extended to
279 MILD oxyfuel combustion. With relative lower OH concentration, as well as
280 dragonfly-wing-like OH distribution, in O_2/CO_2 condition it is easier to sus-
281 tain the MILD oxyfuel combustion regime across the whole domain, which is

282 consistent with the conclusion claimed in Ref.[1].

283 Figure 8 illustrates CO distribution at various f_{o_2} . In Ref.[6], Mei et al. dis-
284 cussed the dimension of CH₄ JHC flame in O₂/CO₂ condition and they sug-
285 gested to use the contour of CO mass fraction $f_{co} = 0.01$ as an indicator to
286 visualize "flame" size. In this work we follow their suggestion. Through Fig. 6,
287 one can observe the "flame" size in oxy-steam condition will grow dramatical-
288 ly with more oxygen addition. However, in its O₂/CO₂ counterpart, the size
289 of "flame" will nearly not change with f_{o_2} . In Ref.[6], Mei et al. claimed that
290 "flame" size would decreased against f_{o_2} in O₂/CO₂ co-flow. Our observation
291 is different from their claim but similar with that reported in Ref.[5] in which
292 oxyfuel combustion in the IFRF semi-industrial scale furnace was investigat-
293 ed. The difference between the present work and Ref.[6] results from that Mei
294 et al. adopted a modified JHC configuration in their research. In Ref.[6], the
295 cold tunnel flow in original JHC burner scheme was removed and replaced
296 by hot co-flow. Consequently, the diameter of the hot co-flow jet in Ref.[6] is
297 so wide that there is sufficient oxygen for combustion anywhere in the whole
298 investigated domain. Accordingly, the consumption speed of CH₄ is mainly
299 determined by reaction rate. It can be looked as a kinetic-controlled combus-
300 tion. However, in the present work, the consumption speed of CH₄ depends
301 not only on reaction rate but also on local available oxygen concentration s-
302 ince in the present JHC configuration there is no oxygen in the tunnel flow. In
303 other words, the combustion in the present work is diffusion-kinetic-controlled

304 where chemical kinetics and aerodynamics (turbulent mixing) compete with
305 each other. No doubt, the combustion style investigated in the present work is
306 much closer to real combustion situation than the modified JHC scheme in Re-
307 f.[6]. It also can explain why the result obtain in the present study is consistent
308 with that from the semi-industrial scale furnace [5]. Nowadays there appear
309 a number of studies (please see [19] and references therein) in which a mod-
310 ified JHC burner like that used in Ref.[6] was adopted as a co-flow research
311 prototype. Through the present work, it is indicated that we should check
312 carefully before extending the conclusions claimed in these studies to realistic
313 co-flow combustion systems. To mimic a realistic MILD oxyfuel combustion
314 system, the present settings may be better. In addition, through Fig. 8 it can
315 be observed that the "flame" size in oxy-steam condition is generally smaller
316 and closer to the fuel jet nozzle, in comparison with its O_2/CO_2 counterpart.
317 This observation is consistent with the above conclusion made from tempera-
318 ture and OH distribution. In Ref. [6], it was observed that with more oxygen
319 addition in the O_2/CO_2 co-flow, the peak value of CO concentration within
320 the reaction zone would increase, similar with its air-firing MILD combustion
321 counterpart [20]. A comprehensive explanation on this phenomenon has been
322 presented in Ref.[12]. Through the present work, we find such conclusion is
323 also true in O_2/H_2O condition. In addition, as Ref.[12] focuses on "feed-back"
324 oxyfuel combustion, through the present work it can be proved the above phe-
325 nomenon is a common feature in oxyfuel combustion, regardless of dilution
326 gases. In Ref.[2], it was reported that CO concentration would decrease slight-

327 ly against f_{o_2} . At first glance it seems that this conclusion is opposed to that
328 in Refs. [6,20] and the present study. In fact, the conclusion in Ref.[2] was
329 tenable within the mix layer (namely the network reactor illustrated by Fig.
330 11 in Ref.[2]) rather than the whole domain of JHC [6,20]. As shown by Fig. 9,
331 the CO maximum in both dilution atmosphere will grow almost linearly with
332 f_{o_2} . Whatever f_{o_2} is, the CO maximum in O_2/CO_2 is always bigger than that
333 in its oxy-steam counterpart. Especially, their gap will be enlarged with f_{o_2}
334 increasing. In our previous work [12], it was observed a similar phenomenon in
335 counter-flow "feed-back" oxyfuel combustion. Consequently, it is also a com-
336 mon feature of oxyfuel combustion. The detailed explanation on how H_2O
337 addition will suppress CO generation please refer to Ref.[12]. Figures 10-11
338 plot the CO profiles at different axial positions $x = 90$ and $x = 120$ mm. The
339 profiles in both O_2/CO_2 and O_2/H_2O condition are similar with their air-firing
340 counterpart: the gradient of CO concentration along radial direction becomes
341 sharp with more oxygen addition [6,20]. Furthermore, it can be observed in
342 O_2/H_2O condition the gradient of CO concentration along radial direction is
343 more gentle than its O_2/CO_2 counterpart. This observation implies that in
344 oxy-steam co-flow condition the MILD combustion regime can be established
345 more easily, agreeing with the conclusion from the counter-flow configuration
346 [1]. Moreover, in our previous study [28], it was found that the co-flow methane
347 MILD combustion would be influenced significantly by the shape of furnace
348 chamber. According to Figs.8, 10 and 11, one may conclude MILD combustion
349 in oxy-steam condition is more flexible as the size of reaction zone in O_2/H_2O

350 condition is smaller (especially at low oxygen concentration) and within the
351 near-field of the fuel jet nozzle. Accordingly it will receive less effect than its
352 O_2/CO_2 counterpart.

353 Figure 12 depicts the distribution of O_2 with various f_{o_2} . One can observe that
354 in the vicinity of the jet, the profiles of O_2 in O_2/H_2O and O_2/CO_2 condition
355 are very similar, however their discrepancies become obvious in the far-field.
356 It is more clear with the aid of Fig.13, where the profiles of O_2 at $x = 30$ mm
357 (near-field) and $x = 90$ mm (far-field) are illustrated. In the near-field, the
358 profiles of O_2 in both dilution atmosphere nearly overlap with each other. It
359 agrees with the observation in Ref.[2] where only O_2/CO_2 condition was con-
360 sidered. In the far-field, O_2 concentration in O_2/H_2O condition is always lower
361 than its O_2/CO_2 counterpart, which is consistent with Fig.10 and indicates
362 oxidants are consumed faster in oxy-steam condition.

363 In Ref.[2], it was reported that in the near field ($x = 30$ mm), the differences
364 between the profiles of CO, O_2 and OH in O_2/N_2 atmosphere and those in
365 O_2/CO_2 condition are very small. However, through the present work, it is
366 observed that except O_2 , there are obvious differences in most scalar distri-
367 butions between in O_2/H_2O and in O_2/CO_2 condition, even in the near field.
368 Consequently, one should pay great attention on burner design for oxy-steam
369 combustion due to its complicated reaction structures. This conclusion is con-
370 sistent with that in Ref.[1].

371 The distribution of formyl (HCO) is shown by Fig.14. In the near-field of the
372 fuel jet nozzle, HCO concentration will increase with more oxygen addition in
373 both dilution atmosphere. In Ref.[6] it was reported in O₂/CO₂ condition the
374 peak value of HCO would grow up with f_{o_2} . The present results are consistent
375 with it and prove this conclusion also can hold water in its oxy-steam counter-
376 part. As HCO is an indicator for heat release during combustion [2,26], it can
377 be concluded that heat release will be enhanced by increasing f_{o_2} . Moreover,
378 HCO concentration in O₂/CO₂ condition is always higher than its O₂/H₂O
379 counterpart, as illustrated by Figs.14 and 16 (a), so in O₂/CO₂ condition
380 heat release intensity is higher than in oxy-steam atmosphere, which is con-
381 sistent with Fig. 4. It can answer why MILD oxyfuel combustion is easier
382 to be sustained in O₂/CO₂ condition. In our previous work [12], it was also
383 observed that HCO concentration in O₂/H₂O condition was lower than its
384 O₂/CO₂ counterpart, which resulted from that H₂O addition would modify
385 the chemical equilibrium of the reaction step R46. Through the present work,
386 it can be proved the analysis in Ref.[12] where counter-flow prototype adopted
387 still works well for JHC configuration. And it is a common feature between
388 "feed-back" oxyfuel combustion and MILD oxyfuel combustion.

389 Figure 15 plots the distribution of formaldehyde (CH₂O) which can serve as
390 an indicator for ignition [2,26]. Since CH₂O predominantly exists in low tem-
391 perature condition, therefore the concentration of CH₂O will decrease against
392 f_{o_2} increasing [6,26]. The present results agree with the conclusion in [6,26].

393 As shown by Fig.4, a higher f_{o_2} implies a higher combustion temperature. Be-
 394 cause H_2O addition will suppress CH_2O generation [12], in oxy-steam atmo-
 395 sphere CH_2O concentration in the near-field is a slightly lower than its O_2/CO_2
 396 counterpart. In O_2/CO_2 condition, the profiles of CH_2O alter sensitively to
 397 the variation of f_{o_2} , while in O_2/H_2O atmosphere the change is relatively
 398 smaller. It implies the establishment of MILD combustion in O_2/H_2O condi-
 399 tion receives less influence by oxygen fluctuation. Consequently, it is easier
 400 to establish MILD combustion regime in oxy-steam condition. It is consistent
 401 with the above analysis and the conclusion in Ref.[1]. Fig. 16 (b) depicts the
 402 maximums of CH_2O in both dilution atmosphere. The peak value of CH_2O in
 403 CO_2 -dilution atmosphere is always larger than its H_2O -dilution counterpart,
 404 which is consistent with its counter-flow "feed-back" counterpart [12]. Togeth-
 405 er with Fig.5, Fig. 16 (b) indicates that over the whole domain the uniformity
 406 of ignition in oxy-steam is better than its CO_2 -dilution counterpart.

407 3.2 Comparison against various temperature T_{cof} of co-flow

408 In order to compare the effects of the temperature of the hot co-flow (T_{cof}) on
 409 combustion behavior in O_2/H_2O and O_2/CO_2 condition, the cases at $f_{o_2} = 9\%$
 410 and $1500K \leq T_{cof} \leq 2100K$ are chosen as the representatives in this section.

411 Figure 17 illustrates the temperature distribution in O_2/H_2O and O_2/CO_2
 412 condition at various T_{cof} . In CO_2 -dilution condition, the maximum temper-

413 ature of the reactants will climb up with a higher T_{cof} and the zone with
414 high temperature will expand towards the exit as T_{cof} increases. The former
415 phenomenon has been reported in Ref.[6] and the latter one was also ob-
416 served in Ref.[2]. Refs.[2,6] just focused on O_2/CO_2 atmosphere. Through the
417 present study, we can confirm these phenomena exist in oxy-steam condition,
418 too. However, the influences of variation of T_{cof} on the temperature field in
419 O_2/H_2O and O_2/CO_2 condition are quite different. The isotherms in these two
420 types of dilution atmosphere differ with each other obviously, especially in the
421 vicinity of the fuel jet nozzle. In addition, the high temperature zone expands
422 more quickly in CO_2 -dilution atmosphere. The maximum temperature of the
423 reactants is illustrated by Fig.18. T_{max} is a monotonic increasing function of
424 T_{cof} in both dilution conditions and since $T_{cof} \geq 1600$ K T_{max} grows up almost
425 linearly. T_{max} in O_2/H_2O atmosphere is always smaller than its CO_2 -dilution
426 counterpart. As mentioned above, it results from that the mass specific heat
427 capacity of H_2O is larger than CO_2 . However, their gap will decrease against
428 T_{cof} increasing, which implies a higher T_{cof} will improve the uniformity of
429 temperature field of MILD oxyfuel combustion in either dilution atmosphere.
430 This observation agrees with that presented in Ref.[6]. Moreover, making a
431 comparison between Figs. 4-5 and Figs.17-18, one may conclude the influence
432 of variation of f_{o_2} on the temperature field is more significant than T_{cof} .

433 The distribution of OH with various T_{cof} is depicted by Fig. 19. It can be
434 observed that the "flame" front region in oxy-steam atmosphere is more sen-

435 sitive to T_{cof} , in comparison with its O_2/CO_2 counterpart. With a relative
436 low co-flow temperature, such as $T_{cof} = 1500$ K, the "flame" front region
437 in oxy-steam atmosphere is much smaller than its O_2/CO_2 counterpart. The
438 shape of OH contours in H_2O -dilution condition looks like a dragonfly's wing,
439 similar with its CO_2 -dilution counterpart although the former is shorter. S-
440 ince $T_{cof} \geq 1600$ K, the "flame" front region in oxy-steam condition expands
441 substantially along the radial direction and now the shape of OH contours
442 in H_2O -dilution condition looks like a butterfly's wing, not resembling that
443 in O_2/CO_2 atmosphere any longer. And now the "flame" front region in the
444 former is much larger than the latter. The sensitivity of OH generation to
445 T_{cof} in oxy-steam condition is also reflected by Fig.20. The maximum of OH
446 concentration in O_2/H_2O condition ascends much faster than in O_2/CO_2 at-
447 mosphere. In our previous study on MILD oxyfuel counterflow combustion [1],
448 it was found that the reaction structures in steam-dilution condition would be
449 more complex than in O_2/CO_2 atmosphere. The present work demonstrates
450 such conclusion can apply to the co-flow scenario. Fig.20 illustrates the varia-
451 tion of maximum of OH concentration at various T_{cof} . The maximum of OH
452 concentration in either dilution atmosphere will grow up with T_{cof} , which is
453 consistent with the result reported in Ref.[6]. As mentioned above, as the peak
454 temperature in O_2/H_2O condition is lower than its O_2/CO_2 counterpart, the
455 maximum of OH concentration in the former is always higher than the latter.
456 The increasing rate of the maximum of OH concentration in oxy-steam atmo-
457 sphere is much faster than its CO_2 -dilution counterpart, which also implies

458 the fine reaction structures in O_2/H_2O condition are more sensitive to T_{cof} ,
459 in comparison with its O_2/CO_2 counterpart. In our previous work [1], it was
460 claimed that the MILD oxyfuel combustion regime was established more eas-
461 ily in oxy-steam condition. Through Figs. 19-20, we find this conclusion may
462 depend on T_{cof} in the present co-flow configuration. Only since $T_{cof} > 1500$ K,
463 in O_2/H_2O condition, the peak value of OH concentration is significantly larg-
464 er than its O_2/CO_2 counterpart and the "flame" front region is substantially
465 wider than that in CO_2 -dilution atmosphere. Consequently, in the present in-
466 vestigated cases, only since $T_{cof} > 1500$ K, it is sure that the MILD oxy-fuel
467 combustion regime can be established more easily in O_2/H_2O atmosphere.

468 Figure 21 plots the distribution of CO with various T_{cof} . The iso-concentration
469 lines of CO are affected significantly by the variation of T_{cof} , especially in oxy-
470 steam condition. If taking the contour of CO mass fraction $f_{co} = 0.01$ as an
471 indicator to visualize the "flame" size, as mentioned above, one can observe
472 that the "flame" size in O_2/H_2O atmosphere changes substantially with T_{cof} .
473 When $T_{cof} = 1500$ K, the "flame" size in H_2O -dilution condtion is much s-
474 maller than its CO_2 -dilution counterpart. Then the "flame" size in the former
475 atmosphere grows quickly with T_{cof} increasing. While $T_{cof} = 2100$ K, the
476 "flame" size in both dilution conditions is almost the same. On the contrary,
477 although the CO iso-concentration lines in O_2/CO_2 condition will alter obvi-
478 ously with T_{cof} , the "flame" size in CO_2 -dilution atmosphere grows slightly.
479 The maximum of CO is depicted by Fig. 22. It is clear that the maximum

480 of CO will ascend with a higher T_{cof} , which is consistent with the conclusion
481 given in Ref.[6]. In Ref.[6] only O₂/CO₂ atmosphere was investigated. The
482 present work shows there is a similar trend in oxy-steam condition. However,
483 the increasing rate of the peak value of CO in O₂/H₂O condition is much
484 slower than its O₂/CO₂ counterpart. Taking Figs. 9 and 22 together, one can
485 conclude that a crucial issue to guarantee the performance of MILD oxyfuel
486 combustion in O₂/CO₂ atmosphere is to ensure fuel to burn out in a finite
487 room as the maximum of CO concentration at the outlet of the investigated
488 domain will jump up quickly, exceeding 10%, with the fluctuation of either
489 T_{cof} or f_{o2} . Such high value of CO concentration at the outlet implies an
490 extremely low combustion efficiency. On the contrary, in the oxy-steam con-
491 dition, the maximum of CO concentration at the outlet of the investigated
492 domain is always less than 4%, no matter whatever T_{cof} and f_{o2} are. From
493 this viewpoint, burner and chamber design, which can improve aerodynamics
494 in furnace and accordingly improve combustion efficiency, is more critical for
495 operation in CO₂-dilution condition.

496 Figure 23 shows the CO radial profiles at $x = 90$ mm. In Ref.[29], it was
497 reported that, in air MILD condition, the peak value of CO concentration
498 along the radial direction would grow up with T_{cof} increasing. The present
499 work proves such conclusion can be extended to MILD oxyfuel regime. In
500 addition, a higher T_{cof} will sharpen the gradient of CO concentration in both
501 dilution conditions. A similar observation was reported in Ref.[6] where only

502 O₂/CO₂ atmosphere was investigated. Through the present work, it is found
503 the radial gradient of CO concentration in O₂/H₂O is always much smaller
504 than its CO₂-dilution counterpart, no matter whatever T_{cof} is. The results
505 reveal that the potential performance of MILD oxyfuel combustion in O₂/H₂O
506 condition may be better than its O₂/CO₂ counterpart not only along the axial
507 direction but also along the radial direction of a chamber as in oxy-steam
508 condition most fuel can be burnt out in a relative small zone, in comparison
509 with its CO₂-dilution counterpart.

510 The O₂ distribution with various T_{cof} is plotted by Fig. 24. Generally, the
511 variation of T_{cof} will alter O₂ distribution significantly in both dilution atmo-
512 sphere, especially in the far-field. Against T_{cof} increasing, O₂ concentration
513 near the exit will decrease as a higher T_{cof} will intensify chemical reactions.
514 Near the fuel jet nozzle, the influence of variation of T_{cof} on O₂ distribution is
515 slight, as illustrated by Fig.25. In Ref.[29], it was also found that, in methane-
516 air MILD combustion, O₂ distribution in the near-field is insensitive to T_{cof} .
517 Through the present work, one may conclude that it is a common feature of
518 methane MILD JHC combustion, regardless of dilution atmosphere. Taking
519 Figs. 13 and 24 together, it can be observed that for any T_{cof} and f_{o2} , in
520 the far-field the O₂ radial concentration in O₂/H₂O condition is always low-
521 er than its O₂/CO₂ counterpart. Such observation demonstrates once again
522 that in oxy-steam condition the "flame" size is smaller than its CO₂-dilution
523 counterpart.

524 Figure 26 illustrates HCO profiles in O₂/H₂O and O₂/CO₂ atmosphere, re-
 525 spectively. HCO concentration will increase with a higher T_{cof} in both dilution
 526 atmosphere as heat release will be enhanced by a hotter co-flow. A similar phe-
 527 nomenon was also observed in methane-air MILD combustion [29]. No matter
 528 whatever T_{cof} is, HCO concentration in O₂/CO₂ condition is always higher
 529 than its O₂/H₂O counterpart, as shown by Fig.27 (a). At a relative low co-
 530 flow temperature ($T_{cof} = 1500$ K), one can observe HCO concentration in
 531 oxy-steam atmosphere is rarefied. According to Fig. 27, it can be observed
 532 that in oxy-steam condition the variation of OH concentration versus T_{cof} is
 533 "smooth", which also can be reflected by Fig. 26 (a). However, it is not true
 534 for its O₂/CO₂ counterpart. As shown by Fig. 26 (b), when $T_{cof} < 1700$, the
 535 peak value of HCO at $x = 30$ mm will increase quickly with T_{cof} , but since
 536 $T_{cof} \geq 1700$, the change becomes slow. It agrees with the results depicted
 537 by Figs.19 and 21. Through these figures, one can observe that in O₂/CO₂
 538 condition the shapes of OH, CO and HCO contours in the near-field change
 539 significantly when T_{cof} rises from below 1700 K to above 1700 K. It implies
 540 there appears a substantial change of the reaction structure in CO₂-dilution
 541 atmosphere. In other words, the MILD oxyfuel combustion performance in
 542 O₂/CO₂ condition is more sensitive to T_{cof} .

543 The radial distribution of CH₂O in the near-field is plotted by Fig.28. In Re-
 544 f.[29], it was found in the near-field of air MILD combustion the maximum
 545 of CH₂O concentration along the radial direction would decrease against T_{cof}

546 growing up . The present results show this conclusion can be extended to CO₂-
547 dilution MILD oxyfuel combustion. However, it is not true in MILD oxy-steam
548 condition. In O₂/H₂O atmosphere, there will appear two obvious peak values
549 of CH₂O concentration along the radial direction while in Ref.[29] only one was
550 observed. In O₂/CO₂ condition, the second peak of CH₂O distribution along
551 the radial direction is not as obvious as that in its H₂O-dilution counterpart.
552 This phenomenon implies in oxy-steam atmosphere the ignition of reactants
553 will take place over a wider range than in O₂/CO₂ or O₂/N₂ condition. Fur-
554 thermore, it also indicates the effect of T_{cof} on ignition is more complicated
555 in H₂O-dilution condition. In addition, in Ref.[29], it was observed that the
556 "sharp angle" of the CH₂O profile at a low T_{cof} (e.g. $T_{cof} = 1500$ K) will be
557 flattened by a high T_{cof} (e.g. $T_{cof} = 1800$ K). Although it was observed firstly
558 in methane-air MILD combustion, the present work reveals that this conclu-
559 sion is also tenable in the MILD oxyfuel combustion regime, either diluted by
560 CO₂ or by H₂O. Such phenomenon indicates chemical reaction will become to
561 vary mildly as T_{cof} increasing, which is consistent with the available research
562 on high temperature air combustion [30].

563 4 Conclusion

564 In order to deepen our insight into MILD oxyfuel combustion, a recently e-
565 merging idea for next generation clean combustion technology, in the present

566 work we carry out a comprehensive comparison study on methane MILD oxy-
567 fuel combustion in different dilution atmosphere (O_2/H_2O and O_2/CO_2). The
568 JHC burner is adopted as a research prototype. The comparison is conducted
569 by varying the mass fraction of oxygen in the co-flow (f_{o_2}) and the temperature
570 of the hot co-flow (T_{cof}), two key parameters affecting fine reaction structures
571 in JHC. The literature survey demonstrates the present work is a pioneering
572 effort in this field.

573 Through the present study, a number of findings are reported for the first time
574 and it is found the combustion characteristics in various dilution atmosphere
575 are obviously different:

576 (1) In oxy-steam condition, the CO contours are affected more significantly
577 by the variation of T_{cof} and f_{o_2} . But generally speaking, the "flame" size in
578 CO_2 -dilution atmosphere is much larger than its O_2/H_2O counterpart. The
579 maximum concentration of CO in O_2/CO_2 atmosphere is about ten times
580 large than its steam-dilution counterpart.

581 (2) In oxy-steam atmosphere the ignition of reactants will take place over a
582 wider range than its O_2/CO_2 or O_2/N_2 counterpart. Especially, the effect of
583 T_{cof} on ignition is more complicated in H_2O -dilution condition.

584 (3) In general, it is easier to establish the MILD oxyfuel regime in H_2O -dilution
585 atmosphere and in O_2/CO_2 condition it is easier to sustain the MILD oxyfuel
586 combustion regime across the whole domain. This conclusion agrees with that

587 drawn from its counter-flow counterpart investigated in our previous work [1].

588 (4) In Ref.[2], it was reported that in the near field of the JHC, the differences
589 between the profiles of CO, O₂ and OH in O₂/N₂ and in O₂/CO₂ atmosphere
590 are very small. However, through the present work, it is observed that ex-
591 cept O₂, there are obvious differences in most scalar distributions between in
592 O₂/H₂O and in O₂/CO₂ condition, even in the near field. Consequently, one
593 should pay great attention on burner design for MILD oxy-steam combustion
594 due to its complicated reaction structures.

595 Finally, several new questions are raised by the present study. For example,
596 whether the shape of OH contours in "feed-back" oxyfuel combustion diluted
597 by H₂O will change from the dragon-wing-style to butterfly-wing-style? It is an
598 important question as "feed-back" oxyfuel combustion diluted by H₂O already
599 appeared in industrial-scale furnaces [14–16] but until now nobody is aware
600 of this issue. We will try to answer it in our future work since it will influence
601 combustion performance, as shown by the present study.

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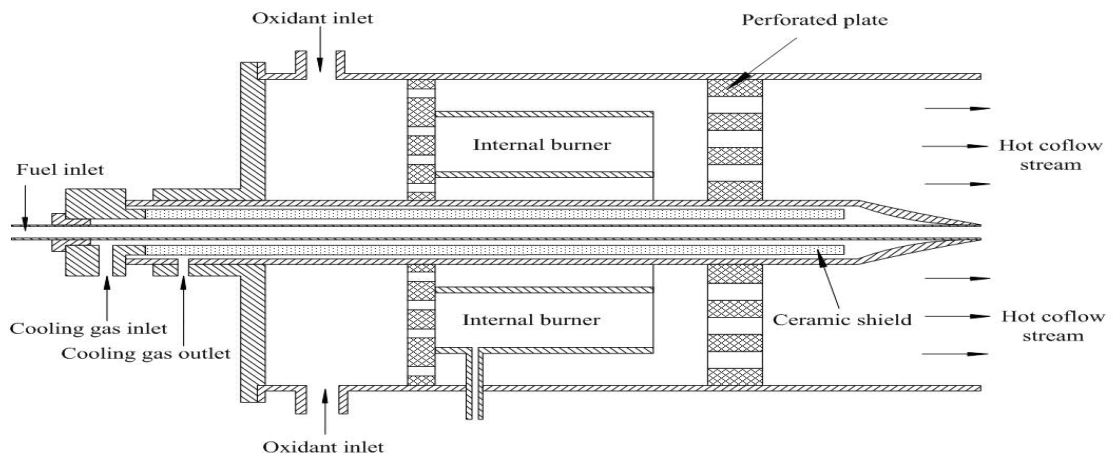


Fig. 1. Configuration of the JHC burner proposed in Ref. [20].

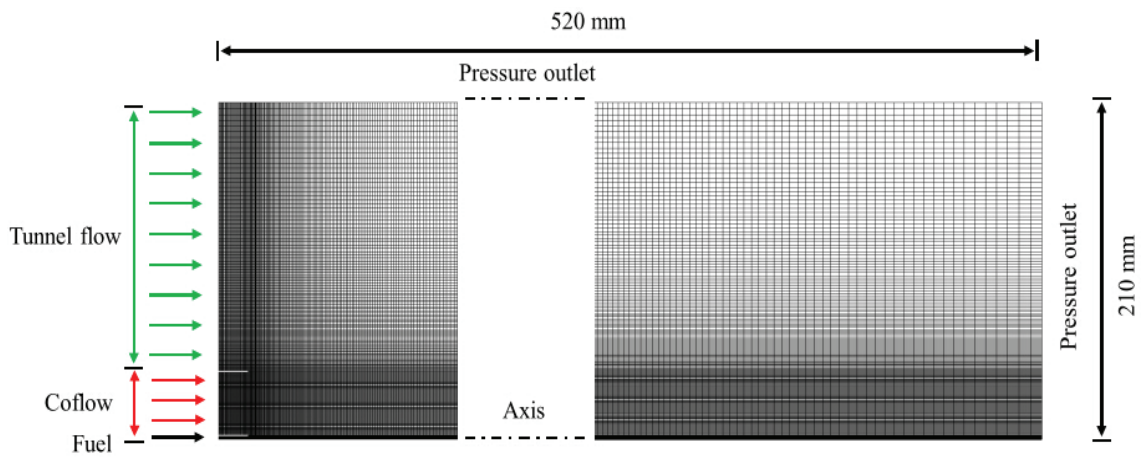


Fig. 2. Schematic configuration and coordinate system of the computational domain.

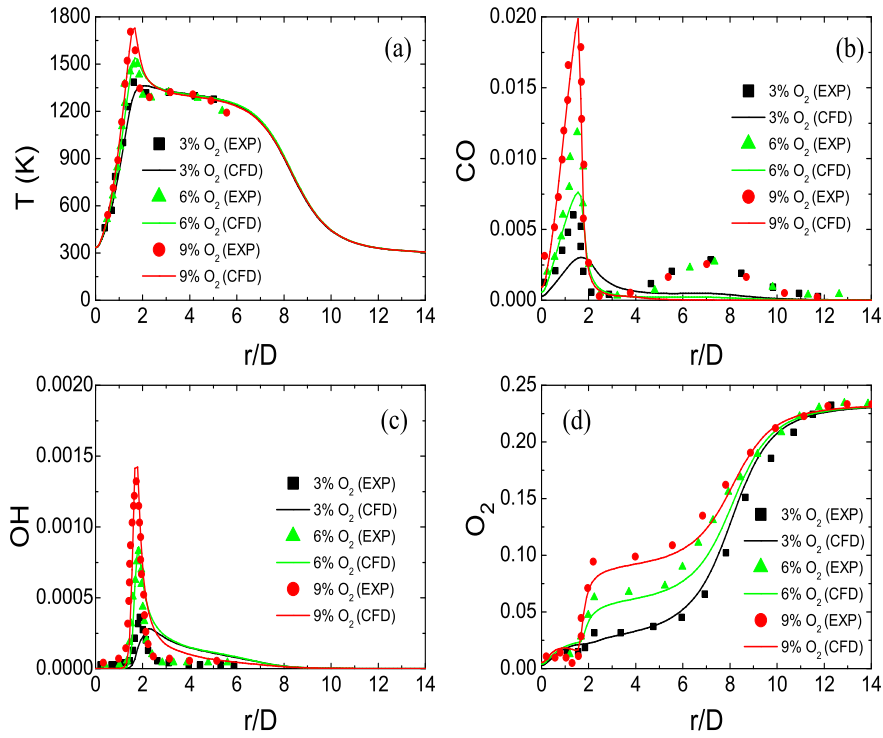


Fig. 3. comparison of (a) temperature, (b) CO mass fraction, (c) OH mass fraction, (d) O₂ mass fraction profiles between the present numerical prediction (CFD) and the experimental measurements (EXP) for JHC air MILD combustion with 3%, 6%, and 9% oxygen mass fraction in the co-flow at the axial location $x = 30$ mm [20].

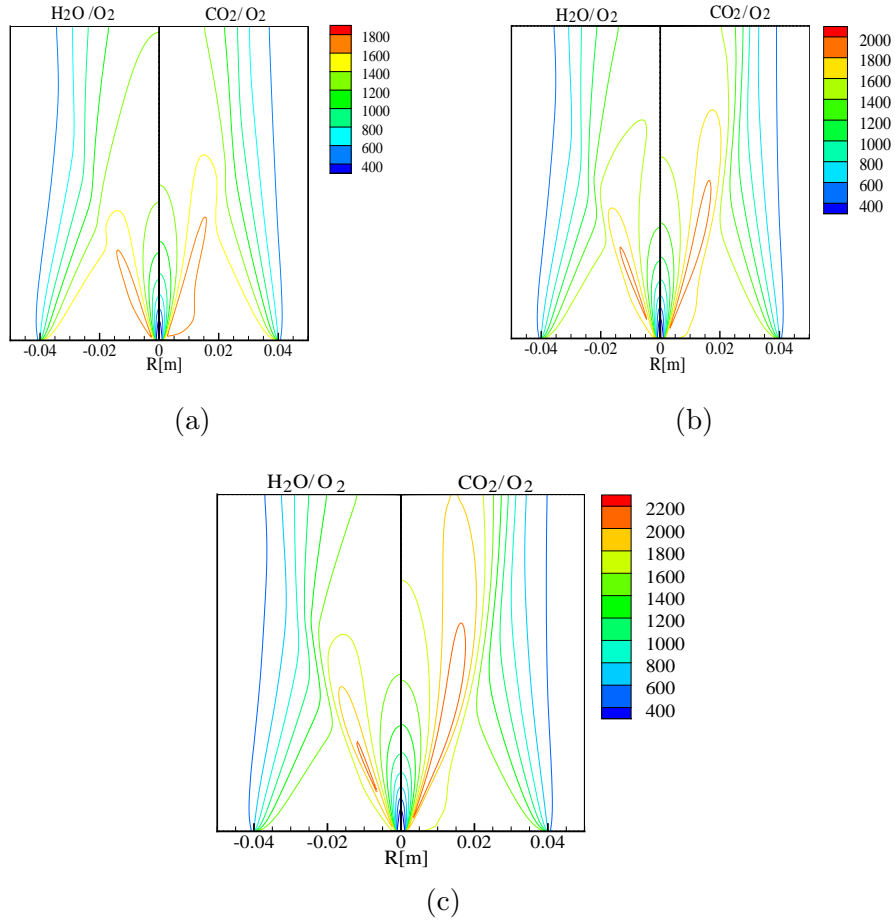
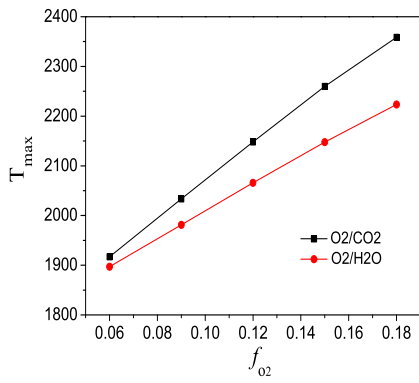
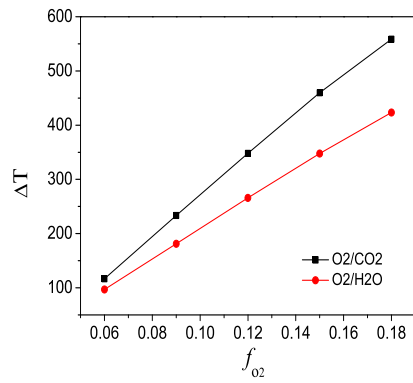


Fig. 4. Temperature distribution in O₂/H₂O or O₂/CO₂ condition at (a) $f_{o_2} = 6\%$ (b) $f_{o_2} = 12\%$ and (c) $f_{o_2} = 18\%$: $T_{cof} = 1800$ K.



(a)



(b)

Fig. 5. Maximum temperature (a) and temperature rise (b) at various f_{o_2} and $T_{cof} = 1800$ K.

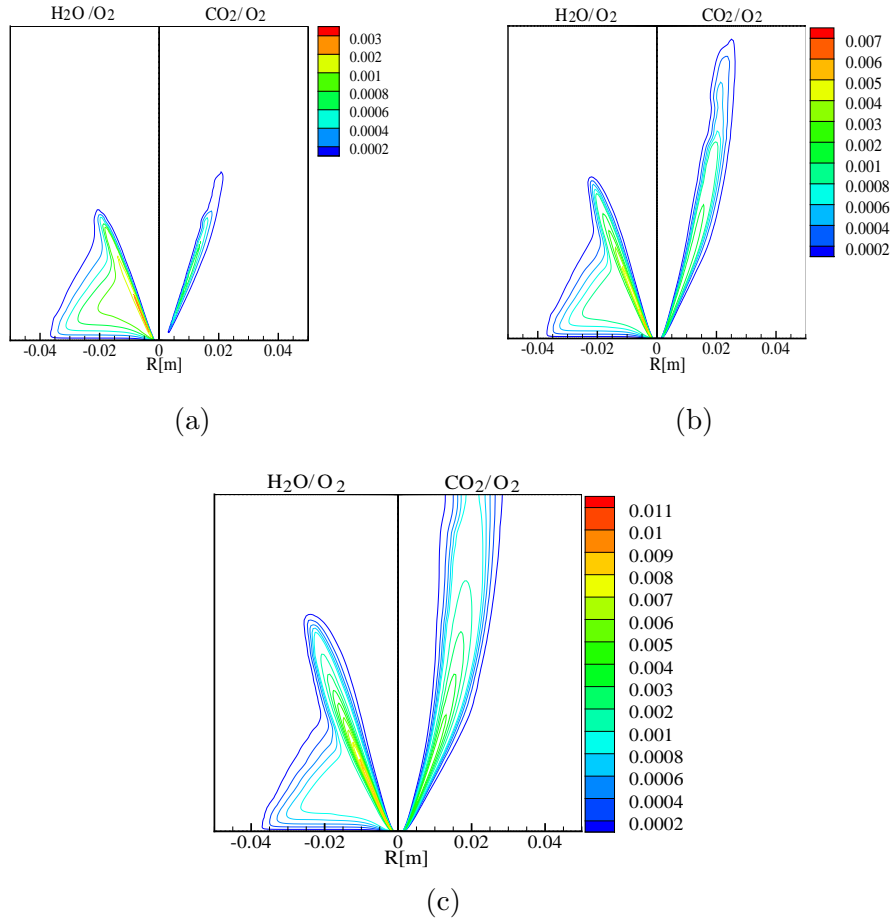


Fig. 6. OH distribution in O₂/H₂O or O₂/CO₂ condition at (a) $f_{o_2} = 6\%$ (b) $f_{o_2} = 12\%$ and (c) $f_{o_2} = 18\%$ and $T_{cof} = 1800$ K.

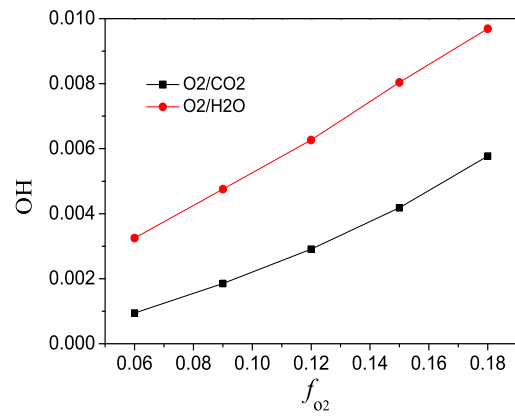


Fig. 7. The maximum of OH concentration at various f_{O_2} and $T_{cof} = 1800$ K.

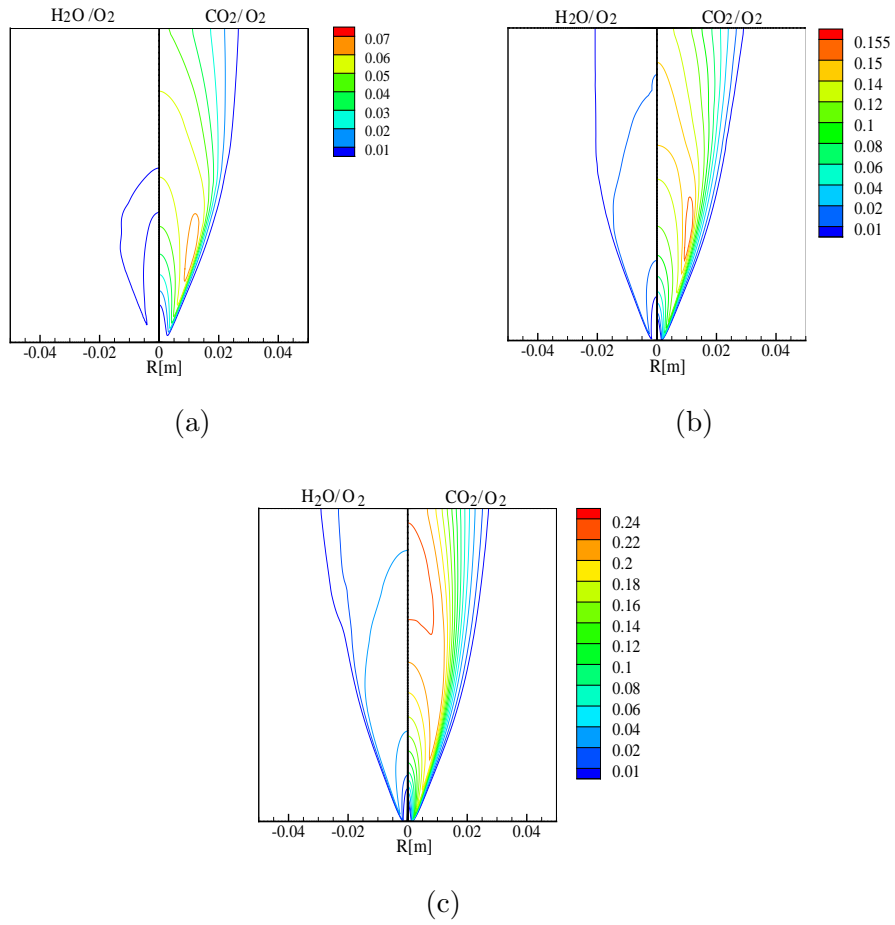


Fig. 8. CO distribution in O_2/H_2O or O_2/CO_2 condition at (a) $f_{o_2} = 6\%$ (b) $f_{o_2} = 12\%$ and (c) $f_{o_2} = 18\%$ and $T_{cof} = 1800$ K.

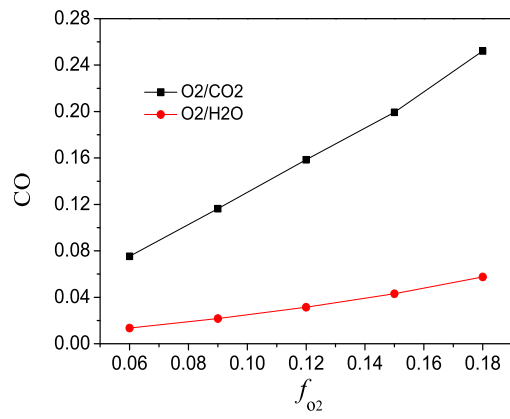


Fig. 9. The maximum of CO concentration at various f_{o_2} and $T_{cof} = 1800$ K.

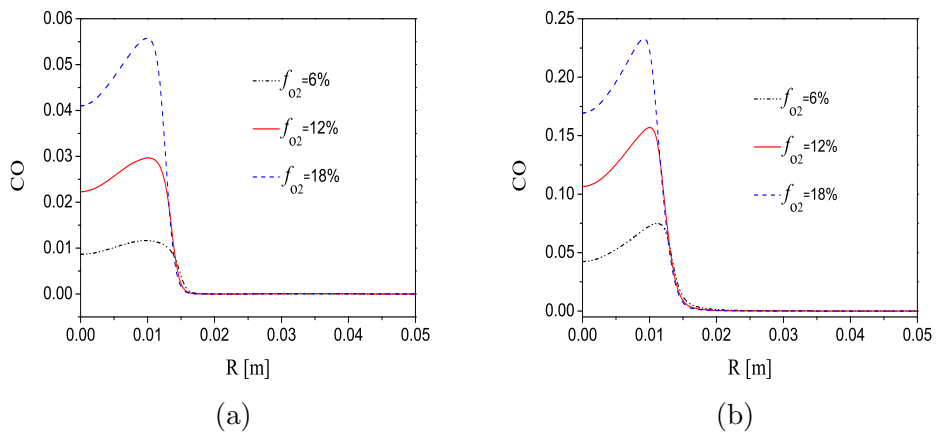


Fig. 10. CO profile in (a) $\text{O}_2/\text{H}_2\text{O}$ and (b) O_2/CO_2 condition at $x = 90$ mm and $T_{cof} = 1800$ K.

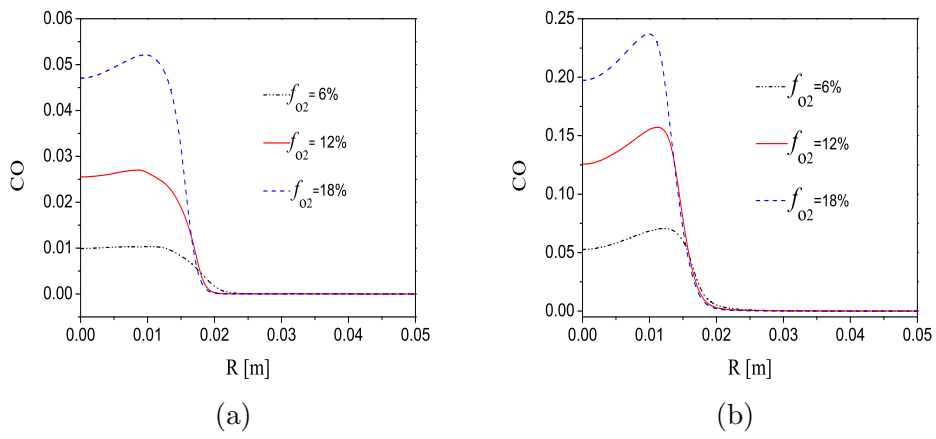


Fig. 11. CO profile in (a) O_2/H_2O and (b) O_2/CO_2 condition at $x = 120$ mm and $T_{cof} = 1800$ K.

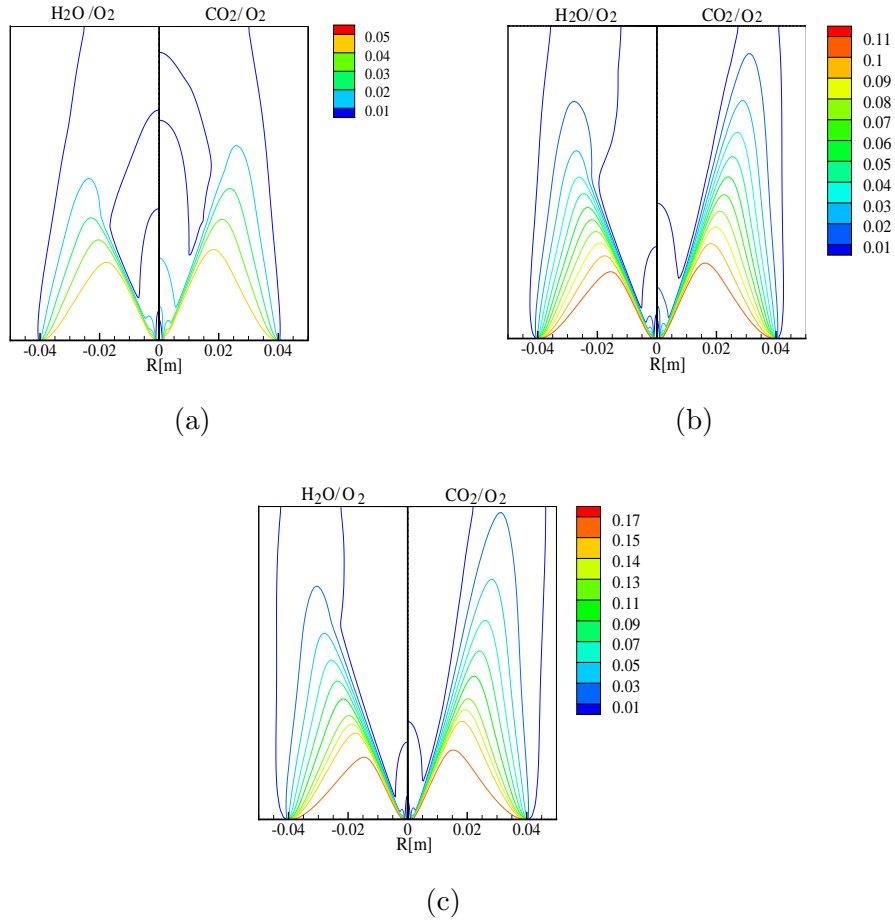


Fig. 12. O₂ distribution in O₂/H₂O or O₂/CO₂ condition at (a) $f_{O_2} = 6\%$ (b) $f_{O_2} = 12\%$ and (c) $f_{O_2} = 18\%$ and $T_{cof} = 1800$ K.

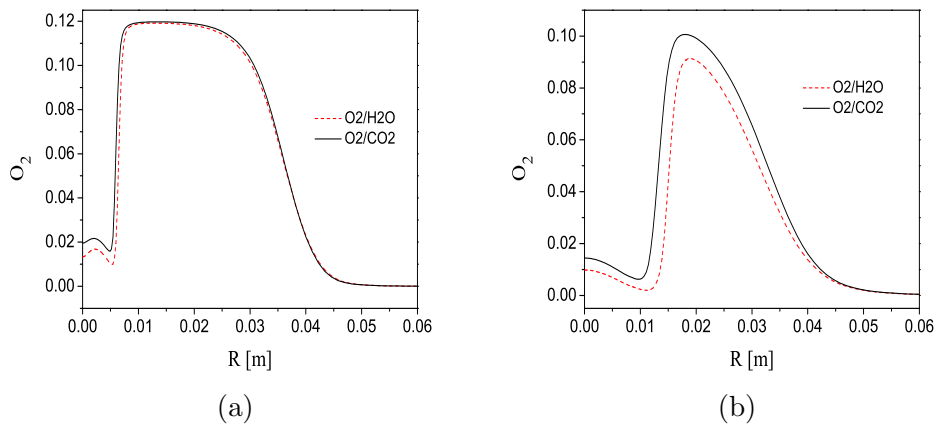


Fig. 13. O_2 profile at (a) $x = 30$ mm and (b) $x = 90$ mm : $f_{O_2} = 12\%$ and $T_{cof} = 1800$ K.

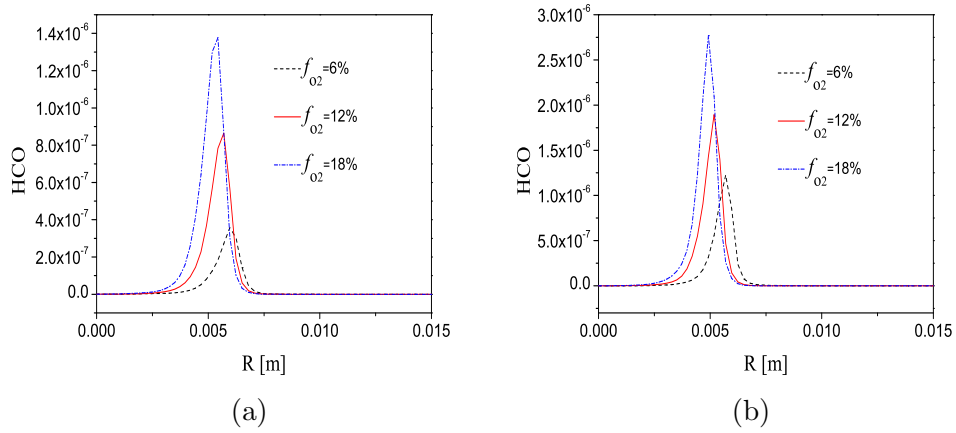


Fig. 14. HCO profile in (a) O_2/H_2O and (b) O_2/CO_2 condition at $x = 30$ mm and $T_{cof} = 1800$ K.

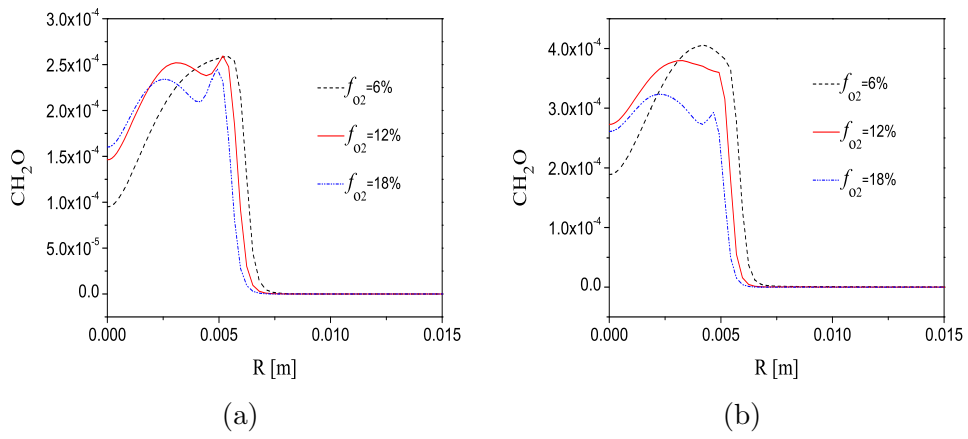


Fig. 15. CH_2O profile in (a) $\text{O}_2/\text{H}_2\text{O}$ and (b) O_2/CO_2 condition at $x = 30$ mm and $T_{\text{cof}} = 1800$ K.

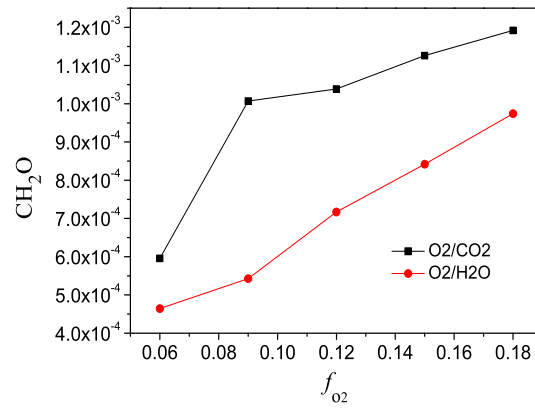
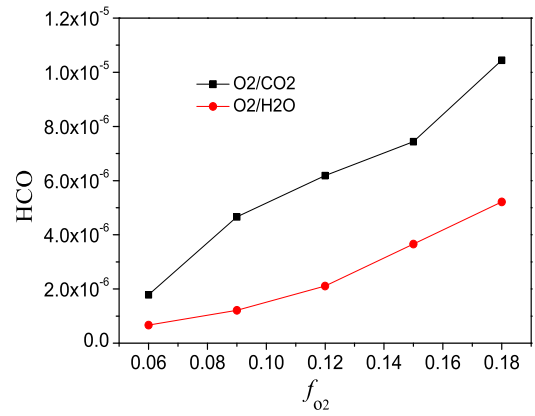


Fig. 16. The maximum of HCO (a) and CH₂O (b) concentration at various f_{O_2} and $T_{cof} = 1800$ K.

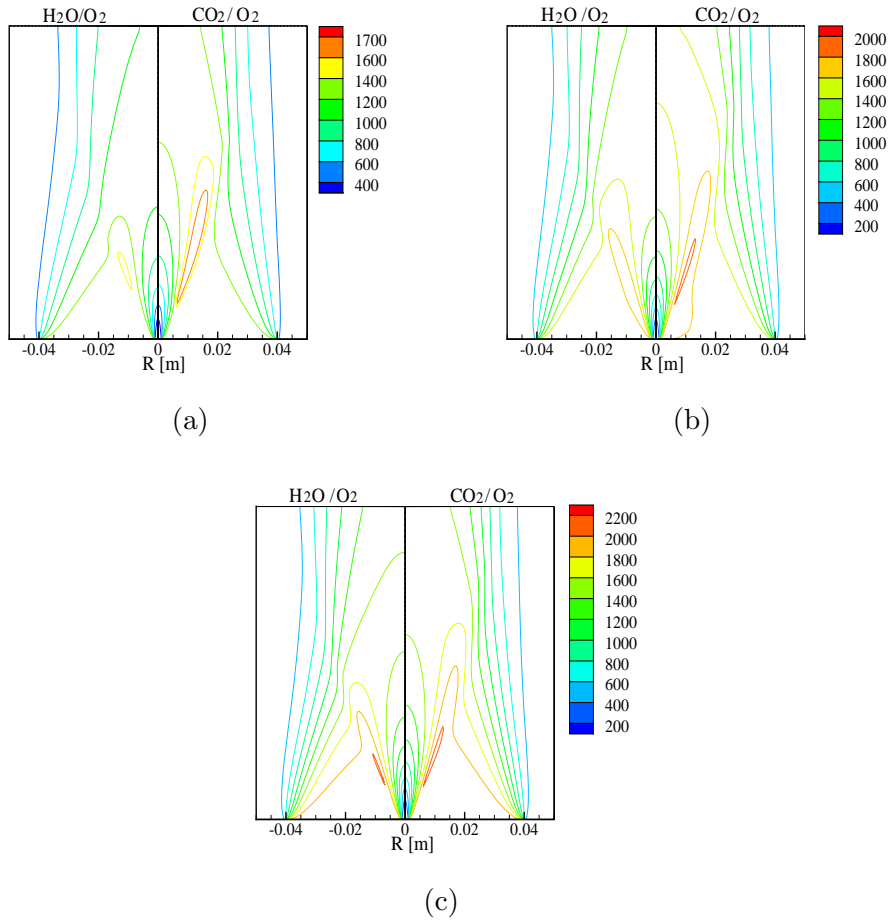


Fig. 17. Temperature distribution in O_2/H_2O or O_2/CO_2 condition at (a) $T_{cof} = 1500$ K (b) $T_{cof} = 1800$ K and (c) $T_{cof} = 2100$ K: $f_{o_2} = 9\%$.

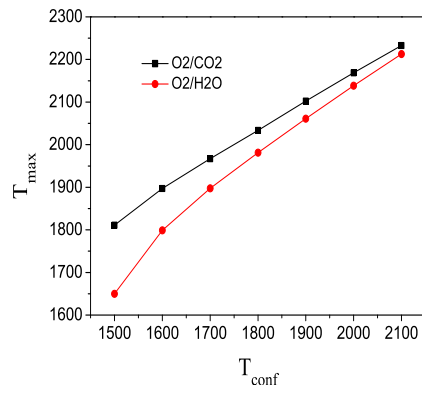


Fig. 18. Maximum temperature at various T_{conf} and $f_{\text{O}_2} = 9\%$.

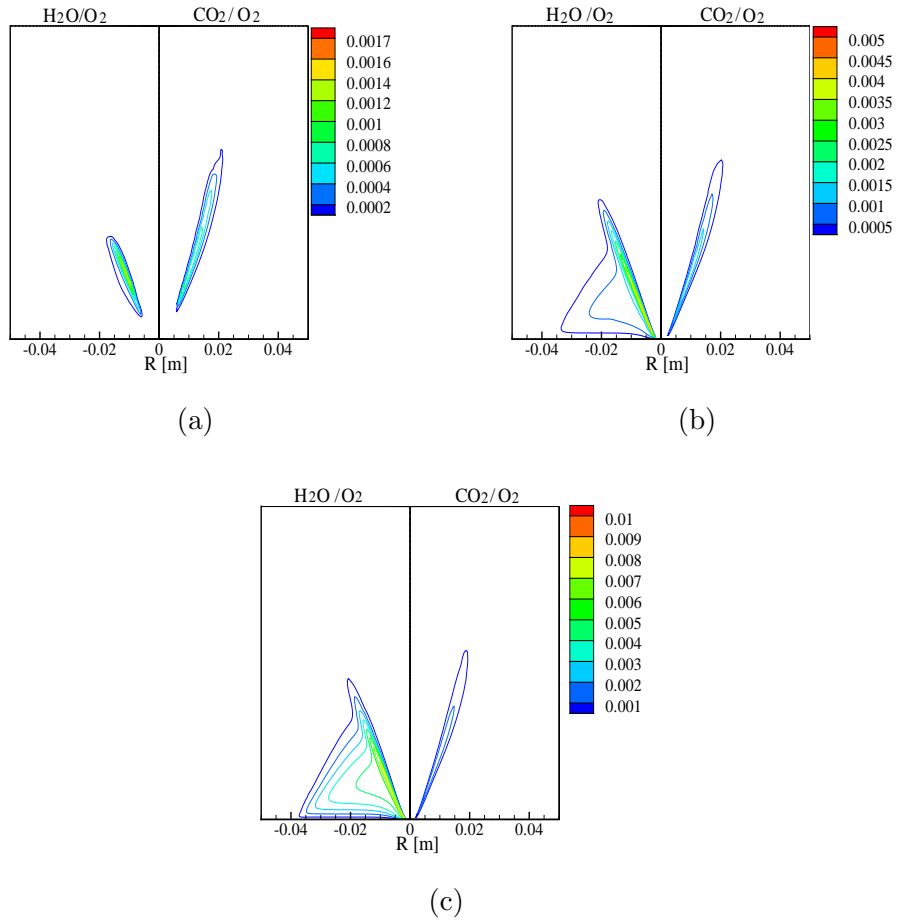


Fig. 19. OH distribution in O₂/H₂O or O₂/CO₂ condition at (a) $T_{cof} = 1500$ K (b) $T_{cof} = 1800$ K and (c) $T_{cof} = 2100$ K: $f_{o_2} = 9\%$.

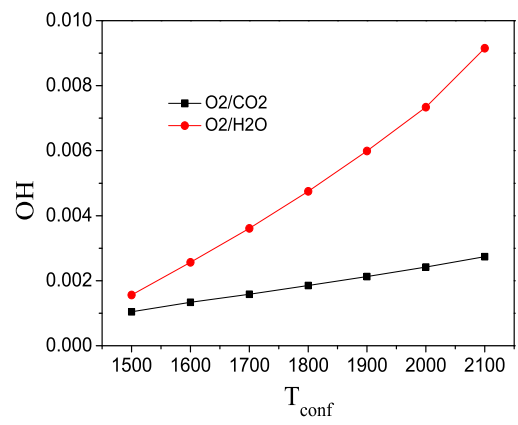


Fig. 20. The maximum of OH concentration at various T_{conf} and $f_{o_2} = 9\%$.

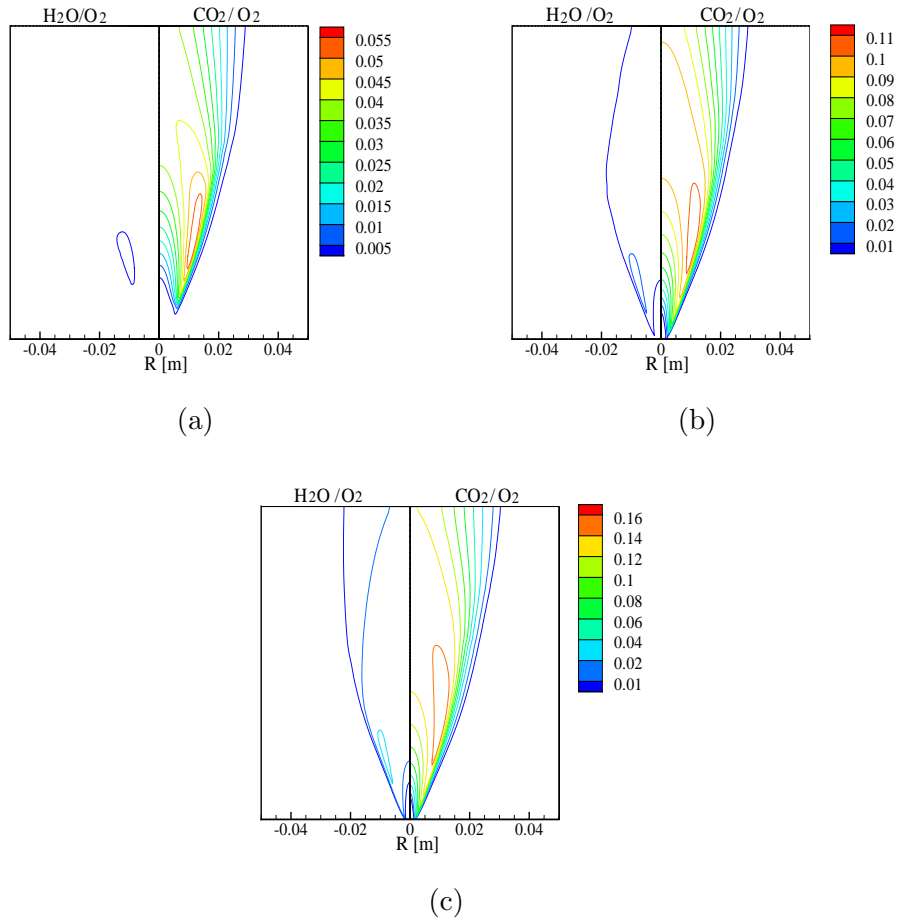


Fig. 21. CO distribution in O_2/H_2O or O_2/CO_2 condition at (a) $T_{cof} = 1500$ K (b) $T_{cof} = 1800$ K and (c) $T_{cof} = 2100$ K: $f_{o_2} = 9\%$.

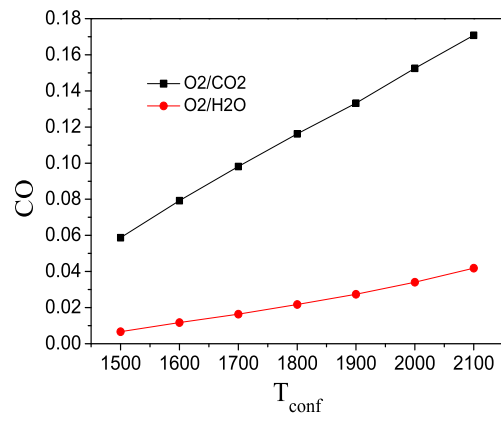


Fig. 22. The maximum of CO concentration at various T_{conf} and $f_{o_2} = 9\%$.

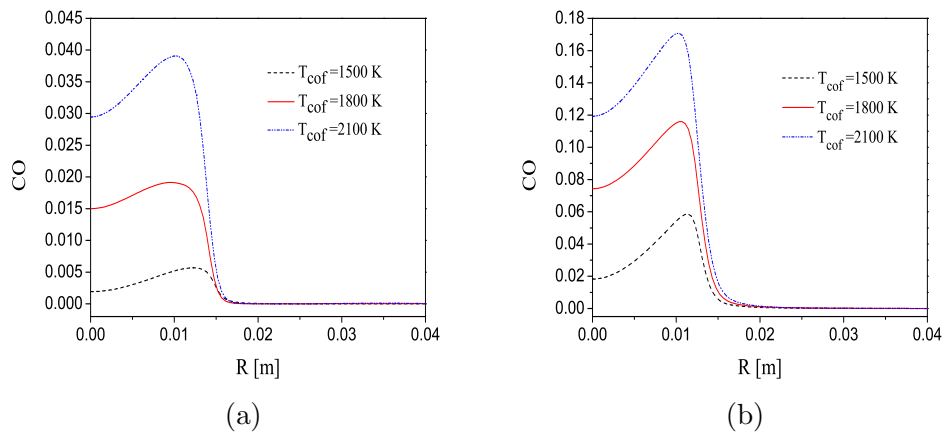


Fig. 23. CO profile in (a) O_2/H_2O and (b) O_2/CO_2 condition at $x = 90$ mm and $f_{O_2} = 9\%$.

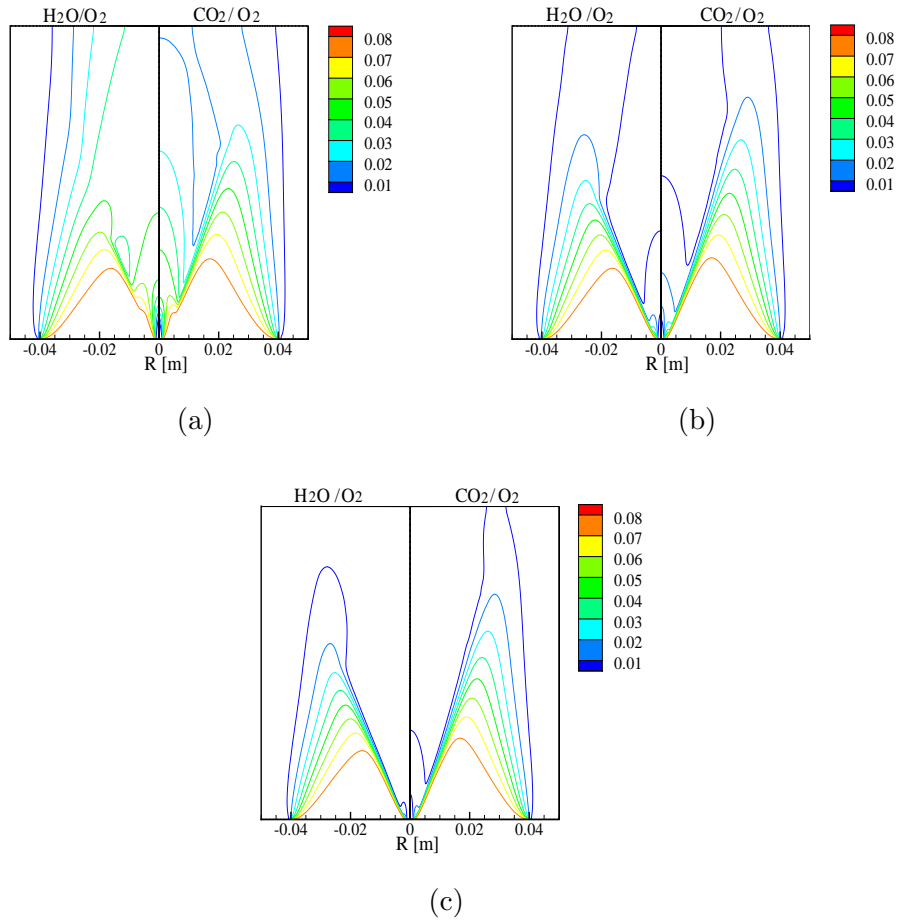


Fig. 24. O₂ distribution in O₂/H₂O or O₂/CO₂ condition at (a) $T_{cof} = 1500$ K (b) $T_{cof} = 1800$ K and (c) $T_{cof} = 2100$ K: $f_{o_2} = 9\%$.

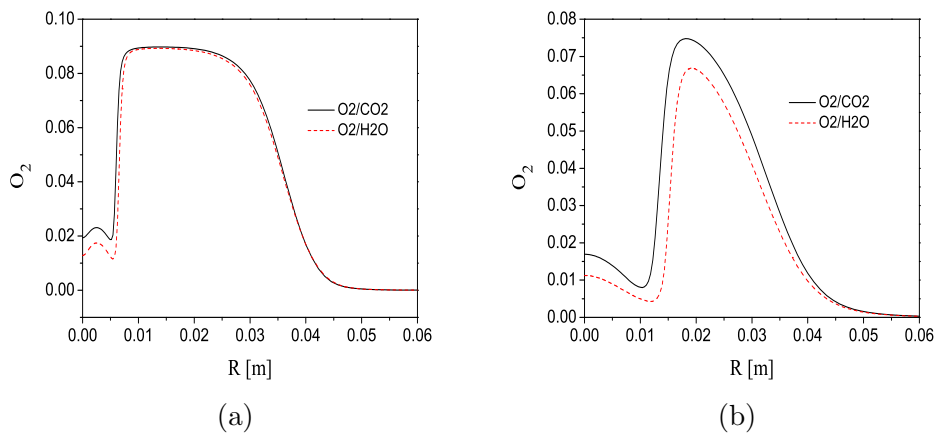


Fig. 25. O_2 profile at (a) $x = 30$ mm and (b) $x = 90$ mm : $f_{o_2} = 9\%$ and $T_{cof} = 2100$ K.

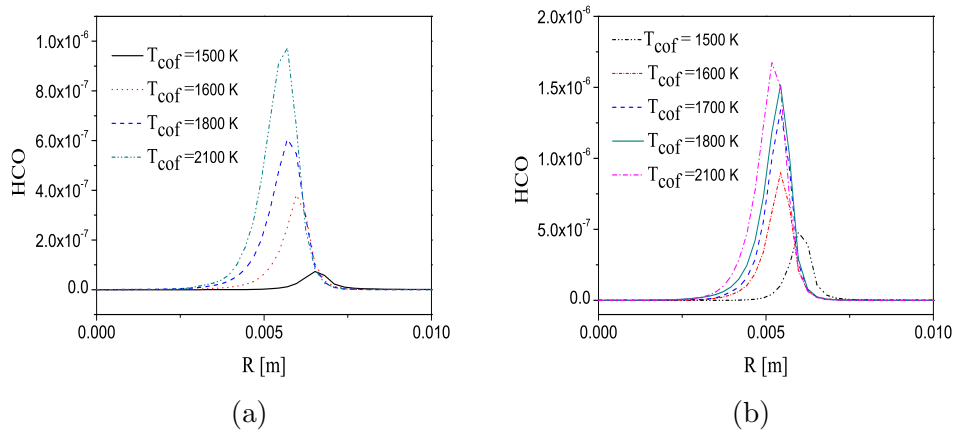


Fig. 26. HCO profile in (a) O_2/H_2O and (b) O_2/CO_2 condition at $x = 30$ mm and $f_{O_2} = 9\%$.

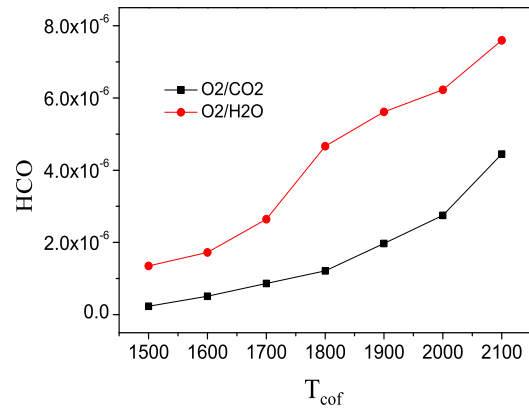


Fig. 27. The maximum of HCO concentration at various T_{cof} and $f_{o_2} = 9\%$.

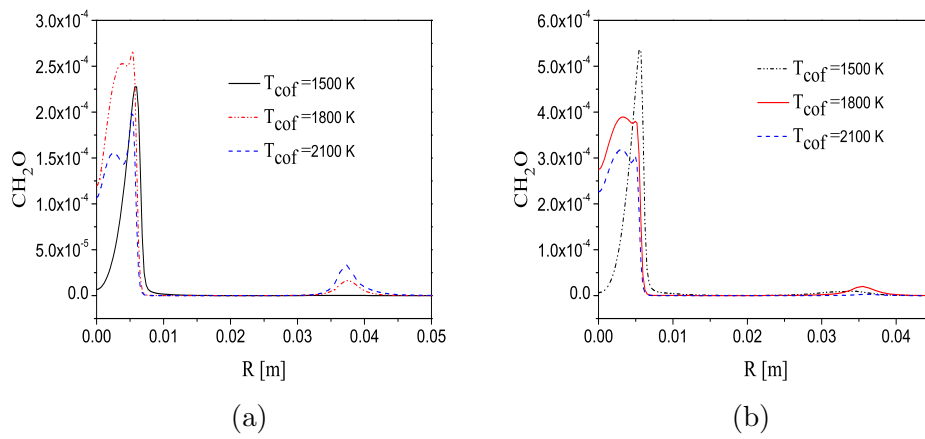


Fig. 28. CH_2O profile in (a) $\text{O}_2/\text{H}_2\text{O}$ and (b) O_2/CO_2 condition at $x = 30$ mm and $f_{\text{O}_2} = 9\%$.

Table 1

Computational conditions of the present work.

Case	Fuel Flow			Co-flow					Tunnel Flow			
	\mathbf{u} (m/s)	T (K)	CH ₄ (%)	\mathbf{u} (m/s)	T (K)	O ₂ (%)	H ₂ O (%)	CO ₂ (%)	\mathbf{u} (m/s)	T (K)	H ₂ O (%)	CO ₂ (%)
O ₂ /H ₂ O	60	305	100	3.2	1500 / 2100	6 / 18	82 / 94	0	3.2	400	100	0
O ₂ /CO ₂	60	305	100	3.2	1500 / 2100	6 / 18	0	82 / 94	3.2	400	0	100