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Comparisons of the Uncoupled Effects of CO₂ on the CH₄/O₂ Counterflow Diffusion Flame under High Pressure

Ying Chen ^{1,2}, Jingfu Wang ^{1,2,*}, Xiaolei Zhang ^{1,2} and Conghao Li ^{1,2}

¹ MOE Key Laboratory of Enhanced Heat Transfer and Energy Conservation, The Faculty of Environment and Life, Beijing University of Technology, Beijing 100124, China; yingchen0511@outlook.com (Y.C.); zhangxl@emails.bjut.edu.cn (X.Z.); S201905113@emails.bjut.edu.cn (C.L.)

² Beijing Key Laboratory of Heat Transfer and Energy Conversion, The Faculty of Environment and Life, Beijing University of Technology, Beijing 100124, China

* Correspondence: jfwang@bjut.edu.cn

Abstract: A comprehensive numerical investigation of the uncoupled chemical, thermal, and transport effects of CO₂ on the temperature of CH₄/O₂ counterflow diffusion flame under high pressure up to 5 atm was conducted. Three pairs of artificial species were introduced to distinguish the chemical effect, thermal effect, and the transport effect of CO₂ on the flame temperature. The numerical results showed that both the chemical effect and the thermal effect of the CO₂ dilution in the oxidizer side can decrease the flame temperature significantly, while the transport effect of CO₂ can only slightly increase the flame temperature and can even be ignored. The reduction value of the temperature caused by the chemical effect of CO₂ grows linearly, while that caused by the thermal effect increases exponentially. The RP_{chem} and $RP_{thermal}$ are defined to explain the temperature reduction percentage due to the chemical effect and the thermal effect of CO₂ in the total temperature reduction caused by CO₂ dilution, respectively. The RP_{chem} decreases with the increase of the pressure, the strain rate, and the CO₂ dilution ratio, while the $RP_{thermal}$ behaves in the opposite manner. In the above conditions, the chemical effect plays a dominant role on the flame temperature reduction.

Keywords: methane; CO₂ dilution; chemical effect; thermal effect; counterflow flame

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1. Introduction

To overcome the difficulties of the multiple goals of CCS (carbon capture and storage) [1–3], reduction of pollutants [3,4], and GHC (greenhouse gas) reduction [5], the technology of Oxy-fuel combustion [6,7] based on the exhaust gas recirculation [8] has been proposed and developed by numerous scholars. As for the so-called Oxy-fuel combustion, the oxidant is pure O₂ combined with recycled flue gas (hereafter, the main component is considered to be CO₂), which is distinguished with traditional combustion [8]. Compared with air combustion (O₂/N₂), the differences between CO₂ and N₂ regarding thermal properties, chemical properties, transport properties, and radiative properties [7,9,10] cause substantially complexities and challenges on the flame characteristics, especially for high-pressure practical application, such as gas turbines [11]. The thermal effect of CO₂ is mainly caused by the difference in the enthalpy, entropy, and specific heat capacity between CO₂ and N₂. What is more, unlike N₂, which is an inert gas, CO₂ can take part in chemical reactions [10]. In a general way, the synergistic effect of CO₂ [12] caused by the above four effects can be easily obtained by experimental facility. Meanwhile, for the isolate effect (uncoupled effect) of CO₂ [13], numerical simulation becomes an efficient method.

Wang et al. [14] carried out experimental and numerical study on the effect of CO₂ on the laminar burning velocities (LBVs) of premixed CH₄/air or CH₄/O₂/CO₂ for pressure up to 0.5 MPa. De Persis et al. [15] and Xie et al. [16] also investigated the influence of CO₂ on the LBVs under 0.1 to 0.8 MPa and 0.1 to 0.3 MPa, respectively. All of them concluded

that the dilution of CO_2 decreased the LBVs and more CO_2 led to a further decrease. Hassan et al. [17], Zhou et al. [18], and Lu et al. [19] also revealed the influence of pressure on the LBVs with dilution gas in the premixed flame. Moreover, all of them revealed that the elevated pressure can increase the laminar speed of the premixed flame. Liu et al. [20] explored a numerical strategy for the first time to isolate the coupled effects (chemical and thermal effect) of an additive introduced to either the fuel stream or the oxidizer stream. Taking CO_2 as an example, the authors explored the chemistry mechanism of the experimentally observed soot suppression by CO_2 addition on both the fuel side and the oxidizer side of ethylene diffusion flame. Liu et al. [21] also carried out numerical simulation to investigate the thermal effect and chemical effect of CO_2 on the burning velocity in CH_4 and H_2 premixed laminar flames by the same isolate strategy. The noteworthy radiative effect of CO_2 compared with the chemical effect and the thermal effect on the flame also drew the attention of Liu et al. [22]. The effects of water vapor addition [23] also applied a similar strategy to the syngas flame. Afterwards, the isolate strategy was developed, updated, and applied to different flames by numerous researchers. Glarborg et al. [24] experimentally explored the chemical effect of CO_2 on CO concentration in an atmospheric-pressure, whereas Galmiche et al. [25] and Hu et al. [26] conducted series studies and discussed the chemical effect and thermal effect of CO_2 addition on the LBVs at ordinary pressure. The numerical results showed that both the chemical effect and thermal effect can reduce the laminar burning velocities; however, the CO concentrations increase greatly. Hu et al. [27] focused on the comparisons of the thermal effect and chemical effect of CO_2 on the LBVs of O_2 /methane under various O_2 mole fraction and equivalence ratios by numerical simulation under ordinary pressure; the results showed that the chemical effect was smaller than the thermal effect, but much bigger than the radiative effect in the calculation domain. Meanwhile, the third body effect was also analyzed to identify important reactions. Shih et al. conducted numerical simulation to illustrate that the dilution effect [28] of CO_2 can decrease the maximum temperature of the one-dimensional diffusion flame and, when the CO_2 added to the fuel side [29], the chemical effect, thermal effect, and radiative effect on the temperature were compared in detail. They conclude that both the chemical and the thermal effect of CO_2 can significantly change the flame temperature. However, it is worthy to note that the above studies of Shih et al. were conducted under atmospheric-pressure. What is more, the NO_x formation and emission of the gas flame with CO_2 dilution by distinguishing the chemical effect and thermal effect were analyzed as well [12,13,30,31].

To summarize the above review, what could be extracted from the literature is that there is no report on the isolate effects of CO_2 on the counterflow diffusion flame along with improving pressure. The chemical effect and thermal effect of CO_2 on the flame (premixed flame or diffusion flame) have been investigated sufficiently. However, the reports investigating the dominant role of the chemical effect and thermal effects of gas dilution (taking CO_2 as an example) based on different flame characteristics are rare. More importantly, whether the chemical effect and the thermal effect of the CO_2 on the specific parameters (LBV, temperature, NO_x emission, main species) will behave differently with the increase of pressure, and whether the dominant role of the two effects along with the increase pressure will exchange, remained to be studied in deeply.

The objective of the present study is to quantitatively explore the effects of CO_2 , which is added into the oxidant side of the CH_4/O_2 counterflow diffusion flame on the flame temperature with high pressure and a large CO_2 dilution ratio, and reveal the trends of the chemical effect and thermal effect of CO_2 caused by pressure. The emphasis is on the comparison of the chemical effect and thermal effect under different pressure and confirming the dominant role between the two effects on temperature. Meanwhile, the effect of strain rate on the temperature was also carried out to quantitatively clarify the CO_2 effect on the flame temperature under a low strain rate and high strain rate.

2. Numerical Simulation Model

In the Oxy-fuel combustion process, the combustion reaction becomes very complicated owing to the coupling effects of chemical kinetics, molecular diffusion, and turbulent transport. However, as a basic component of non-premixed flame structure, laminar counterflow diffusion flame is widely used in the study of combustion mechanism, which can also analyse and reveal the effects of diffusion, transport, and chemical reactions on the combustion process in detail. Figure 1 schematically shows the structure of a typical counterflow diffusion flame system. Fuel and oxidant are injected from different nozzles to form a stable axisymmetric diffusion flame. Various reactants enter the flame surface through molecular diffusion to participate in the combustion reaction. The complete mathematical description of the counterflow diffusion flame (including mass, momentum, energy, composition equation, and the boundary conditions on the fuel side and oxidizer side) can be found in the works of [23,32]. The OPPDIF [33] code was used in the current study to solve the mathematical equations of the counterflow diffusion flame. The convection term adopts the upwind difference scheme, and the multi-component diffusion and thermal diffusion models are used to calculate the diffusion coefficient. The adaptive refinement grid is applied in the calculation process, and the damped Newton method is used to solve the equation. The relative and absolute errors of the iteration process are less than 10^{-6} . The GRI-Mech 3.0 [34] mechanism was selected as the reaction mechanism, which contains 53 species and 325 elementary reactions including the NO_x formation, and is also the most popular mechanism for CH_4 .

Figure 1. The configuration of the counterflow flame.

In order to ensure the stagnation surface of the counterflow flame does not deviate from the centre of the fuel and oxidizer nozzles, the calculation limits the two opposing gases to satisfy the momentum balance equation [34]:

$$\rho_o V_o^2 = \rho_F V_F^2 \quad (1)$$

The global strain rate α_s is defined as follows [23]:

$$\alpha_s = \frac{2(-V_O)}{L} \left[1 + \frac{V_F}{(-V_O)} \sqrt{\frac{\rho_F}{\rho_O}} \right] \quad (2)$$

where the subscripts 'O' and 'F' stand for oxidizer and fuel flow streams, respectively. ρ and V represent the density and the velocity of the flow streams, respectively. L is the distance between the fuel and oxidizer nozzles, which is specified as 4 cm. For Equations (1) and (2),

only considering the absolute value of the velocity, the expressions of the velocity on both sides can be expressed as follows:

$$|V_F| = |V_o| \sqrt{\frac{\rho_o}{\rho_F}} \quad (3)$$

$$|V_O| = \frac{\alpha_s L}{4} \quad (4)$$

The counterflow diffusion flame of CH₄ versus O₂ or β CO₂/(1 − β)O₂ (β is defined as CO₂ dilution ratio) with six CO₂ dilution ratios, 0–50% (10% as steps), was conducted. The pressure range is 1 atm to 5 atm, and the global strain rate α_s is set to be 10 s^{−1}, 30 s^{−1}, or 50 s^{−1}. The inlet temperature of both the fuel and the oxidizer was specified as 300 K. The velocities of both sides were decided by Equations (1)–(4), and can be seen in Appendix A.

The temperature distribution is the most basic flame characteristic of the counterflow diffusion flame, and it can be regarded as the most basic performance of other flame characteristics (flame front position, generation of thermal NO_x, generation of important intermediate components). Therefore, the flame temperature has been selected as the target parameter of the current analysis. Guided by the research goals of this article, the author introduces three groups of artificial species to distinguish the chemical effect, thermal effect, and transport effect of CO₂ on the flame temperature, which is similar to the isolate strategy proposed by Liu et al. [20–22]. The properties of the three groups' artificial species are listed in Table 1. First, FCO₂ is introduced to compare the chemical effect of CO₂, which has the same thermal, transport, and radiative properties as CO₂, but does not participate in the chemical reaction. Therefore, the differences in the results between FCO₂ and CO₂ are entirely contributed by the chemical effect of CO₂. Similarly, TCO₂ was employed, which has the same chemical, transport, and radiative effect as FCO₂, but has the same thermal properties as normal N₂. The differences of the results between FCO₂ and TCO₂ is totally caused by the thermal effect of CO₂. The third introduced artificial species is XCO₂, which has the same chemical, thermal, and transport properties as FCO₂, with the same transport properties as N₂. The transport effect of CO₂ is revealed by the difference between the results of FCO₂ and XCO₂.

Table 1. The specific properties of the artificial species.

	Chemical	Thermal	Transport
CO ₂	✓	✓	✓
FCO ₂	-	✓	✓
TCO ₂	-	N ₂	✓
XCO ₂	-	✓	N ₂

3. Results

3.1. The Effect of CO₂ Dilution on the Flame Temperature

Figure 2 displays the temperature distribution of the flame along with the distance between the two nozzles at different CO₂ dilution at $p = 1$ atm, $\alpha_s = 10$ s^{−1}. What can be clearly seen from the figure is that the temperature distribution of the counterflow diffusion flame is symmetrical parabolic. CO₂ dilution can significantly reduce the temperature at any location in the flame; the greater the CO₂ dilution, the greater the reduction. The negative influence of CO₂ dilution on the temperature is more obvious in the downstream of the flame front (the location of the maximum temperature) than in the upstream. CO₂ dilution also remarkably narrowed the reaction zone. What is more, when the CO₂ dilution ratio increases in an arithmetic progression (10% as common difference), the flame temperature distribution curves shift to the center of the flame with equal intervals.

Figure 2. The effect of the CO₂ dilution ratio at $p = 1 \text{ atm}$, $\alpha_s = 10 \text{ s}^{-1}$.

To distinguish the chemical effect, the thermal effect, and the transport effect of CO₂ on the flame temperature, FCO₂, TCO₂, and XCO₂ were introduced to identify the discrepancies. Figure 3 qualitatively depicts the flame temperature distribution of the counterflow diffusion flame diluted by the ordinary CO₂ and the three specific artificial CO₂. To enlarge the difference between the flame with and without CO₂ dilution, the maximum dilution ratio $\beta = 50\%$ was selected to demonstrate the effects. As seen in Figure 2, the influence of different dilution ratios on flame temperature distribution is only reflected in the size of the temperature drop. From Figure 3, the effects including the chemical effect, thermal effect, and transport effect were mainly presented in the downstream of the flame front (in the oxidizer side), and all three effects reduced the flame temperature. It is worth noting that the chemical effect and the thermal effect not only narrowed the reaction zone, shifting the position of the flame front, but also decreased the maximum flame temperature significantly. However, the transport effect (compare FCO₂ and XCO₂) of CO₂ only showed a weak influence on the flame temperature near the oxidizer, and no obvious change occurred on the maximum flame temperature. In the following analysis, the maximum flame temperature is the target parameter. The transport effect is too small to be ignored.

Figure 3. The comparison of the effect of the three artificial species on the flame temperature at $p = 1 \text{ atm}$; $\alpha_s = 10 \text{ s}^{-1}$; $\beta = 0\%, 50\%$.

Before analysing and comparing the chemical effect and thermal effect on the maximum flame temperature, the reduction of the maximum flame temperature caused by the chemical effect and the thermal effect with different dilution ratio is defined firstly as follows:

$$\Delta T_{Chem}^{max} = T_{max}[\beta FCO_2] - T_{max}[\beta CO_2] \quad (5)$$

$$\Delta T_{Therm}^{max} = T_{max}[\beta TCO_2] - T_{max}[\beta FCO_2] \quad (6)$$

The reduction percentages of the maximum flame temperature caused by the chemical effect (RP_{chem}) and the thermal effect (RP_{therm}) in the total temperature decrease due to CO_2 dilution were calculated as follows:

$$RP_{chem} = \frac{T_{max}[\beta FCO_2] - T_{max}[\beta CO_2]}{T_{max}[\text{undiluted}] - T_{max}[\beta CO_2]} \times 100\% \quad (7)$$

$$RP_{therm} = \frac{T_{max}[\beta TCO_2] - T_{max}[\beta FCO_2]}{T_{max}[\text{undiluted}] - T_{max}[\beta CO_2]} \times 100\% \quad (8)$$

The total effect of CO_2 on the flame maximum temperature equal to $T_{max}[\text{undiluted}] - T_{max}[\beta CO_2]$ at βCO_2 dilution ratio, while the sum of RP_{chem} and RP_{therm} is not 100%. This is because the transport effect is ignored and the three-body effect and radiative effect are not taken into consideration in the current study.

Curves and bar graphs of the quantitative influence of CO_2 chemical and thermal effects at a different CO_2 dilution ratio on flame temperature maximum are given in Figure 4. From Figure 4, we can extract the following results: the chemical effect and the thermal effect increase with the increasing CO_2 dilution ratio. The chemical effect takes the dominant role between the two effects. However, the difference between the two effects is that the two effects show different growth patterns as the CO_2 dilution ratio increases; that is, linear increases for the former and exponential increases for the latter. In other words, with the increase of the CO_2 dilution ratio, the negative effect of the CO_2 physical effect on the maximum flame temperature increases faster than the chemical effect.

Figure 4. The comparison of the chemical effect and thermal effect on the flame temperature at $p = 1 \text{ atm}$, $\alpha_s = 10 \text{ s}^{-1}$, $\beta = 0\text{--}50\%$.

3.2. The Effect of Pressure on the Flame Temperature

In practical applications of combustion equipment such as gas turbines, pressure is a very important flame influence parameter. Figure 5 plots the flame temperature distribution curves along with the distance at different pressure with and without CO_2 dilution. The negative effects of CO_2 on the flame temperature at 3 atm and 5 atm behave similarly to that at atmospheric-pressure. The increase in pressure not only causes the combustion zone

to become narrower, but also improves the maximum flame temperature. The coordinate positions of the flame front without CO₂ dilution in 1 atm, 3 atm, and 5 atm are 1.60 cm, 1.5 cm, and 1.47 cm, respectively. The coordinate positions of the flame front with 50% CO₂ dilution in 1 atm, 3 atm, and 5 atm are 1.57 cm, 1.42 cm, and 1.36 cm, respectively. By comparing the above coordinate positions of the flame front, the addition of CO₂ makes the influence of pressure on the flame front more obvious.

Figure 5. The effect of CO₂ on the flame temperature at different pressure (1–5 atm); $\alpha_s = 10 \text{ s}^{-1}$; $\beta = 0\%, 50\%$.

Figure 6 gives the reduction percentage of the maximum temperature caused by the chemical effect and thermal effect of the CO₂ with and without CO₂ dilution at different pressures. What can be seen from Figure 6 is that the CO₂ dilution causes the peak value of the flame temperature to decrease significantly, whether in ordinary pressure or high pressure (5 atm). More CO₂ dilution leads to a greater decrease. The reduction percentage of the flame temperature peak value caused by the chemical effect (RP_{chem}) declines with the increasing CO₂ dilution ratio. However, the reduction percentage of the flame temperature peak value caused by the thermal effect (RP_{therm}) behaves in the opposite manner to RP_{chem} , which increases with the increasing CO₂ dilution ratio. What needs to be specifically pointed out is that Figure 4 shows the decrease value of the flame peak temperature, which shows that it increases with the increase of the CO₂ dilution ratio, but that does not mean that it accounts for an increase in the total impact of CO₂ on temperature. Figure 6 shows the reduction percentage of the peak temperature caused by the chemical effect and the thermal effect in the total temperature decrease, which can more efficiently reveal the primary and secondary effects and changing trends of chemical effects and thermal effects of CO₂ dilution on temperature.

As a supplement to Figure 6, Figure 7 clearly shows the RP_{chem} and RP_{therm} lines with the CO₂ dilution ratio in different pressure. At the same CO₂ dilution ratio β , RP_{therm} increases with the pressure increase, while the RP_{chem} behaves in the opposite manner. This means the rise in pressure can promote the thermal effect and reduce the chemical effect in the total effect of the CO₂ dilution on the peak of the flame temperature. Corresponding to Figure 6, RP_{chem} and the RP_{therm} have different performances on the increase of CO₂ dilution ratio; that is, the former decreases, while the latter increases.

(a) $p = 1 \text{ atm}$, $\alpha_s = 10 \text{ s}^{-1}$, $\beta = 0\text{--}50\%$

(b) $p = 3 \text{ atm}$, $\alpha_s = 10 \text{ s}^{-1}$, $\beta = 0\text{--}50\%$

(c) $p = 5 \text{ atm}$, $\alpha_s = 10 \text{ s}^{-1}$, $\beta = 0\text{--}50\%$

Figure 6. The comparison of the chemical effect and thermal effect on the maximum flame temperature with different pressure at $\alpha_s = 10 \text{ s}^{-1}$, $\beta = 0\text{--}50\%$.

Figure 7. The comparison of RP_{chem} and RP_{therm} with different pressures at $\alpha_s = 10 \text{ s}^{-1}$, $\beta = 0\text{--}50\%$.

3.3. The Effect of the Strain Rates

The global strain rate is selected as a variable parameter in the present study. According to the definitions in Equations (1)–(4), the differences in the global strain rate were reflected on the velocities of the fuel inlet and the oxidizer inlet. Further, the flame temperature distribution along with the distance between the two nozzles under different strain rate with or without CO_2 dilution is depicted in Figure 8. The effect of the strain rate on the temperature distribution of the flame is similar to the effect of the pressure (corresponding to Figure 5). The increase of the strain rate narrowed the reaction zone and shifted the flame front to the fuel side. However, the strain rate does not affect the peak value of the flame temperature, which is different from the effect caused by the pressure. The above effects of the strain rate on the flame temperature without CO_2 dilution were more obvious than those with CO_2 dilution.

Figure 8. The distribution of the flame temperature with different global strain rates at $p = 1 \text{ atm}$ and $\beta = 0\%$, 50% .

Figure 9 shows the histogram of the comparisons of RP_{chem} and RP_{therm} over the strain rate of 10 s^{-1} to 50 s^{-1} at $p = 1 \text{ atm}$ and $\beta = 0\%$, 50% . It can be clearly seen that the reduction percentage of the temperature caused by the chemical effect (RP_{chem}) of the CO_2 in the total reduction decreased with the increasing strain rate. Meanwhile, the reduction percentage of the temperature caused by the thermal effect (RP_{therm}) shows the exact opposite effect to the former. The chemical effect of CO_2 on the peak value of temperature always occupies

the dominant role compared with the thermal effect, whether in low stretch or high stretch. The discrepancy between RP_{chem} and RP_{therm} gradually decreases with the increase of the stretch rate. The maximum stretch rate in this article is only 50 s^{-1} . We could boldly suspect that, when the stretch rate reaches a certain level, RP_{therm} will be greater than RP_{chem} , and instead of RP_{chem} dominance.

Figure 9. The comparison of RP_{chem} and RP_{therm} with different global strain rate at $p = 1\text{ atm}$ and $\beta = 0\%$, 50% .

4. Conclusions

The comparisons of the chemical effect and thermal effect of CO_2 dilution on the flame temperature in the CH_4/O_2 counterflow diffusion flame under high pressure (up to 5 atm) were numerically studied with detailed chemistry mechanisms. The main conclusions can be summarized as follows:

1. Both the chemical effect and the thermal effect of CO_2 dilution in the oxidizer side can decrease the flame temperature significantly, while the transport effect of CO_2 on the flame temperature can be ignored.
2. The decreases in value of the peak flame temperature caused by both the chemical effect and the thermal effect increased with the increasing CO_2 dilution ratio, with linear increases for the former and exponential increases for the latter.
3. The increasing pressure can narrow the reaction zone and elevate the peak value of the flame temperature. RP_{chem} and RP_{therm} behave in opposite ways along with the pressure. The former decreases, but the latter increases with the pressure.
4. The increasing strain rate can narrow the reaction zone, but has no obvious influence on the peak value of the flame temperature. The change in RP_{chem} and RP_{therm} with the increasing strain rate shared similarities with the pressure influence.
5. The flame temperature is predominantly influenced by the chemical effect of CO_2 , while the thermal effect increases with the increase of CO_2 volume fraction, the increase of pressure, and the increase of stretch rate, and tends to exceed the chemical influence.

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Appendix A

Table A1. The boundary conditions of the fuel side and the oxidizer side.

Strain Rate (s ⁻¹)	Fuel	Oxidant Composition	ρ_f (g/L)	ρ_O (g/L)	V_f (m/s)	V_O (m/s)
10	Pure CH ₄	0%CO ₂ (FCO ₂ , TCO ₂ , XCO ₂) + 100%O ₂	0.7143	1.4286	10	14.14
	Pure CH ₄	10%CO ₂ (FCO ₂ , TCO ₂ , XCO ₂) + 90%O ₂	0.7143	1.4821	10	14.4
	Pure CH ₄	20%CO ₂ (FCO ₂ , TCO ₂ , XCO ₂) + 80%O ₂	0.7143	1.5357	10	14.66
	Pure CH ₄	30%CO ₂ (FCO ₂ , TCO ₂ , XCO ₂) + 70%O ₂	0.7143	1.5893	10	14.92
	Pure CH ₄	40%CO ₂ (FCO ₂ , TCO ₂ , XCO ₂) + 60%O ₂	0.7143	1.6429	10	15.17
	Pure CH ₄	50%CO ₂ (FCO ₂ , TCO ₂ , XCO ₂) + 50%O ₂	0.7143	1.6964	10	15.41
30	Pure CH ₄	0%CO ₂ (FCO ₂ , TCO ₂ , XCO ₂) + 100%O ₂	0.7143	1.4286	30	42.42
	Pure CH ₄	10%CO ₂ (FCO ₂ , TCO ₂ , XCO ₂) + 90%O ₂	0.7143	1.4821	30	43.2
	Pure CH ₄	20%CO ₂ (FCO ₂ , TCO ₂ , XCO ₂) + 80%O ₂	0.7143	1.5357	30	43.98
	Pure CH ₄	30%CO ₂ (FCO ₂ , TCO ₂ , XCO ₂) + 70%O ₂	0.7143	1.5893	30	44.76
	Pure CH ₄	40%CO ₂ (FCO ₂ , TCO ₂ , XCO ₂) + 60%O ₂	0.7143	1.6429	30	45.51
	Pure CH ₄	50%CO ₂ (FCO ₂ , TCO ₂ , XCO ₂) + 50%O ₂	0.7143	1.6964	30	46.23
50	Pure CH ₄	0%CO ₂ (FCO ₂ , TCO ₂ , XCO ₂) + 100%O ₂	0.7143	1.4286	50	70.7
	Pure CH ₄	10%CO ₂ (FCO ₂ , TCO ₂ , XCO ₂) + 90%O ₂	0.7143	1.4821	50	72
	Pure CH ₄	20%CO ₂ (FCO ₂ , TCO ₂ , XCO ₂) + 80%O ₂	0.7143	1.5357	50	73.3
	Pure CH ₄	30%CO ₂ (FCO ₂ , TCO ₂ , XCO ₂) + 70%O ₂	0.7143	1.5893	50	74.6
	Pure CH ₄	40%CO ₂ (FCO ₂ , TCO ₂ , XCO ₂) + 60%O ₂	0.7143	1.6429	50	75.85
	Pure CH ₄	50%CO ₂ (FCO ₂ , TCO ₂ , XCO ₂) + 50%O ₂	0.7143	1.6964	50	77.05

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