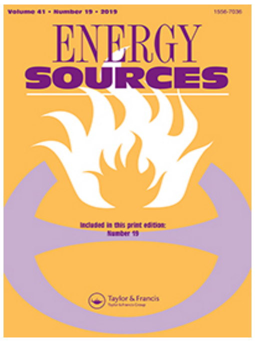

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Combustion characteristics of various biogas flames under reduced oxygen concentration conditions

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ABSTRACT

Distributed combustion is a promising method to obtain more uniform thermal field inside a combustor and reduced ultra-low pollutant emission levels at a combustor outlet. In this way, oxygen concentration in the oxidizer is reduced, resulting in a lower reaction rate. This study aims at investigating thermal field distributions and pollutant levels of various biogas flames under distributed combustion conditions. Combustion characteristics of biogas flames have numerically been investigated by a commercial code on distributed combustion conditions in terms of fuel flexibility, diluent temperature, and diluent composition. k-Ɛ standard turbulence model, PDF/The Mixture Fraction combustion model and P-1 radiation model have been used during the predictions. The oxygen concentration in the oxidizer has been reduced to the oxygen concentration of 15% to investigate various types of biogas, different mixture temperature, and diluent composition. The results resulting from conventional conditions show that the predictions have been in good agreement with the existing measured temperature profiles in terms of values and trends. According to the further modellings obtained from distributed combustion conditions, it can be said that more uniform thermal field has been emerged inside the combustor as the oxygen concentration has been reduced. Therefore, it can be concluded that distributed combustion conditions have been achieved. It can also be determined that pollutant emission levels have been decreased to ultra-low levels as the oxygen concentration has been reduced in the oxidizer.

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KEYWORDS
Distributed combustion; biogas; burner; modelling; emissions

Introduction

Energy is the main criteria to maintain life nowadays. All humans and most of systems are needed to one of energy forms. Heating, for instance, is a substantial requirement for human or electricity generation is an inevitable process anymore. As it is known, most of energy required may be procured by conventional resources. Among gaseous fuels, natural gas containing high amount of methane occupies a most important place and it is included high heating value in accordance with the other fossil fuels. In addition, it has fewer issue in terms of environmental problems. It is however estimated that natural gas is also running out of in the near future just as crude oil and coal are consumed away. Because of that, most of scientists try to find out new energy resources such as biomass-derived biogas. Biogas contains more than methane of 55%. Methane is a combustible component in the biogas. Even though biogas is an alternative fuel over natural gas, the flame is appeared in the flame region and there is relative non-uniform thermal field inside the combustor when it is burned. In addition, non-uniform thermal field leads to more emission levels at the combustor outlet. It can be consequently said that distributed combustion provides far uniform

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temperature distributions inside the combustor and reduced emission levels at the combustor outlet (Arghode and Gupta 2010, 2013; Karyeyen 2018; Khalil and Gupta 2011a, 2011b).

It is commonly known that distributed combustion technique is achieved by reducing oxygen concentration in the oxidizer. For this purpose, a diluent is added into the oxidizer. In other words, hot combustion products are recirculated into the oxidizer mixture prior the ignition to take place. This process enables a lower reaction rate, which suggests that more uniform thermal field and reduced emission levels appear inside the combustor and at the combustor outlet. Reaction occurs over the whole inside of the combustor. Therefore, distributed combustion is achieved and provides in mitigating NO_X and CO levels (Khalil and Gupta 2015a).

There are some works related to distributed/flameless combustion in the existing literature. Khalil and Gupta (Khalil and Gupta 2015b) conducted an experimental study regarding the methane flame under high intensity distributed combustion conditions. They revealed that reducing oxygen percentage in the oxidizer is essential in providing more uniform thermal field. Khalil and Gupta have conducted some another studies related to distributed combustion such as determination of the role of CO_2 on oxy-colorless distributed combustion (Khalil and Gupta 2017a), investigation of some combustion characteristics such as acoustic (Khalil and Gupta 2017b), characterization of flame-front interaction (Khalil and Gupta 2016). They also investigated the effects of oxygen concentration, equivalence ratio, mixture temperature, and thermal power on temperature profiles of the methane flame (Khalil and Gupta 2015c) and flame fluctuations for oxy-CO_2-methane mixtures (Khalil and Gupta 2017c). In addition to these studies conducted by Khalil and Gupta, It is also known that there are some works performed under flameless, moderate or intense low oxygen dilution (MILD), or distributed combustion conditions for methane or different fuels (Arghode, Gupta, and Bryden 2012; Cavaliere and de Joannon 2004; Duwig et al. 2012; Goktolga, van Oijen, and de Goey 2017; Hosseini, Bagheri, and Wahid 2014; Khalil et al. 2012; Khidr, Eldrainy, and EL-Kassaby 2017; Lammel et al. 2010; Luhmann et al. 2017; Ozdemir and Peters 2001; Weber, Smart, and Vd Kamp 2005; Wunning and Wunning 1997; Yu et al. 2010; Zornek, Monz, and Aigner 2015).

As it is mentioned above, flameless or distributed combustion method is very common in burning of any fuel as it slow downs the reaction rate and in consequence of this, more uniform thermal field and more reduced emission levels are obtained. Nowadays, this technique is commonly investigated by the scientists. In particular, under distributed or flameless combustion conditions, methane being a major part of natural gas is mostly burned. However, there are few studies on biogas flameless combustion in the literature. In the present study, some types of biogases have numerically been combusted for the existing natural gas burner under the conditions representing lower O_2 concentration. For this purpose, a CFD (computational fluid dynamics) code has been used. Thermal field inside the combustor and emission levels at the combustor outlet have been modeled for biogas combustion under the conditions. Therefore, more uniform thermal field and less emission levels have been achieved by adding the diluent mixture into the oxidizer.

The combustion system

The existing natural gas burner has been used in the present study. The details of the existing natural gas burner are given in Figure 1. Air and fuel streams are coaxially included. The burner involves two types of air inlets, one of which is the annular inlet having diameter of 2 mm. The other type of air inlet is an angular inlet having the swirl generator that has a swirling angle of 15°. The burner also includes a radial fuel inlet.

The details of the combustor used in the present study are shown in Figure 2. The combustor length and the combustor diameter are of 100 cm and 40 cm, respectively. There are five measuring ports positioned on the combustor wall by which temperature levels can be measured in the combustor, and a measuring port located at the combustor outlet by which emission levels can be determined for any fuel.

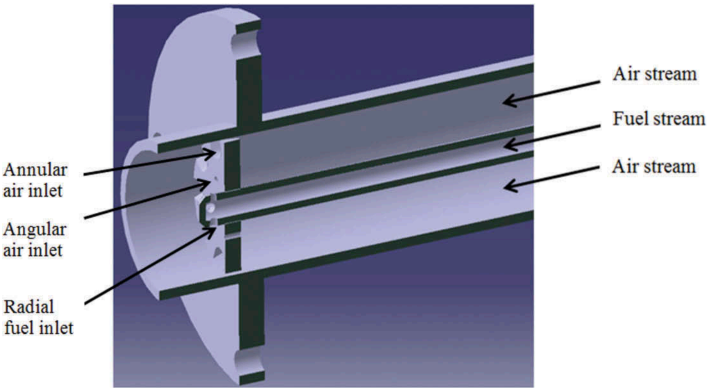

Figure 1. The burner.

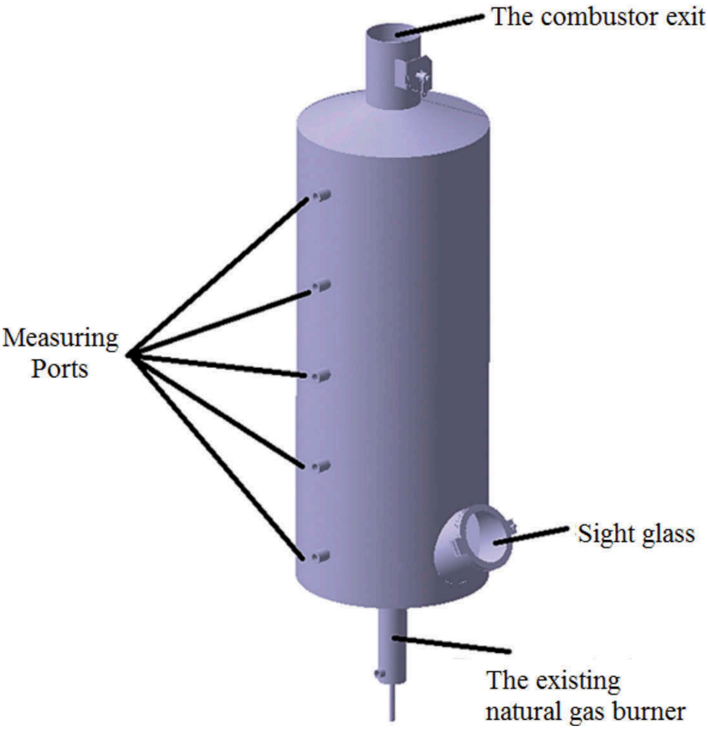

Figure 2. The combustor.

Boundary conditions

The present study aims at investigating thermal field distributions and emission levels of the non-premixed biogas flames. For this reason, a CFD code Ansys Fluent (Fluent Incorporated, Fluent 13.0, User's Guide 2011) has been used to model the combustion phenomena. The operating conditions for the study are given in Table 1. For all cases, thermal power of 10 kW was the same, which means that the fuel flow rates for all cases were the same. But, however, the required oxidizer rate used was reduced to provide the conditions representing the lower oxygen percentage. Nevertheless, amounts of oxygen corresponding to equivalence ratio of 0.83 were kept constant when the diluent mixture

Table 1. Operating conditions.

	Biogas type	Diluent temperature (K)	Oxygen percentage (% by volume)	Diluent mixture composition (% by volume)
Case 1	Biogas 1	300	21	90% N_2 – 10% CO_2
Case 2	Biogas 1	300	18	90% N_2 – 10% CO_2
Case 3	Biogas 1	300	15	90% N_2 – 10% CO_2
Case 4	Biogas 2	300	21	90% N_2 – 10% CO_2
Case 5	Biogas 3	300	21	90% N_2 – 10% CO_2
Case 6	Biogas 1	600	18	90% N_2 – 10% CO_2
Case 7	Biogas 1	600	15	90% N_2 – 10% CO_2
Case 8	Biogas 1	300	18	80% N_2 – 20% CO_2
Case 9	Biogas 1	300	15	80% N_2 – 20% CO_2

Table 2. Types of biogases (by volume).

Biogas Type	CH_4 (%)	CO_2 (%)
Biogas 1	55	45
Biogas 2	60	40
Biogas 3	65	35

was added into the oxidizer. Thus, the oxygen percentage in the oxidizer was reduced based on the amounts of diluent mixture supplied. There are nine cases for the present study. Cases 1–3 are to determine the effect of oxygen concentration in the oxidizer for biogas 1 (Table 2). The effect of methane and carbon dioxide concentrations in the biogas are also investigated via cases 4 and 5. Cases 6 and 7 enable to investigate the effect of diluent mixture temperature due to real hot product gas temperature. Lastly, the effect of diluent mixture composition is tried to exhibit by cases 8 and 9 as hot product gases may be included more carbon dioxide composition when a biogas containing carbon dioxide at considerable level is combusted.

Model validation

When a numerical model is carried out, mesh independency is an important application in order to minimize computational time. Therefore, the best mesh structure should be determined. Mesh independency was performed in the previous study conducted by Ilbas et al. for different mesh structures (Ilbas, Sahin, and Karyeyen 2018). The error percentage between the results predicted and measured was of less then 10%. The maximum and minimum errors were of 9.55% and 1.48%, respectively. Therefore, when the predicted axial temperature distributions are evaluated, with the number of meshes more than 613947, they concluded that there was a slight difference between the predicted axial temperature distributions. Thus, mesh structure with 613947 meshes was selected as the best mesh structure for this study.

It is noted that modelling studies can be validated with the measured data. Validation provides more accurate and reliable prediction results for the present and further predictions. Therefore, this numerical study was compared with the experimental study under similar conditions (Ilbas, Sahin, and Karyeyen 2018). Comparisons of the predicted and the measured profiles are shown in Figures 3 and 4. When it is examined in Figures 3 and 4, it can be concluded that the prediction results are in good agreement with the measurement values. In few measuring points, comparison may be not acceptable. However, especially in combustion modellings, this circumstance is a reasonable result. Therefore, it can be readily concluded that further modellings can be acceptable.

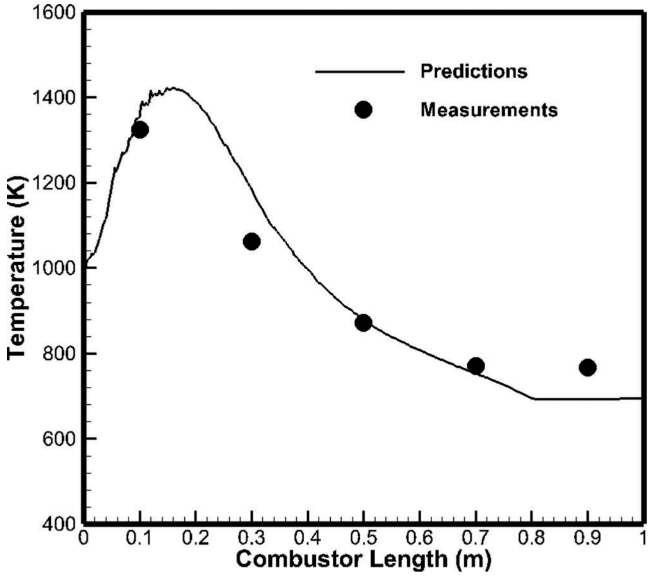

Figure 3. Model validation for the predicted axial temperature profiles.

Results and discussion

The effect of oxygen concentration in the oxidizer on thermal field distributions

In this part of the present study, the effect of oxygen concentration in the oxidizer on thermal field distributions is presented inside the combustor. Figure 5 presents the predicted radial temperature profiles for cases 1, 2 and 3. When thermal fields are examined in detail, the first result that could be concluded is that considerable changes in thermal fields have not been. This circumstance may be explained by the fact that the biogas contains carbon dioxide as a diluent although distributed combustion condition reduces the flame temperature. However, thermal field of biogas 1 has been changed somewhat over the entire of the combustor. Under distributed combustion conditions, it may also be said that more uniform thermal field has been achieved inside the combustor. Moreover, at the exit of the combustor, temperature levels for cases 1, 2 and 3 have been predicted nearly the same. It has consequently been concluded that distributed combustion method enabled more uniform thermal field over the entire of the combustor.

The effect of biogas type on thermal field distributions

The effect of biogas type on the predicted temperature levels has also been investigated and presented in this part of the present study. Different types of biogases being biogas 1, 2, and 3 have been modeled and the predicted radial temperature profiles are given in Figure 6. As can be seen from Figure 6, it has been demonstrated that the maximum flame temperature emerged during biogas 3 combustion. This situation is directly related to components of biogas 3 because biogas 3 contains more amount of methane that is a major species of any biogas.

The effect of diluent mixture temperature on thermal field distributions

As it is mentioned before, distributed combustion means that hot reactive product gases recirculate and reburn in the flame front. In a real combustion process, combustion products have high

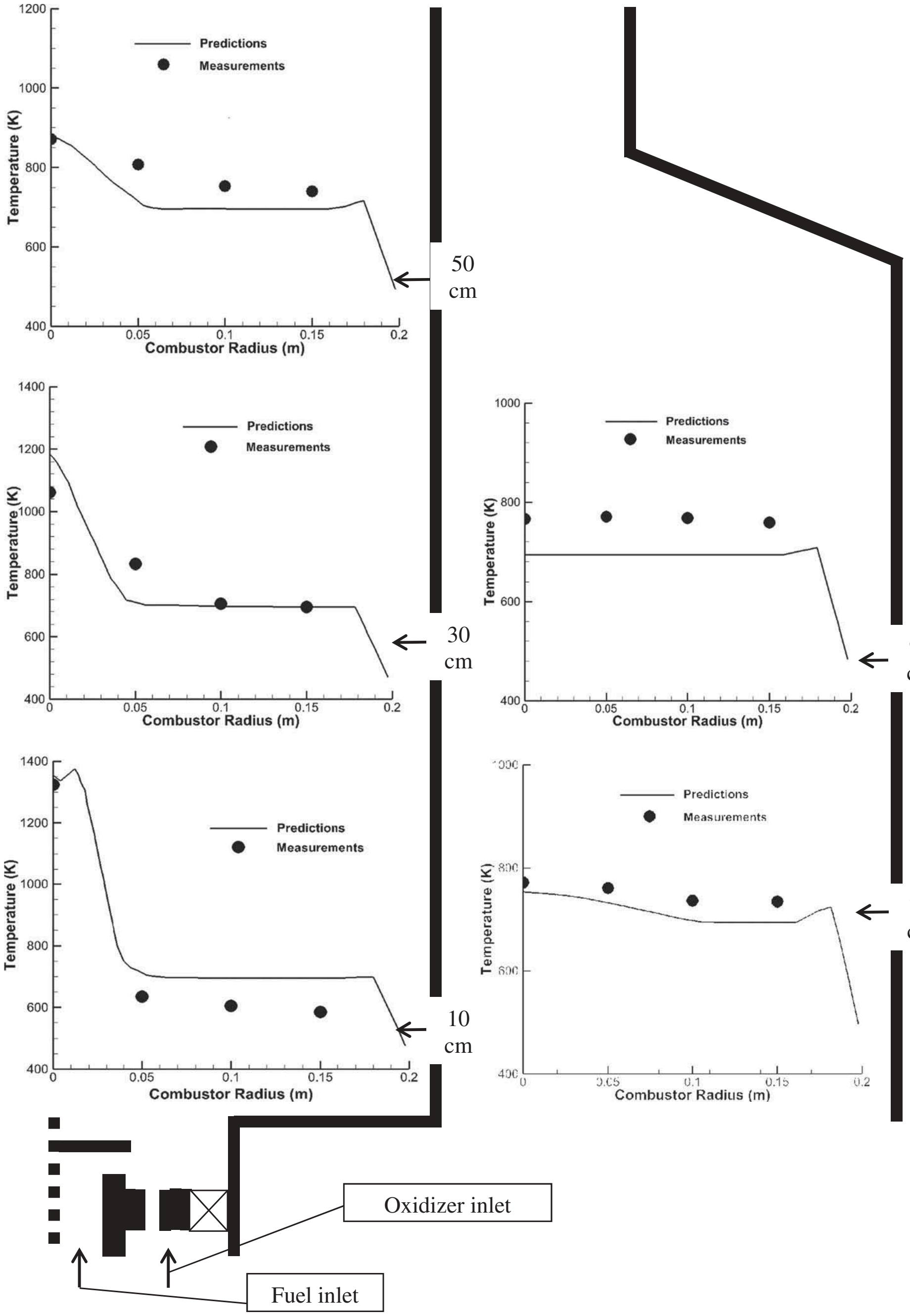

Figure 4. Validation for radial temperature profiles.

temperature generally. Therefore, to consider that combustion products have high temperature levels can be reasonable approach. In the present study, for cases 6 and 7, it has been considered that the temperature levels of the combustion products are of 600 K under distributed combustion conditions and their predicted thermal field profiles are presented in Figure 7 comparatively. It can be said that this conditions have enabled to slow down the reaction rate resulting in more uniform thermal

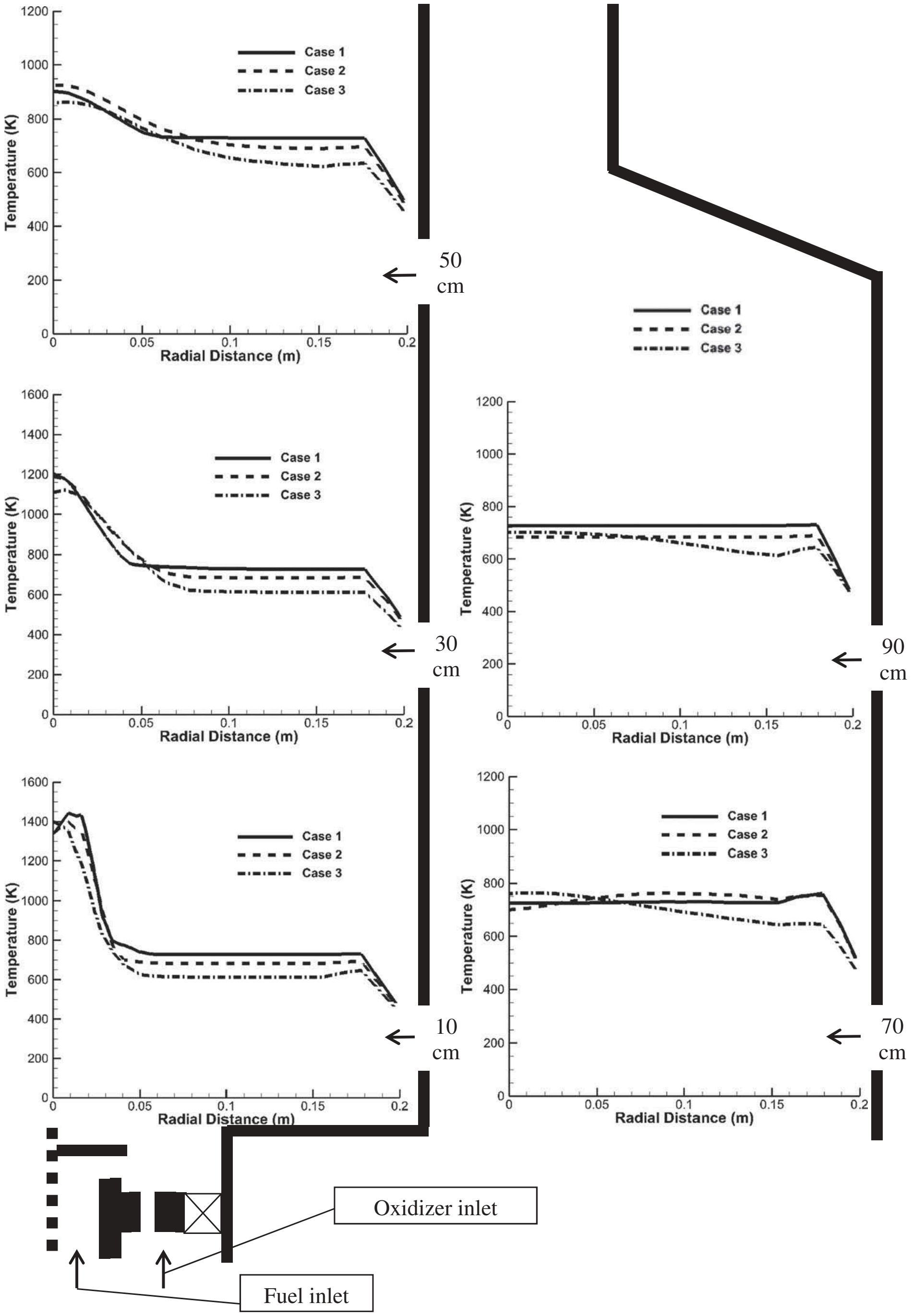

Figure 5. The predicted radial temperature profiles for different oxygen percentages.

field throughout the combustor. In addition, at the exit of the combustor, it can be concluded that the predicted temperature levels of biogas 1 have been higher relatively, which means that HiTAC (high temperature air combustion) (Tsuji et al. 2003) technology can be suitable for any gas turbine application. For cases 6 and 7, it has been determined that the predicted flame temperatures of

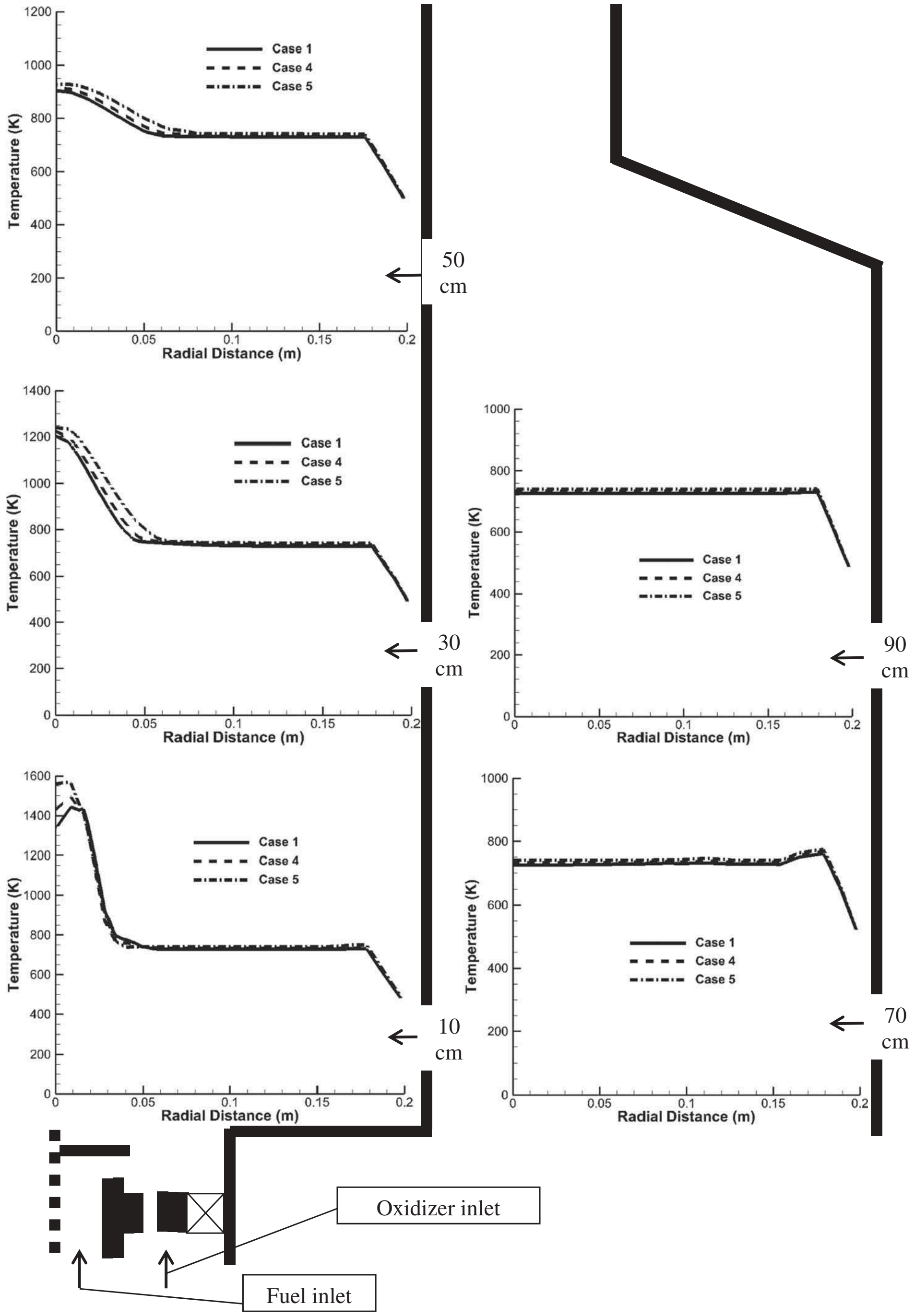

Figure 6. The predicted radial temperature profiles for different biogas types.

biogas 1 have been lower in comparison to that of case 1. This situation may also be explained that distributed combustion leads to slow down the reaction rate of the biogas. There are slight differences between the temperature profiles of all cases from predicted at the center of the combustor and the wall temperatures in Figure 7.

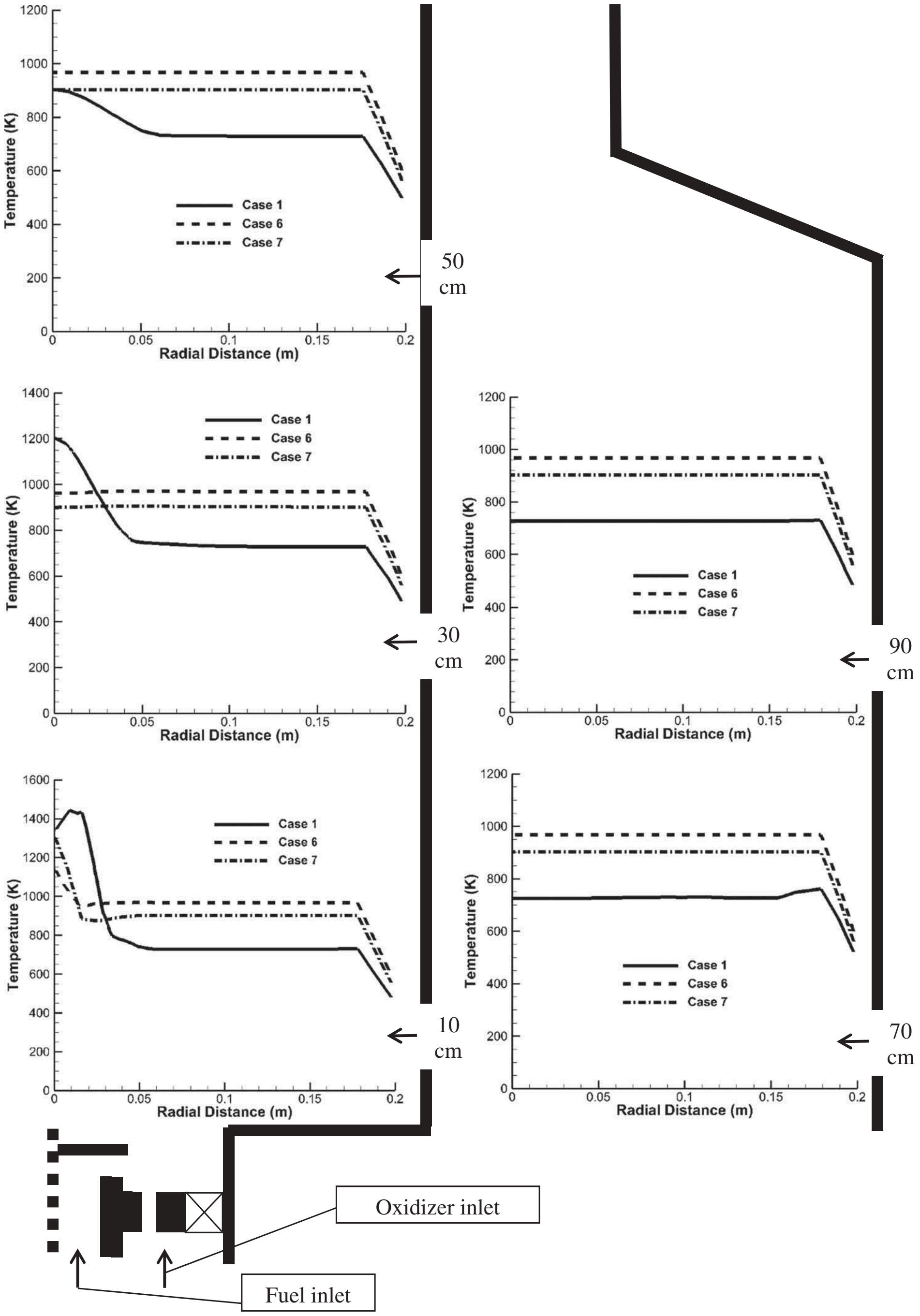

Figure 7. The predicted radial temperature profiles for different diluent mixture temperatures.

The effect of diluent mixture composition on thermal field distributions

The effect of diluent mixture composition on thermal field profiles has been investigated in the present study and is presented in this section. In general, 90% N_2 –10% CO_2 mixture being majority of combustion products can be acceptable for recirculation mixture. This case can be suitable for methane combustion. When it is, however, burned any type of biogas, to consider that combustion products have more amount of carbon dioxide is reasonable as biogas has considerable amount of carbon dioxide. Therefore, content of the combustion products have been considered as 80% N_2 – 20% CO_2 mixture in the present study and their results are presented in Figure 8. According to the

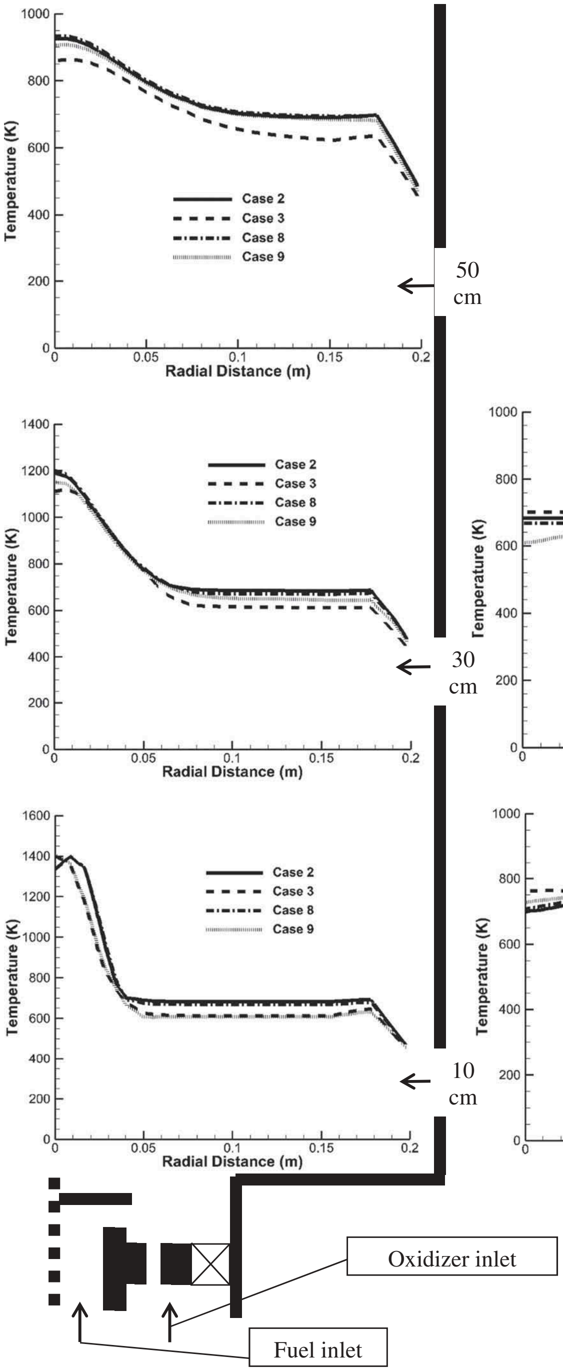

Figure 8. The predicted radial temperature profiles for different diluent mixture compositions.

predicted results, it can be concluded that mixture of 80% N_2 –20% CO_2 has reduced the predicted temperature levels slightly. It is thought that high specific heat of carbon dioxide is the main reason why the predicted results for cases 8 and 9 are low. In other words, it can be said that mixture of 80% N_2 –20% CO_2 has led to further slow down biogas reaction. But yet, it is not wrong to say that there are slight differences between the predicted temperature levels for all cases. Therefore, to consider combustion products of any biogas as a mixture of 80% N_2 –20% CO_2 under distributed combustion conditions is not affected thermal fields significantly.

Uniformity of thermal field

Temperature profiles have been determined for all of cases in the present study. In this section, it is investigated how distributed combustion technique affects thermal uniformity comparatively. The predicted maximum and the outlet temperature levels and their differences are given for all cases in Table 3. For cases 2 and 3, it may be said that the reduction of oxygen percentage meaning distributed combustion has reduced temperature differences slightly. It can, however, be concluded that distributed combustion conditions have highly been affected differences of temperature levels for cases 6 and 7, which means that the biogas has more uniform thermal field inside the combustor.

When the diluent content is changed as a mixture of 80% N_2 –20% CO_2, according to the predicted temperature levels, temperature differences (for cases 8 and 9) have been nearly the same in comparison to those of cases 2 and 3. It has consequently been revealed that changing the diluent content during biogas combustion is slightly affected thermal field of the biogas. When all cases are evaluated, it is said that distributed combustion has highly been achieved by simulating recirculation of hot combustion products.

Pollutant emissions

As it is known, less pollutant levels are essential after any combustion process due to strict environmental limitations. Distributed combustion technique enables reduced emission levels because of lower reaction rate. In particular, to add diluent into the reactive mixture suppress NO_X emission level resulting from thermal NO_X mechanism. Thus, pollutant levels have also been investigated in this study. Table 4 gives some important results about the predicted emission level obtained from the combustor outlet. According to Table 4, it can firstly be said that NO_X and CO emission levels are decreased as the oxygen concentration is reduced in the oxidizer. When cases 6 and 7 are evaluated, it is revealed that the mixture temperature affects NO_X and CO emission levels considerably. For cases 8 and 9, it is concluded that the diluent mixture composition affects the predicted emission levels relatively. When CO_2 emission levels are examined, it is demonstrated that CO_2 level is increased somewhat as the oxygen concentration is reduced.

Table 3. The predicted maximum and the outlet temperatures and differences.

	Diluent temperature (K)	Oxygen percentage (% by volume)	Flame temperature (K)	Flue temperature (K)	Maximum differences
Case 1	300	21	1450	750	700
Case 2	300	18	1400	750	650
Case 3	300	15	1400	750	650
Case 6	600	18	1200	950	250
Case 7	600	15	1300	900	400
Case 8	300	18	1400	700	700
Case 9	300	15	1400	700	700

Table 4. The predicted emission levels obtained from the combustor outlet.

	Oxygen percentage (% by volume)	NO_X (ppm)	CO_2 (%)	CO (ppm)
Case 1	21	7.08	8.12	5.10
Case 2	18	3.22	8.45	3.21
Case 3	15	~0	8.67	1.85
Case 6	18	2.98	7.98	2.27
Case 7	15	~0	8.22	~0
Case 8	18	4.12	8.78	3.11
Case 9	15	~0	9.01	~0

Conclusions

Biogas flame for the existing natural gas burner has been investigated numerically under distributed combustion conditions in this study. Reduction of the oxygen concentration has been provided in order to achieve distributed combustion by simulating of combustion products recirculation. It can be readily said that distributed combustion provides more uniform thermal field inside the combustor. Therefore, it is concluded that biogas can be burned under distributed combustion conditions. In addition of this conclusion, different types of biogases on thermal field have also been investigated and it has been revealed that different types of biogases have not affected thermal field substantially. The mixture temperature has been determined as 600 K to simulate a real combustion process and its effect on thermal field has also been examined within the present study. It is demonstrated that the high mixture temperature leads to reduced emission levels in terms of NO_X and CO. When the oxygen concentration in the oxidizer is decreased, the predicted NO_X and CO levels are nearly zero whereas the predicted CO_2 levels are higher slightly. It can be consequently concluded that distributed combustion method burning biogas fuel can be used in any combustion equipment such as furnace, and gas turbine. In this way, both more uniform thermal field and less emission level can be obtained.

Highlights

- This study investigates combustion characteristics of biogas diffusion flame
- Distributed combustion was achieved by simulating of hot product gas recirculation
- Distributed combustion enabled more uniform thermal field
- Distributed combustion reduced pollutant emissions

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