Research Article

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An experimental study on premixed CNG/H_2/CO_2 mixture flames

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Abstract: In this study, the effect of swirl number, gas composition and CO_2 dilution on combustion and emission behaviour of CNG/H_2/CO_2 gas mixtures was experimentally investigated in a laboratory scale combustor. Irrespective of the gas composition, thermal power of the combustor was kept constant (5 kW). All experiments were conducted at or near stoichiometric and the local atmospheric conditions of the city of Kayseri, Turkey. During experiments, swirl number was varied and the combustion performance of this combustor was analysed by means of centreline temperature distributions. On the other hand, emission behaviour was examined with respect to emitted CO, CO_2 and NO_x levels. Dynamic flame behaviour was also evaluated by analysing instantaneous flame images. Results of this study revealed the great impact of swirl number and gas composition on combustion and emission behaviour of studied flames.

Keywords: Combustion, swirl, gas composition

1 Introduction

In addition to their negative impact on environment, increasing prices of crude oil and natural gas, plus depletion of fossil fuel resources motivated many researchers to investigate alternatives and renewable energy sources, and to improve combustion and emission characteristics of conventional fuels with additives. Most of these researchers used inert components such as steam, N_2or CO_2 as an additive to evaluate impact of these components on fundamental combustion properties [1–5]. Aside from adding inert or active components [6–9], relative effect of gas components on flame behaviour has also been investigated [10, 11]. Some of the related studies existing in literature are summarized in the following paragraphs.

Ilbas and Karyeyen numerically investigated the effect of H_2 addition on combustion behavior of low heating value coal gases and concluded that H_2 addition improves fundamental flame characteristics; but, this situation causes increased NO_x emissions in turn [12]. Park and Kim numerically investigated flame structure and emission characteristics of H_2/CO/CH_4 blending synthetic gases by examining the effect of gas blending and the amount of N_2 dilution. They used GRI 3.0 mechanism for NO_x prediction and validated their results with published experimental data. It was concluded that dominant NO_x formation and destruction mechanisms are: (i) thermal, prompt and reburn routes in non-diluted counterflow non-premixed synthetic gas flames; (ii) an increment in H_2 mole fraction in gas composition increases the peak NO_x amount; (iii) when fuel is diluted with N_2, NO formation rate increases with rising H_2 and CH_4, and decreasing CO amount; (iv) CH_4 decreases positive effect of N_2 dilution on NO decrement [13]. Micro mixing injection combustion is one way of decreasing NO_x emissions of gas turbine combustors. But, it increases temperature levels near burner outlet. Motivated by this, Zhang et al. built an experimental setup to solve this problem with N_2 dilution. Results of their study showed that N_2 dilution decreases temperature levels and protects burner from high thermal loads; as the dilution amount increases, temperature and NO_x emission levels decrease [14]. Lee et al. conducted an experimental study to examine N_2, CO_2 and steam dilution effect on combustion and emission behavior of H_2/CO mixtures by measuring temperature, NO_x and CO levels and observing flame shape, with particular emphasis on flame instabilities. It was concluded that increased heat capacity of the mixture with diluent addition decreases NO_x emissions and an increment in diluent amount increases CO emissions [15]. Ilbas and Yilmaz performed experiments on CH_4/H_2 mixture flames in a natural gas burner. They investigated the effect of gas composition on CO, NO_x and O_2 emissions and temperature distribution throughout the combustor. They reported that compared

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to 100 % H_2 burning, temperature values and NO_x emissions decrease with methane addition; contrarily, temperature values and CO emissions increase with H_2 addition; H_2/CH_4 mixtures emit less CO (compared to natural gas) because of the reduced C/H ratio [16].

Apart from the effect of fuel composition on fundamental flame characteristics, particular interest has been shown to potential effect of this composition on flame stability characteristics. Operating range of premixed and diffusion flames (defined by flashback and blowout limits) have been investigated by many investigators. These researchers have studied how gas components affect flame stability characteristics. Because, different gases have different chemical and transport properties, which will cause flame speed to alter and so will the flame behavior. For example, H_2 and CO generate high-temperature and high-speed flames by allowing them to operate at low equivalence ratios (this reduces emissions). However, such fuels cause flashback, which is a safety hazard. For these reasons, many researchers have investigated flame stability characteristics of gas mixtures [17–21] and some of these researchers have tried to improve flame stability limits via introducing swirl into the flow [22–25].

In this study the effect of gas composition, swirl number and inert dilution on combustion and emission behavior of CNG/H_2/CO_2 mixtures was experimentally investigated in a combustion system.

2 Experimental Setup

2.1 Burner

During burner design, characteristics of the fuels to be used and operating conditions of the burner must be considered. In Figure 1, solid model of the manufactured burner can be seen. This is a premixed burner and it can operate at thermal powers up to 10 kW. Burner outlet houses swirl vane and can be easily dismantled to change swirl wane.

Swirling flows are used in most combustion devices because of their positive impact on fundamental flame characteristics [26]. Swirling flows are characterized by swirl number which is the ratio of the axial flux of the tangential momentum (G_φ) to the axial flux of the axial momentum (G_x).

$$Swirl\ Number = \frac{G_\varphi}{G_x R}$$

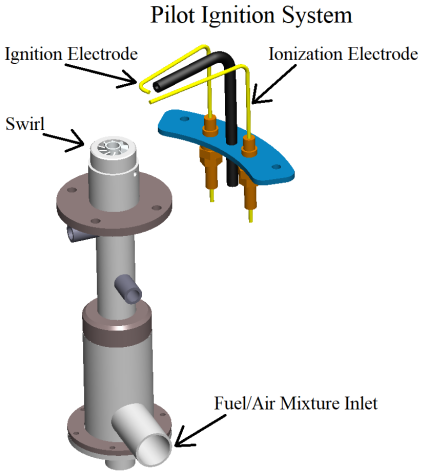

Figure 1: Solid model of the burner.

$$G_\varphi = \int_0^R (Wr)\,\rho U 2\pi r dr$$

$$G_X = \int_0^R U\rho U 2\pi r dr$$

In these equations; U and W are the axial and tangential velocity components, R is the radius of the cross section plane, r is the radial coordinate [27].

For practical calculations, approximate swirl number can be expressed as

$$Swirl\ Number = \frac{2}{3} \cdot \left[\frac{1-\left(\frac{d_h}{d_o}\right)^3}{1-\left(\frac{d_h}{d_o}\right)^2}\right] .tan(\theta)$$

d_h, swirler hub diameter; d_o, swirler outer diameter; θ, swirl vane angle [28].

2.2 Gas Supply Lines

Each gas is supplied to burner from a pressurized (200–300 bar) gas tank and pressure of the gas is reduced via a pressure regulator. The amount of individual gas is metered by a digital mass flow controller. Desired mass flow rate is set through a vacuum system controller. This combustion system was designed to operate at 20 mbar gauge pressure. So, pressure regulators and manometers

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are mounted to each gas supply line to regulate pressure and to monitor pressure value, respectively. For security reasons (in the case of flashback occurrence), electrically controlled solenoid valves are assembled to each gas line to cut gas flow. All equipment is in the same order for each gas supply line. Combustion air is supplied from an air compressor and air supply line consists of a mass flow controller, a manometer and a valve. All gases are mixed in a gas collector prior to air fuel pre-mixer; then, fuel/air mixture is inclined to the burner.

2.3 Combustor

In Figure 2, fabricated combustor is illustrated. It has 1650 mm length, 330 mm outer diameter and is made of stainless steel. On combustor wall, there are numerous ports for axial and radial temperature and emission measurements. To make flame optically accessible, demountable tempered glasses are placed at two sides of the combustor.

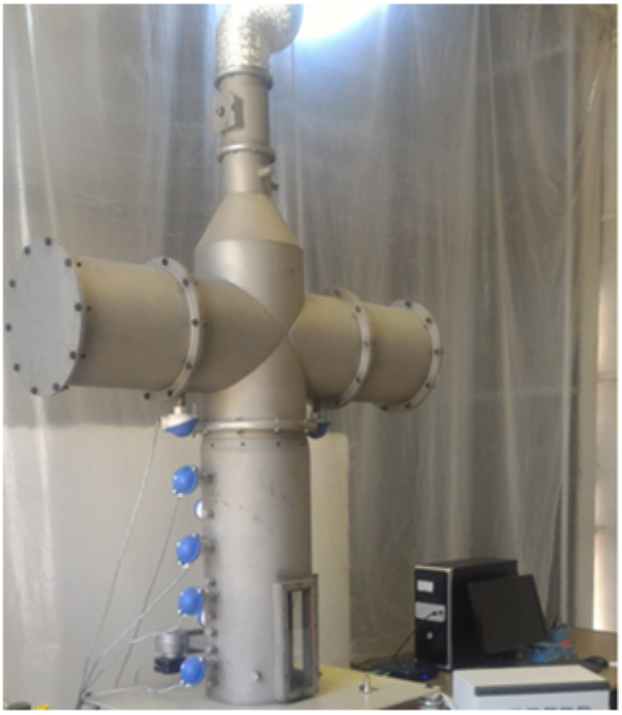

Figure 2: Combustor.

Temperature and emission measurements are performed with K and B type thermocouples and a flue gas analyser, respectively. Thermocouple (2,4,6,8,9,10) and emission (4,7,9) measurements points are illustrated in Figure 3. Data obtained from these thermocouples are stored in a computer via a data logger.

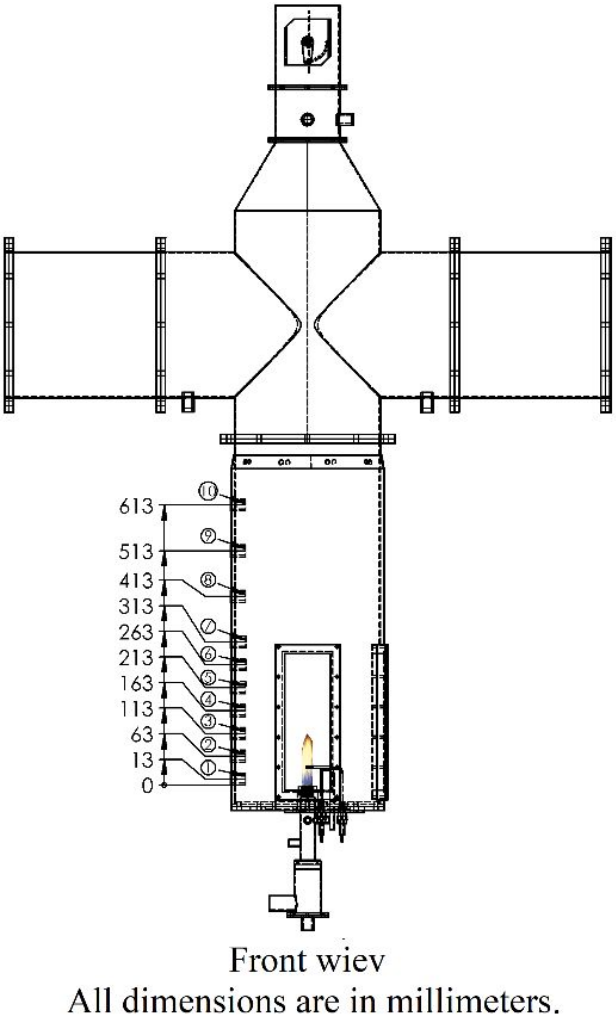

Figure 3: Thermocouple and emission measurements points.

2.4 Operating Conditions

Tested gas compositions, composition and properties of CNG are tabulated in Table 1, 2 and 3 respectively. Irrespective of the gas composition, thermal power was kept constant and mass flow rate of each mixture was specified based on thermal power. Equivalence ratio was set as 0.9 and 1.0 while swirl number was set as 0.4, 0.6 and 0.8. All experiments were carried out at room temperature and 20 mbar.

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Table 1: Gas Compositions.

Gas Compositions	CNG (%)	H_2 (%)	CO_2 (%)
1	100	-	-
2	90	10	-
3	80	20	-
4	90	-	10
5	80	-	20
6	80	10	10
7	70	20	10
8	70	10	20
9	60	20	20
10	60	30	10
11	60	10	30

Table 2: Components of CNG.

Component	Molar (%)
Methane (CH_4)	91.18
Ethane (C_2H_6)	3.02
Propane (C_3H_8)	1.45
Butane (C_4H_{10})	0.59
Pentane (C_5H_{12})	0.09
Hexane (C_6H_{14})	0.07
Nitrogen (N_2)	2.98
Carbon Dioxide (CO_2)	0.62

Table 3: Properties of CNG.

Density (kg/m^3)	0.748
Low Heating Value (Mj/kg)	46.67
Low Heating Value (Mj/m^3)	34.91

3 Uncertainty in Experimental Data

During experiments, temperature measurements were performed with thermocouples. Data obtained from thermocouples was transferred and stored in a computer via a data logger which has 100 kS/s sampling rate. Measured values were also corrected taking radiation losses into consideration, and found to be 20–100 K lower than real state.

Emission measurements were conducted with a portable flue gas analyzer. Typical accuracy of the analyzer is: for O_2, ± 0.2%; for CO in the range of 0–4000 ppm, ± 5% (or ±10 ppm, whichever is higher), for CO > 4000 ppm, ± 10%; for NO in the range of 0-1000 ppm, 5% (or ±5 ppm, whichever is higher), for NO >1000 ppm 10%; for NO_2 in the range of 0–200 ppm, 5% (or ±5 ppm, whichever is higher), for NO_2 >200 ppm 10%; for SO_2 in the range of 0–2000 ppm, 5% (or ±10 ppm, whichever is higher), for SO_2>2000 ppm 10%; and for CO_2 ± 0.3%.

Besides these measurements mentioned above, the amount of each gas in gas mixture was measured with a digital mass flow controller. The accuracy of mass flow controllers was: for gas supply lines, ± 1% of set point for 20 to 100% of full scale, ± 0.2% of set point for 0 to 20% of full scale; for air supply line, ± 1% of full scale.

4 Results and discussion

Different transport and chemical properties of each component of gas mixtures bring many challenges to their usage in practical systems from combustion and emission behavior and flame stability point of view [29]. This study aims to evaluate the relative effect of each gas component on key combustion properties.

In Figure 4, axial temperature distributions of 100% CNG, 90% CNG - 10% H_2 and 80% CNG - 20% H_2 mixtures at 0.4 swirl number and 1.0 equivalence ratio can be seen. Temperature distribution profiles of tested gas mixtures show an agreement in terms of trend and value. Peak temperature values were reached in the flame region and then temperature levels decreased towards the outlet of the combustor. 80%CNG - 20%H_2 mixture formed the highest temperature value. Temperature distributions of 100%CNG and 80%CNG - 20%H_2 mixture were nearly the same near burner outlet. On the other hand, temperature profiles of 90%CNG - 10% H_2 and 80%CNG - 20%H_2 mixtures got closer towards the combustor outlet. Compared to 100%CNG and 80%CNG - 20%H_2 mixture, 90%CNG - 10%H_2 mixture formed the lowest temperature value in the flame region; but, temperature distribution throughout the combustor of 90%CNG - 10%H_2 mixture got a higher value. As the H_2 amount in gas mixture increased, heating value of the gas mixture and heat transfer rate increased. With this and the fact that thermal power of the combustor was kept constant may have caused temperature distribution to be higher. 100% CNG formed the lowest temperature distribution.

To evaluate the effect of inert dilution on combustion and emission behaviour, CNG and mixture of CNG/H_2 was diluted with varying amounts of CO_2 and these mixtures were tested under the same boundary and physical conditions. In Figure 5, axial temperature distributions of 90% CNG - 10% CO_2 and 90% CNG - 20% CO_2 mixtures are illustrated. Combustible mixtures will only burn when concentration of fuel and air are in an experimentally determined range. Upper and lower value of this range is referred as

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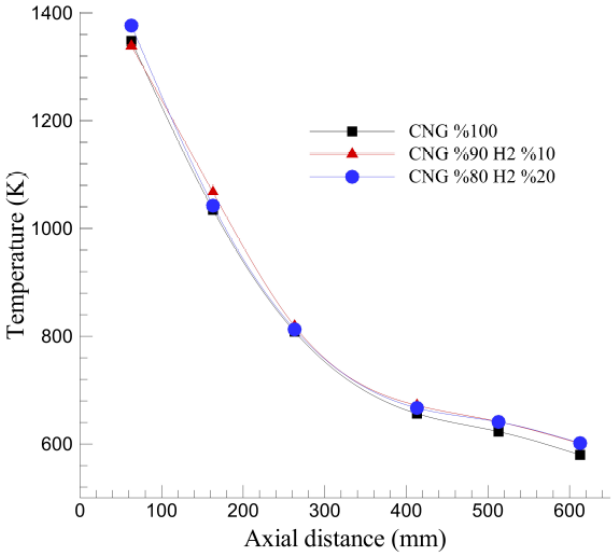

Figure 4: Axial temperature distributions (Swirl number: 0.4, Equivalence ratio: 1.0).

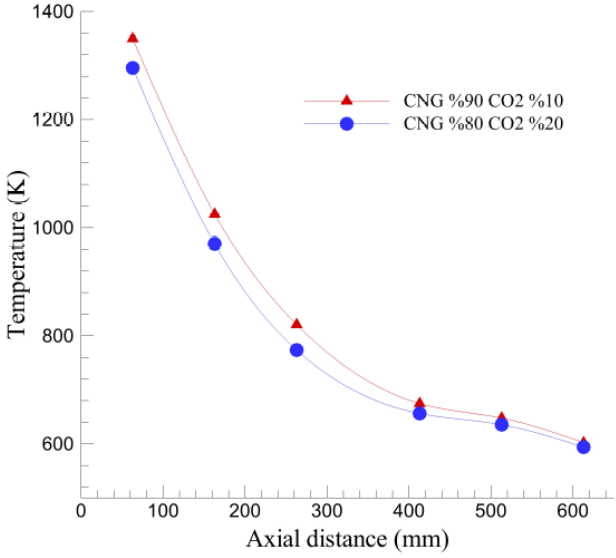

Figure 5: Axial temperature distributions (Swirl number: 0.4, Equivalence ratio: 0.9).

flammability limits [30]. Considering upper flammability limit, we could not attain a stable flame at stoichiometric conditions and thus equivalence ratio was set as 0.9. Temperature profiles of respective mixtures show a similar behavior. Compared to 100% CNG burning, maximum temperature value in the flame region was nearly the same for the 90% CNG - 10% CO_2 mixture. In the case of 20% CO_2 dilution, maximum temperature value decreased by a value of 100 K. Unlike N_2, CO_2 is an infrared active molecule and is reported to cause extra heat loss to environment [31]. Temperature decrement with CO_2 addition is attributed to this phenomenon.

Temperature profiles of the gas mixtures that contain varying amounts of CNG, H_2 and CO_2 are demonstrated in Figure 6. Due to the high reactivity of H_2, first H_2 was consumed in the flame region, then other combustible constituents of CNG were consumed. Therefore, H_2 amount in the gas mixture positively correlated temperature value in the flame region. Axial temperature distributions of 80% CNG - 10% H_2 - 10% CO_2 and 70% CNG - 20% H_2 - 10% CO_2 mixtures are nearly the same throughout the combustor. 70% CNG - 10% H_2 - 20% CO_2 had the lowest temperature value in the flame region; but, it formed the highest temperature distribution towards the outlet of the combustor. This is because of reduced burning rate of such mixture. An increment in CO_2 amount decreased burning rate and combustion process was completed further downstream.

60% CNG - 20% H_2 - 20% CO_2 mixture formed the highest temperature distribution (except for the flame region) in all gas mixtures tested (Figure 7). Besides, it was observed that 60 % CNG – 20 H_2 – 20 % CO_2 mixture burns more intensively and shows less axial and radial fluctuations than 60 % CNG – 10 H_2 – 30 % CO_2 and 60 % CNG – 30 H_2 – 10 % CO_2 mixture flames. Hence, to evaluate the effect of swirl number on temperature distribution, 60% CNG - 20% H_2 - 20% CO_2 mixture was used.

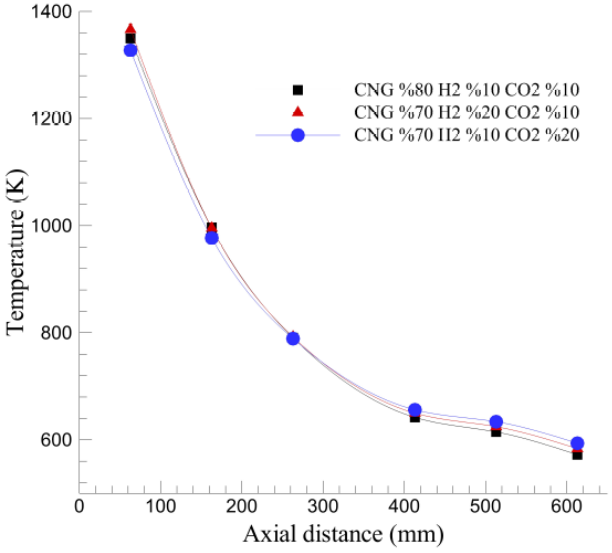

Figure 6: Axial temperature distributions (Swirl number: 0.4, Equivalence ratio: 0.9).

In Figure 8, axial temperature distributions of 60% CNG - 20% H_2 - 20% CO_2 mixture at 0.4, 0.6 and 0.8 swirl numbers can be seen. Temperature profiles showed a good

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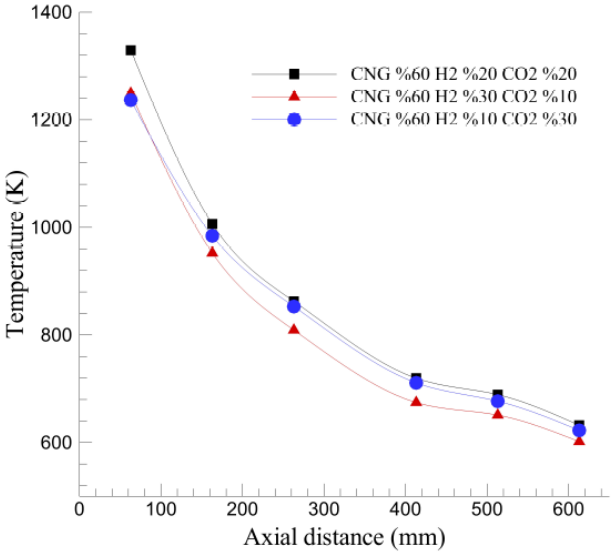

Figure 7: Axial temperature distributions (Swirl number: 0.4, Equivalence ratio: 0.9).

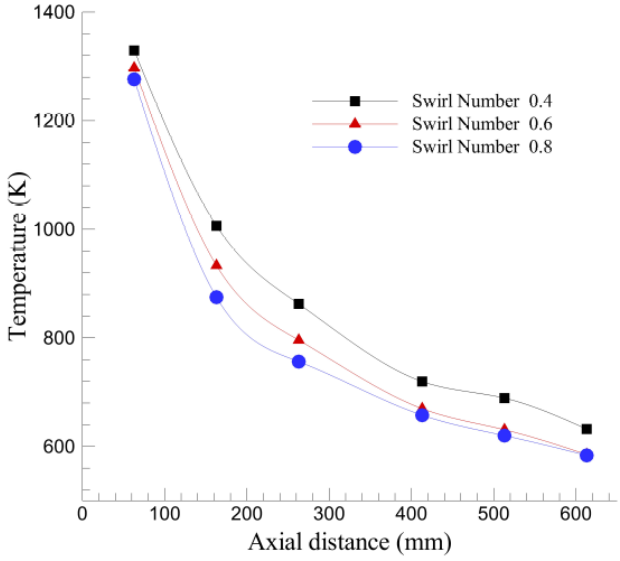

Figure 8: Axial temperature distributions of 60% CNG - 20% H_2 - 20% CO_2 mixture (Swirl numbers: 0.4, 0.6 and 0.8).

agreement in terms of trend for all swirl numbers tested but, they differed by in terms of values. Compared to 0.4 swirl number, temperature profiles were very close at 0.6 and 0.8 swirl numbers. As the swirl number increased, temperature values throughout the combustor reduced. At high swirl numbers; mixing condition of fuel/air mixture improves and heat better diffuses radially . Thus, axial temperature values were reduced.

From instantaneous flame images at different swirl numbers (Figure 9), it can be seen that, as the swirl number increases; reaction zone propagates radially outward (wider flame), burning intensity increases and flame length reduces.



(a) 0.4 **(b)** 0.6 **(c)** 0.8

Figure 9: Flame images at different swirl numbers

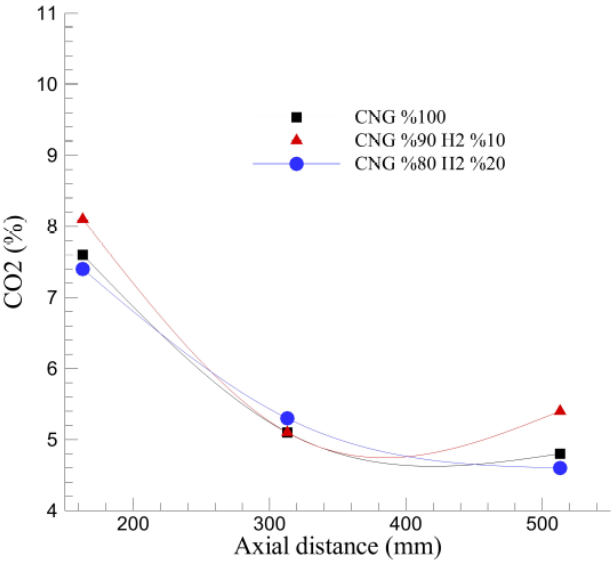

Figure 10: Axial CO_2 concentration profiles (Swirl number: 0.4, Equivalence ratio: 0.9).

Axial CO_2 concentration (in percentage of exhaust gases) profiles of 100% CNG, 90% CNG - 10% H_2, 80% CNG - 20% H_2, 90% CNG - 10% CO_2 and 90% CNG - 10% CO_2 mixtures are illustrated in Figures 10–11. As expected, CO_2 amounts in exhaust gases were very high in the flame region but it reduced towards the outlet of the combustor. As H_2 amount in the gas mixture increased, CO_2 concentration reduced.

CO_2 concentration in the flame region decreased with increasing amount of CO_2 in the gas mixture because of the inhibiting effect of CO_2. However, CO_2 concentration increased towards the outlet of the combustor in the case of 20% CO_2 dilution. This indicates that fuel is consumed further downstream.

Based on the temperature decrement in axial direction, CO_2 concentration values decreased in the same direction with increasing swirl number (Figure 12).

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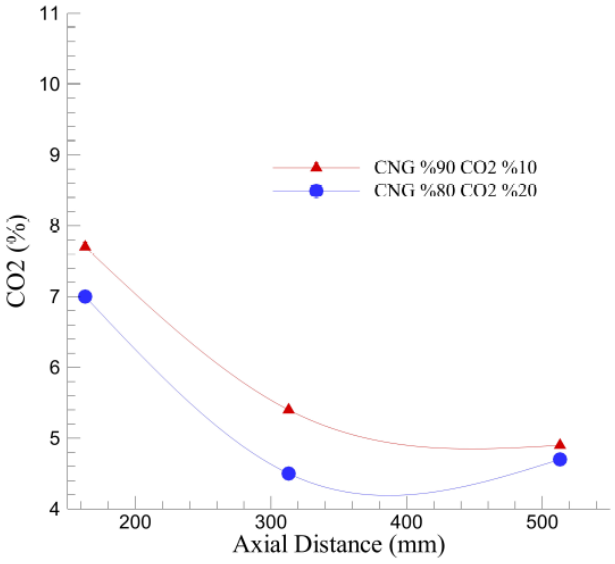

Figure 11: Axial CO_2 concentration profiles (Swirl number: 0.4, Equivalence ratio: 0.9).

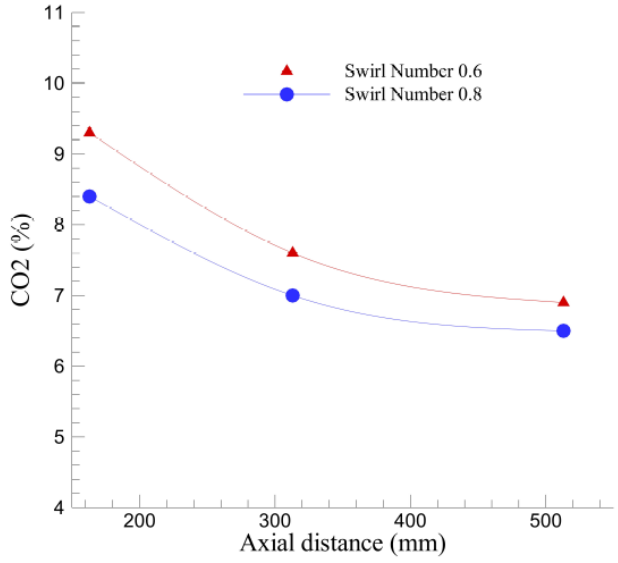

Figure 12: Axial CO_2 concentration profiles (Swirl number: 0.6, 0.8).

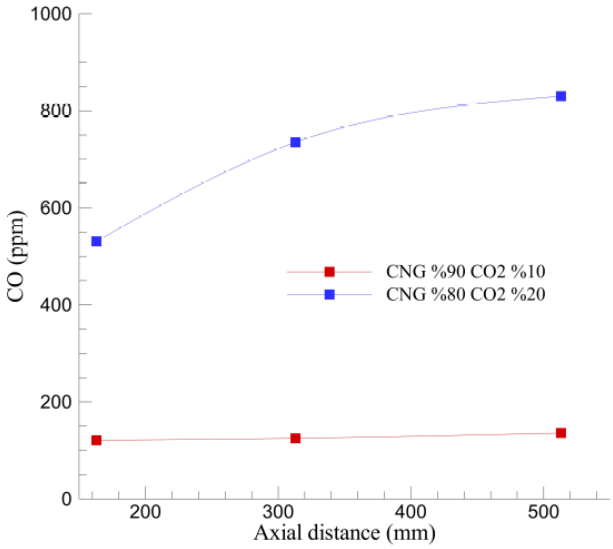

Figure 13: Axial CO emission profiles (Swirl number: 0.4, Equivalence ratio: 0.9).

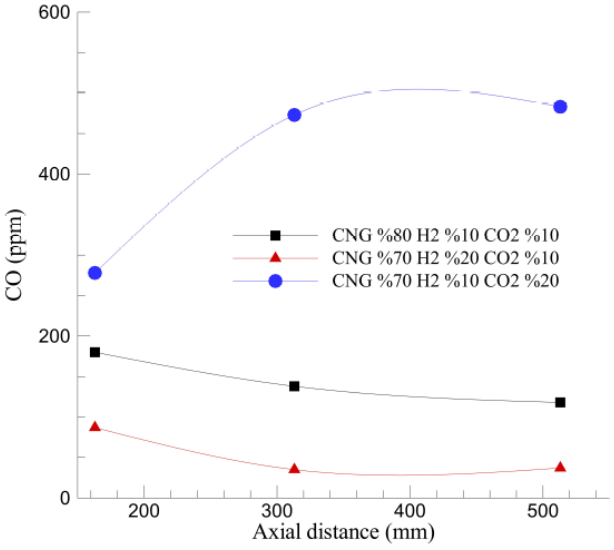

Figure 14: Axial CO emission profiles (Swirl number: 0.4, Equivalence ratio: 0.9).

Because CO is an incomplete combustion product, emissions of CO are directly proportional to CO_2 amount. CO_2 presence in a fuel mixture increases heat capacity of the mixture and reduces reaction rate. An increase in CO_2 amount inhibits oxidation of fuel molecules through reducing usability of oxygen for H and leads to increased emissions of unburnt CO [29]. In Figure 13, it can clearly be seen that as the CO_2 amount in gas mixture increases, CO emissions increases.

Effect of H_2 on CO emissions is positive in terms of environmental effects. As the hydrogen amount increases, CO emissions reduce due to the high reaction kinetics of H_2 (Figure 14).

Axial NO_xprofiles of 100% CNG, 90% CNG - 10% H_2, 80% CNG - 20% H_2, 90% CNG - 10% CO_2 and 90% CNG - 10% CO_2 mixtures can be seen in Figure 15 and 16. As the H_2 amount (also swirl number-Figure 17) increases and CO_2 amount decreases, NO_x emissions increase based on the temperature increment.

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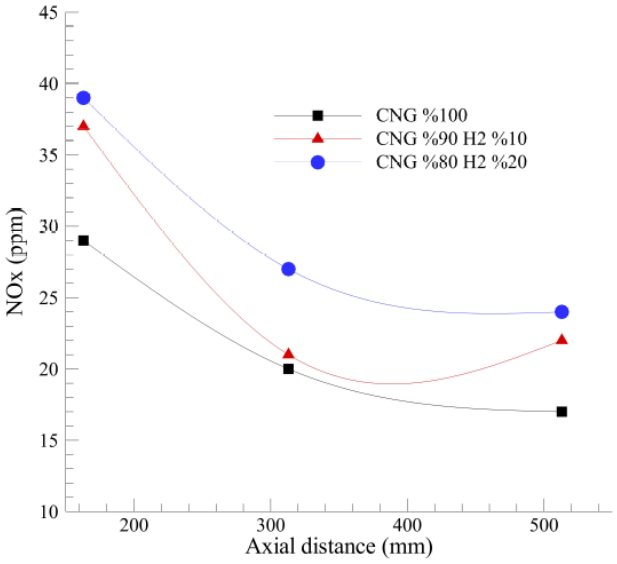

Figure 15: Axial NO_x profiles (Swirl number: 0.4, Equivalence ratio: 0.9).

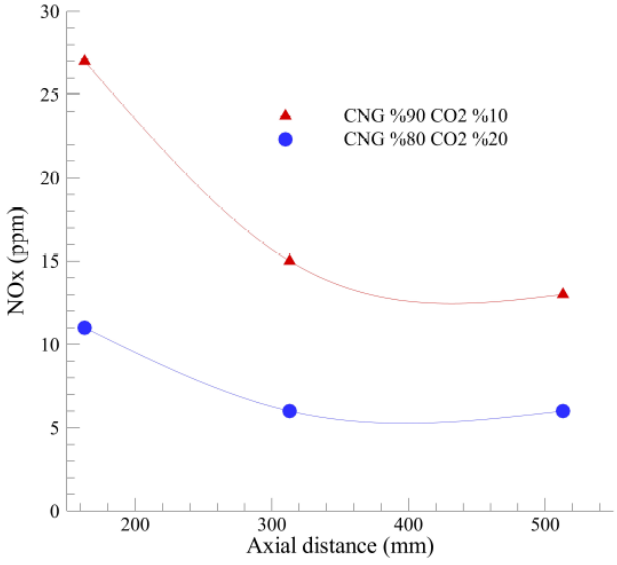

Figure 16: Axial NO_x profiles (Swirl number: 0.4, Equivalence ratio: 0.9).

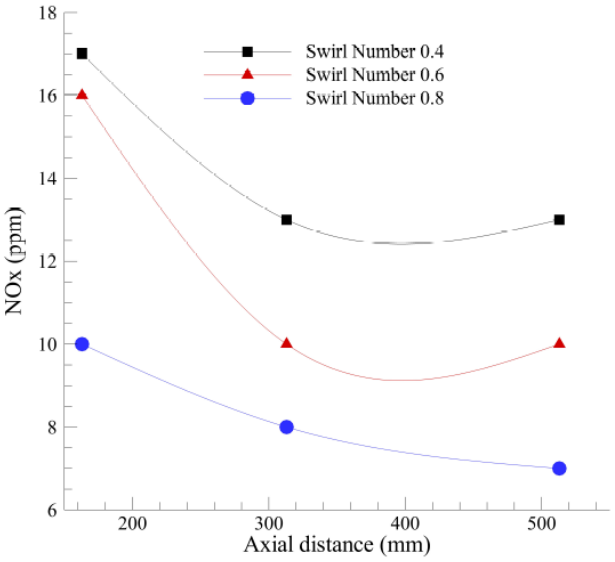

Figure 17: Axial NO_x profiles (Swirl number: 0.6, 0.8).

5 Conclusions

In this study, the effect of gas composition and swirl number on combustion and emission behavior of premixed CNG/H_2/CO_2 mixtures was experimentally investigated in laboratory scale combustor. Results obtained from this study are:

- Irrespective of the gas mixture, temperature profiles of tested flames show an agreement in terms of trend. Gas composition is found to be decisive for temperature value.
- Due to the enhanced heat transfer characteristics in radial direction, axial temperature values decrease as the swirl number increases.
- Depending on the degree of completion of reaction, CO_2 emissions are high in the flame region. Axial CO_2 concentration reduces with increasing swirl number and H_2 and CO_2 amounts in the gas mixture.
- Emissions of CO is highly susceptible to gas composition.
- Thermal Zeldovich mechanism is the dominant NO_x formation mechanism for the tested gas mixtures.

Nomenclature

G_φ	Axial flux of the tangential momentum
G_x	Axial flux of the axial momentum
U	Axial velocity component
W	Tangential velocity component
R	Radius of the cross section plane
r	Radial coordinate
d_h	Swirler hub diameter
d_o	Swirler outer diameter
θ	Swirl vane angle

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