Measurement of Gas Emissions and Flame Temperature on Hydrogen Addition to the Boiler Burner

Hydrogen has the ability to reduce the amount of fossil fuels used in industry and help countries in achieving their net-zero emission goals. In this present study, hydrogen is used as a fuel in an industrial-grade natural gas boiler burner. The overall energy input of the fuel stream was kept at 9000 kcal/sm^3 over a range of hydrogen concentrations up to 50 vol %. Measurements of the flame temperature and pollutant emissions were employed to verify the findings. This scenario will lead to the enrichment of hydrogen as a fuel in domestic boiler applications. The results showed that with the increase in hydrogen concentration, the carbon emission CO reduces monotonically, but the NO emission increases. The increase in NO can be attributed to the increase in thermal NO_x as flame temperature rises with H_2 concentration. Additionally, with an increase in H_2 concentration 50 vol %, the CO_2 concentration in flue gas reduces significantly.

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One of the major challenges faced by the energy-intensive sector is lowering its carbon emissions to meet international regulations. Therefore, the imperative to mitigate greenhouse gas emissions has propelled a global shift towards the adoption of clean and sustainable energy sources. Hydrogen can be a promising energy vector, enabling countries and industries to meet their net-zero emission targets. The demand for hydrogen by 2050 would rise to 660 million metric tons (MT), accounting for 22 % of the world's energy consumption and preventing the release of 7 gigatons (GT) of CO_2 annually [1]. Therefore, hydrogen blending in existing infrastructure has emerged as an important part of a sustainable future [2].

However, the introduction of hydrogen into conventional fossil fuels presents difficulties since it alters the fuel blend's fundamental combustion characteristics. The fuel blend may therefore make it more difficult to comply with the safety and pollution regulations, which would prevent hydrogen from being seamlessly integrated as a fuel into the current fossil fuel energy systems. The addition or premixing of hydrogen on the commercial burner poses a greater risk of flashback as the flame velocity of hydrogen is higher relative to that of natural gas [3, 4].

El-Ghafour et al. [7] investigated the combustion characteristics of a natural gas-hydrogen fuel mixture. The study revealed that with an increase in hydrogen concentration, the flame temperature also increases. However, it was noted that the addition of hydrogen proved to be an ineffective strategy for reducing pollutant emissions. Wu et al. [5] studied the hydrogen addition effect on methane laminar diffusion flame. The addition of hydrogen resulted in an increase in flame temperature, a decrease in flame length, and a reduction in carbon emissions. However, there is an increase in NO emissions attributed to the rise in both prompt and thermal NO_x. In these studies, the extent to which hydrogen can be mixed with natural gas without altering the burner's performance or posing safety concerns was not evident. Zhao et al. [9] studied the hydrogen addition effect on the natural gas pipeline burner. According to the result, it was found that by adding 15 vol% hydrogen, the performance of the cooktop burner was not affected significantly.

Therefore, it can be concluded from the prior studies that in order for end users to utilize the hydrogen addition in natural gas-fired boilers, there are a number of technological challenges that need to be addressed. These challenges, as indicated by current literature, are not extensively studied [6] .

In the present study, rather than premixing an industrial grade, a turbulent diffusion burner is utilized to investigate the flame characteristics of hydrogen addition to the natural gas mixture. The hydrogen concentration was varied up to 50 vol %. To investigate the hydrogen addition effect, flame temperature, flue gas temperature, and gas emissions (CO, NO, CO_2) measurements were carried out.

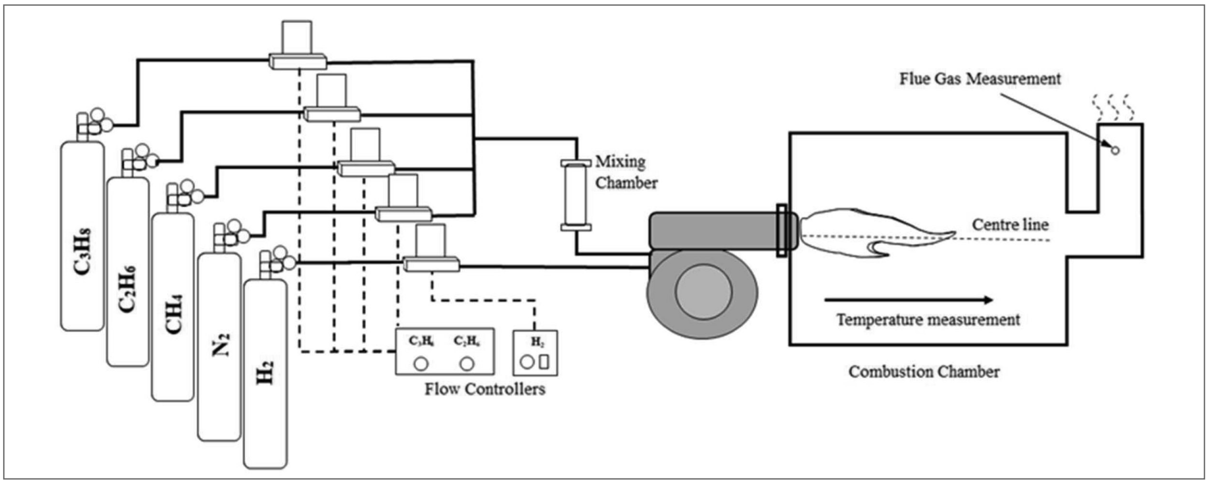

Figure 1. Experimental setup

Experimental Setup

The layout of the experimental setup used in this study is schematically shown in **Fig. 1**. The major components of the experimental setups are gas supply bottles, flow controllers, an industrial burner, and a combustion chamber. The combustion chamber is constructed of steel sheet and fabricated of a rectangular cuboid (800 mm × 820 mm and 800 mm in height). This chamber is designed with two glass windows to facilitate photography and temperature measurement. In addition, a 6-inch flue gas exhaust duct is utilized, and it is positioned in the middle of the opposite end of the chamber.

The fuel supply system includes separate hydrogen and natural gas feeding lines, mixing chambers, and a manifold that connects to the burner. Within the mixing chamber, a blend of natural gas (comprising 85 % CH_4, 8 % C_2H_6, and 7 % C_3H_8) is prepared and then fed to the burner. Throughout this investigation, the hydrogen concentration injected into the burner ranged from 0 to 50 vol %. The fuel flowrates are controlled and precisely measured by mass flow meters. The heat input of the gas mixture is maintained at 9000 kcal/ sm^3. The flame temperature was measured axially using sets of 3 K-type thermocouples positioned along the horizontal axis of the flame. These thermocouples were vertically placed at a distance of 4 cm from each other. The gas emissions were measured using a flue gas analyzer positioned at the flue gas exhaust duct. The experiments were carried out at atmospheric pressure and temperature. The test conditions are summarized in **table 1**.

Table 1. Operating conditions of the experiments

Hydrogen (vol %)	Q_{H2} (l/min)	Q_{CH4} (l/min)	Q_{C2H6} (l/min)	Q_{C3H8} (l/min)	Q_{N2} (l/min)
Baseline 0	0.00	36.16	3.40	2.98	7.37
5	0.80	35.58	3.35	2.93	7.25
10	1.60	34.99	3.29	2.88	7.13
20	3.21	33.83	3.18	2.79	6.90
25	7.67	30.60	2.88	2.52	6.24
30	9.16	29.52	2.78	2.43	6.02
40	16.93	23.90	2.25	1.97	4.87
50	21.05	20.91	1.97	1.72	4.26

Results and Discussion

The measurement of the flame temperature was carried out for different hydrogen concentrations up to 50 vol %, as depicted in **Fig. 2**. The flame temperature profile was recorded at different axial positions up to 30 cm. The radial flame temperature profile was measured both above and below 4 cm of the centreline. The distribution of flame temperature is classified into three distinctive regions: near burner, mid flame, and far burner [7, 8]. **Fig. 2** clearly shows that the flame temperature rises with increasing hydrogen concentration. A greater hydrogen content of 50 vol % results in a considerable peak flame temperature of 1427K in the flame centreline axis, as shown in **Fig. 2(c)**. **Fig. 2** also depicts that with an increase in hydrogen concentration above 30 vol %, the flame peak temperature shifts towards the near burner region and goes through fluctuations. This result can be attributed to the dominance of gas-phase reactions in this specific region. Furthermore, the introduction of H_2 into the natural gas stream increases the molecular diffusivity of the fuel combination since H_2 has a higher molecular diffusivity than natural gas. As a result, the flame length decreases with a higher hydrogen concentration > 30 vol%. This trend aligns with findings reported in various literature sources [5, 7, 8].

Moreover, in **Fig. 2(a)** and **(b)** above and below the centreline, a disparity in flame temperature distributions can be seen. In both cases, the peak flame temperature area can be seen in the far burner region. Additionally, for the region above the centreline, the flame temperature is higher compared to the lower centreline region. The disparity is explained by the flame's being primarily affected by buoyancy in the far-burner zone [7]. This phenomenon is observed for hydrogen concentrations up to 20 vol %, in which the natural gas mixture primarily influences the flame and the flame soot length elongates.

Following the injection of hydrogen, the measured flue gas properties (CO, NO, and NO_x) in natural gas burners are adjusted to conform to industry standards. It is evident to take into

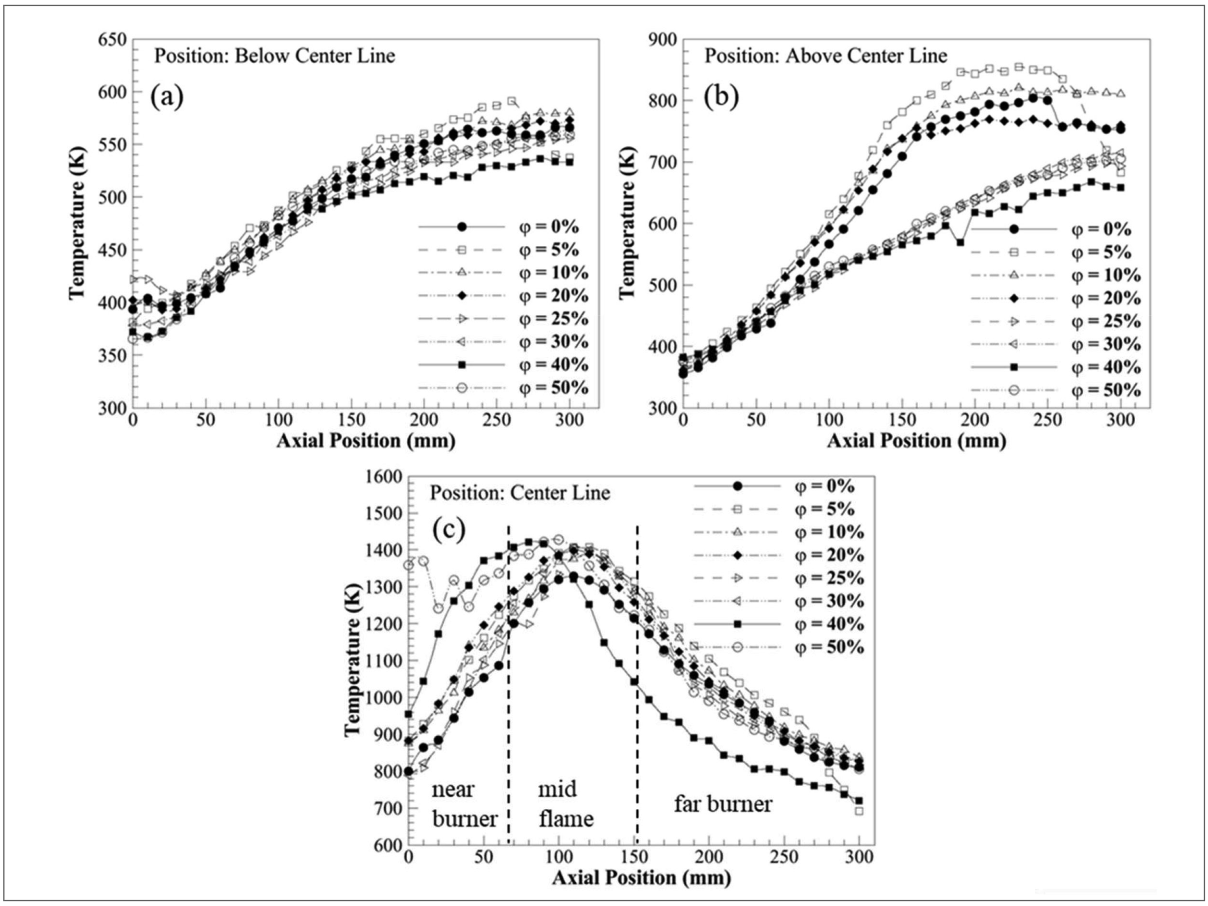

Figure 2. Effect of H_2 addition on flame temperature distribution (a) below centreline (b) above centreline (c) centreline.

consideration the reporting basis for emissions results. The oxygen correction level that is widely used in the industry [9, 10] is shown in Eq. (1) and Eq. (2), where X is concentration of dry pollutant measured in flue gas. In this study, the gas emissions are corrected to 6 % of O_2 as shown in Eq. (3).

Fig. 3 illustrates the effect of varying hydrogen addition concentrations on NO and CO emissions. It is evident that the addition of hydrogen causes CO emissions to decline monotonically. The decrease in CO emissions with increasing H_2 addition is probably because carbon input, which is a crucial component in CO formation, is reduced as H_2 addition concentration increases [5]. Additionally, CO_2 oxidation increases at higher temperature with an increase in H_2 concentration.

$$[X]_{3\%\,O_2,\ ppm} = [X]_{abs,\ ppm}\frac{20.9-3}{20.9-[X]_{abs,\ \%}} \tag{1}$$

$$[X]_{12\%\,CO_2,\ ppm} = [X]_{abs,\ ppm}\frac{12}{[CO_2]_{abs,\ \%}-[X]_{air,\ \%}} \tag{2}$$

$$[X]_{6\%\,O_2,\ ppm} = [X]_{abs,\ ppm}\frac{20.9-6}{20.9-[X]_{abs,\ \%}} \tag{3}$$

However, the NO emission increases as the concentration of hydrogen addition increases. This can be attributed to the fact that an increase in flame temperature increases the formation of thermal NO_x. Furthermore, with an increase in H_2 in natural gas, the formation of radical OH would be enhanced, which plays an important role in the formation of prompt NO_x [5].

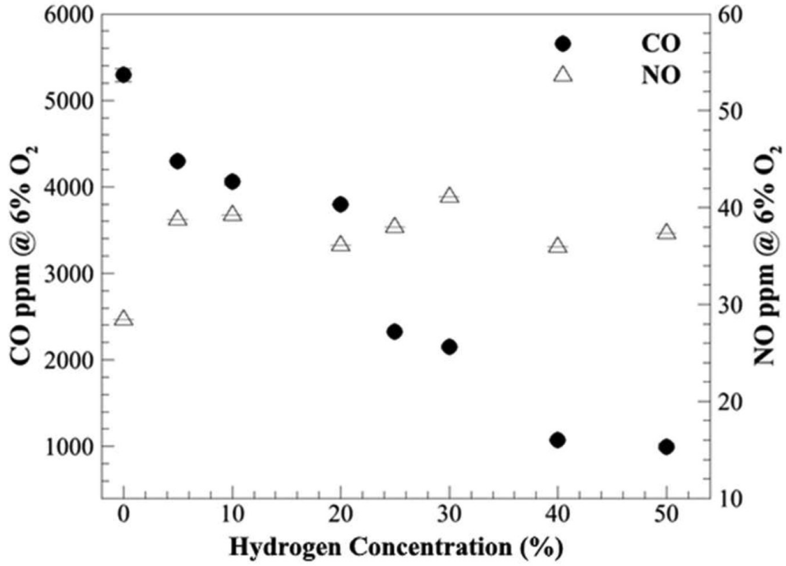

Figure 3. CO and NO emissions under various H_2 addition to the natural gas

The changes in the molar concentrations of O_2 and CO_2 in the exhaust gas as a function of different H_2 concentrations in the fuel are shown in **Fig. 4**. The monotonic reduction of CO_2 is due to the effect of a decrease in carbon input, as discussed earlier. When the H_2 concentration increases from 0 to 40 vol %, an increase in O_2 concentration can be seen. Similar result can be found in Ghafour et al. [7] study, where increase in O_2 concentration is attributed to the partial premixing upon the increase in fuel-air mixing rate.

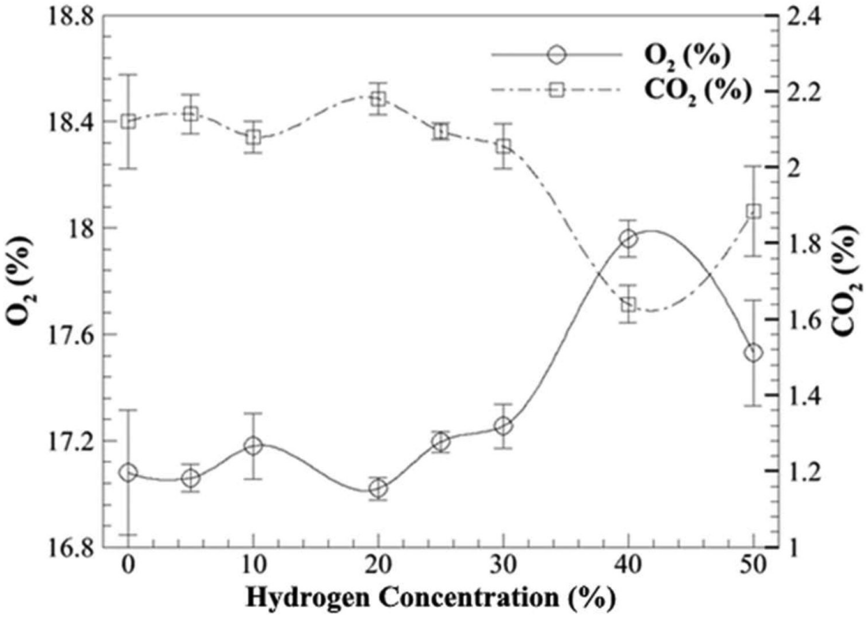

Figure 4. Measured O_2 and CO_2 molar concentrations as function of various H_2 concentrations

Conclusion

In this study, the addition of different concentrations of hydrogen and natural gas to a turbulent diffusion flame was investigated. With the addition of hydrogen up to 0 to 50 vol % in natural gas, the flame temperature measurement results can be classified into three distinct regions: near burner, mid flame, and far burner. It was seen that with an increase in hydrogen concentration at 40 vol% and 50 vol %, the peak flame temperature shifts towards the near burner region for the centreline. However, the peak temperature for both the above and below centreline was seen in the far burner region. This obvious transition is due to the increase in soot flame length and the buoyancy effect. The pollutant emissions CO and NO are measured. It was found that higher hydrogen concentrations resulted in lower CO emissions as the carbon input decreased. However, the increase in NO with an increase in hydrogen concentration is due to the formation of thermal NO_x and prompt NO_x for hydrocarbon fuels. Moreover, a significant reduction in CO_2 concentration can be seen for higher hydrogen concentrations of 50 vol %.

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