Experimental Investigation of Premixed H2/CO/CNG/CO₂ Blending Syngas Flames: Effect of Swirl Number and Equivalence Ratio

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Abstract— In this study, effect of swirl number and equivalence ratio on combustion and emission behavior of premixed H₂/CO/CNG/CO₂ blending syngas flames was experimentally investigated in a swirl stabilized, laboratory scale combustor. At tested syngas mixture, composition (% 30H₂ % 30CO % 20CNG % 20CO₂ by volume) and H₂/CO (moderate) ratio were kept constant while equivalence ratio (ϕ) and swirl number (SN) were changed 0.6-0.7 and 0.2-1.0, respectively. Combustion behavior of the tested gas composition was assessed via examining axial and radial temperature profiles, which are measured by K and B type thermocouples. On the other hand, emission profiles of O₂, CO, CO₂ and NOₓ were analyzed to define emission behavior. Results shows that increase from ϕ=0.6 to ϕ=0.7 raises the axial temperature gradients. The temperature difference in the flame front is more than the difference in the outlet. On the other hand, axial temperature declines from SN=0.2 to SN=1.0, gradually. Increase in the equivalence ratio reduces the CO emissions while it increases CO₂ emissions. NOₓ emissions increase because of higher peak flame temperature at ϕ=0.7. Also, the conversion of CO to CO₂ reduces the percentage of O₂ at the exit of combustor. The SN=0.2 has the highest temperature in the axial direction, from the opposed point of view it has low temperature values in the radial direction. Because high swirl numbers allow to spread temperature in radial direction. For this reason, in desired situations, the usage of high swirl numbers can provide a more stable temperature distribution in all combustor.

Keywords— Syngas, combustion, emission, equivalence ratio, swirl number.

I. INTRODUCTION

In many burners, flow conditions that will make flow fully turbulent are designedly created. Almost all power generators operate in turbulent combustion conditions, as turbulence increases mass consumption rates of the reactants. Based on this increment, rate of chemical energy release increases and thus power output of the burner increases [1]. Additionally, swirling flows are preferred in most combustion applications because of their positive impact on flame stability, combustion intensity and consequently burner performance [2]. If it is desired to briefly express equivalence ratio, it can be defined as proportion of the amounts of air and fuel by mass or volume. In all combustion systems, this ratio affects the flame height, temperature distribution and flame gas emissions directly.

Increasing the equivalence ratio raises the temperature, so the NOₓ emissions rise while the CO emissions show the opposite behavior [3-4]. In addition, limits of flame dynamics such as flashback and blowout are comprehended by this term easily. Sayad et al. studied the stability limits of various synthetic gas compositions at different swirl number in premixed burner. At two different swirl numbers (0.66-0.53) near the critical swirl number [5-7] flashback and lean blowout (LBO) experiments were determined for various compositions of H₂/CO/CH₄ mixtures and they found that decrease in swirl number reduce the tendency of flashback, in the meantime LBO is not affected remarkably. Furthermore, particle image velocimetry, OH chemiluminescence image were obtained for examining the flow field and flashback behavior caused by combustion induced vortex breakdown (CTVB) mechanism [8]. Kutte et al. investigated syngas combustion at different thermal power and equivalence ratios in swirl-stabilized gas turbine combustor. At all experiments, syngas flames were stable and no major acoustic fluctuations were observed. According to the obtained data, burning behavior and shape of flame were not affected considerably [9]. Ibas and Karyeyen determined temperature and emissions on axial and radial positions of the combustor is performed for 10kW thermal power and ϕ=0.83. Experimentally obtained data was validated with numerical results and as a result of these, high NOₓ emission values were associated with high flame temperature [10]. Huang and Yang studied combustion dynamics and development of the flow in premixed combustor numerically. They found that excessive swirl may guide flame flashback and a higher swirl number pioneer high turbulence intensity [11]. Valera-Medina et al. experimentally and numerically evaluated synthetic gas fuels with a constant swirl number in combustor. Particle image velocimetry (PIV) data was validated with simulations and flame structure was analyzed. Consequently, they found that changes made in nozzle geometry affect flame blowoff [12]. De and Acharya considered 3 main subjects (geometry, swirl and premixedness) on premixed combustion. Swirl number increase raise the mixing quality, premixedness and reaction along flame front. Besides, geometry on flame behavior examined and they observed that higher swirl numbers and presence of H₂ increase the flammability of syngas [13].
In this study, effect of equivalence ratio and geometric swirl number on temperature and emission characteristics of premixed syngas flame was analyzed in a swirl stabilized, laboratory scale combustor. H₂/CO ratio was kept constant and selected as 1. Combustor was operated with an invariable composition (%30H₂ %30CO %20CNG %20CO₂ by volume) while equivalence ratio and swirl number were variable.

II. EXPERIMENTAL SETUP

A. Burner

A premixed burner that can be operated up to 10 kW thermal power is designed and manufactured. The 3D solid model of the burner is shown in Fig. 1. Demountable and replaceable swirl generators were designed and placed to end of the nozzle to ensure desired swirling flows in the combustion.

![Fig. 1 The 3D model of the burner](image)

To describe briefly, approximate swirl number can be expressed as;

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

where \(d_h\) is swirler hub diameter; \(d_o\) is swirler outer diameter; \(\theta\) is swirl vane angle [14-15]. Swirlers are formed with 6 vanes that has 1.6 mm thickness. The ratio between hub and outer diameter is 0.5. For example, dimensions of swirl number 0.2 is given in Fig. 2.

![Fig. 2 Swirl number 0.2 with dimensions](image)

B. Combustor and Flow Delivery System

All gases were supplied purely in cylinders. Mass flow controllers (MFC) fed air/fuel mixture in desired composition and equivalence ratio from cylinders to collector, premixer and burner, respectively. The ignition is controlled fully electronic and the system safety is provided with the ionization system in case of flashback or blowout. In Fig. 3 whole combustion system is shown. Combustor is made of stainless steel and has a cylindrical shape with an inner diameter of 320 mm, a length of 1.65 m, and a thickness of 0.5 mm. 10 different measurement ports with different distances are placed for emissions and thermocouples. By this way radial and axial measurement are easily taken. Two sides of the combustor has rectangle shape tempered glasses with size of 100x300 mm to examine the instant flame structure and to make the necessary intervention without dismantling the burner.

C. Operating Conditions

The experiments were carried out at a constant thermal power of 3 kW. The equivalence ratio was varied 0.6-0.7 and the geometric swirl number was varied 0.2, 0.6 and 1. Syngas composition and properties is given in Table I. Component and properties of CNG is given in Tables II-III. Lastly, Experimental conditions are presented in Table IV. The information about CNG is obtained from the company (Kayseri Natural Gas Marketing and Trading Inc.) that supplies the CNG. And information in Tables I-IV calculated by Ref. [16-17].

### Table I: Syngas Composition and Properties

<table>
<thead>
<tr>
<th>Mixture</th>
<th>H₂ (%)</th>
<th>CO (%)</th>
<th>CO₂ (%)</th>
<th>CNG (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHV (MJ/kg)</td>
<td>15.1383</td>
<td>30.0</td>
<td>20.0</td>
<td>20.0</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>0.9413</td>
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<td></td>
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</table>

### Table II: Components of CNG

<table>
<thead>
<tr>
<th>Component</th>
<th>Molar (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane (CH₄)</td>
<td>91.5243</td>
</tr>
<tr>
<td>Ethane (C₂H₆)</td>
<td>3.3592</td>
</tr>
<tr>
<td>Propane (C₃H₈)</td>
<td>1.0077</td>
</tr>
<tr>
<td>Isobutane (C₄H₁₀)</td>
<td>0.1795</td>
</tr>
<tr>
<td>Normal Butane (C₄H₁₀)</td>
<td>0.2449</td>
</tr>
<tr>
<td>Isopentane (C₅H₁₂)</td>
<td>0.0603</td>
</tr>
<tr>
<td>Normal Pentane (C₅H₁₂)</td>
<td>0.0422</td>
</tr>
<tr>
<td>Hexane (C₆H₁₄)</td>
<td>0.0474</td>
</tr>
<tr>
<td>Nitrogen (N₂)</td>
<td>3.0110</td>
</tr>
<tr>
<td>Carbon Dioxide (CO₂)</td>
<td>0.5235</td>
</tr>
</tbody>
</table>

### Table III: Properties of CNG

| Density (kg/m³) | 0.745 |
| Low Heating Value (MJ/kg) | 46.781 |
| Low Heating Value (MJ/m³) | 34.992 |
| Mean Molecular Weight (g/mol) | 17.573 |
TABLE IV

<table>
<thead>
<tr>
<th>EXPERIMENTAL CONDITIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{fuel}$ [slpm]</td>
</tr>
<tr>
<td>12.631</td>
</tr>
<tr>
<td>12.631</td>
</tr>
</tbody>
</table>

D. Uncertainty in Experimental Data

Temperature measurements during the experiments were made with K and B type thermocouples. Temperature correction were made for taking radiation losses into consideration and measured values were found to be maximum 50 K lower than true values. Emissions were measured with flue gas analyzer. Its accuracy and range are given Table V.

TABLE V

<table>
<thead>
<tr>
<th>FLUE GAS ANALYZER ACCURACY AND MEASUREMENT RANGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>O$_2$</td>
</tr>
<tr>
<td>±5% or ±10ppm*</td>
</tr>
<tr>
<td>CO</td>
</tr>
<tr>
<td>±10.0%</td>
</tr>
<tr>
<td>NO</td>
</tr>
<tr>
<td>±10.0%</td>
</tr>
<tr>
<td>NO$_2$</td>
</tr>
<tr>
<td>±10.0%</td>
</tr>
<tr>
<td>SO$_2$</td>
</tr>
<tr>
<td>±10.0%</td>
</tr>
<tr>
<td>CO$_2$</td>
</tr>
<tr>
<td>*whichever is higher</td>
</tr>
</tbody>
</table>

1. Air Compressor (5.5 hp, 500 lt)
2. Air Vessel (1 m$^3$)
3. Filter
4. Regulator (1 MPa to 0.3 MPa)
5. Mass Flowmeter Controller (MFC)
6. Manometer
7. Pneumatic Regulator
8. Solenoid Valve
9. Float Type Flowmeter
10. CNG Cylinder
11. High Pressure Regulator
12. CO$_2$ Cylinder
13. CO Cylinder
14. H$_2$ Cylinder
15. Vacuum System Controller
16. Fuel Collector
17. Mixer
18. Ignition and Solenoid Control Panel
19. Premixed Burner
20. Combustion Chamber
21. Flue
22. Electrical Connections
23. Gas pipeline
III. RESULT AND DISCUSSIONS

In this study, effect of different swirl numbers and equivalence ratios on combustion characteristics of synthetic gas fuels investigated experimentally. Behavior of the syngas flames that has moderate H₂/CO ratio and 20% CO₂ inert diluent studied. Blowout and flashback limits of mixture of %30H₂ %30CO %20CNG %20CO₂ by volume was determined as ϕ=0.495 and ϕ=1.45, respectively. The study was examined in two parts under the title of the effect of the equivalence ratio and the swirl number.

A. Effect of the Equivalence Ratio

In Fig. 4, axial temperature distribution of ϕ=0.6 and ϕ=0.7 is shown. Peak and outlet temperature values for ϕ=0.6 and ϕ=0.7 are 1150.93-519.82 K and 1094.03-517.25 K, respectively. The temperature difference in the flame front is more than the difference in the outlet as seen in Fig. 4.

Instant flame photos are shown in Fig. 5. The flame length is shortened, and the luminosity is increased.
7-10, CO, CO₂, NOₓ and O₂ emissions are given. Increase in the equivalence ratio reduces the CO emissions while it increases CO₂ emissions. NOₓ emissions increase because of higher peak flame temperature at ϕ=0.7. Also, the conversion of CO to CO₂ reduces the percentage of O₂ at the exit of combustor.

When equivalence ratio increases in lean side, mole fractions of fuel increase in the mixture. CO₂ formation increases, on the contrary, O₂ mole fraction decreases in products. Heat of reaction remains constant, but N₂ in products decreases. So, flame temperature rises [18].

**B. Effect of the Swirl Number**

The effect of the swirl number is very apparent on axial temperature distribution in Fig. 11. There has been a decrease in axial temperatures with an increase in the swirl number. The peak flame temperature, which was 1094.03 K in 0.2 swirl, was 1058.57 and 990.94 in 0.6 and 1.0 swirl, respectively. Same status is observed at the outlet of the combustor.
In Fig. 13, radial temperature change is shown. The swirl number 0.2 has high temperature in the axial direction, from the opposed point of view it has low temperature values in the radial direction. Because high swirl numbers allow to spread temperature in radial direction. For this reason, in desired situations, the usage of high swirl numbers can provide a more stable temperature distribution in all combustor.
Fig. 14-17 show emission behavior of different swirl numbers at flue. At swirl number 0.6, CO emissions are reached the highest values. Similar situation is seen on CO$_2$ emissions. NO$_x$ emissions are lower at high swirl number because of low peak temperatures. Finally, O$_2$ emissions is found highest at swirl number 1.0.

### IV. CONCLUSIONS

In this paper, effect of swirl number and equivalence ratio on combustion and emission behavior of premixed H$_2$/CO/CNG/CO$_2$ blending syngas flames was experimentally investigated in a swirl stabilized, laboratory scale combustor. H$_2$/CO ratio was kept constant and selected as 1. Combustor was operated with a composition while equivalence ratio and swirl number were variable. Combustion behavior of tested gas compositions were assessed via examining axial and radial temperature profiles, which are measured by K and B type thermocouples. On the other hand, emission profiles of O$_2$, CO, CO$_2$ and NO$_x$ were analyzed to define emission behavior. Results shows that:

- Increase from $\phi=0.6$ to $\phi=0.7$ raises the axial temperature gradients. The temperature difference in the flame front is more than the difference in the outlet.
- Axial temperature declines from SN=0.2 to SN=1.0, gradually.
- Increase in the equivalence ratio reduces the CO emissions while it increases CO$_2$ emissions.
- NO$_x$ emissions increase because of higher peak flame temperature at $\phi=0.7$.
- The conversion of CO to CO$_2$ reduces the percentage of O$_2$ at the exit of combustor.
- The SN=0.2 has the highest temperature in the axial direction, from the opposed point of view it has low temperature values in the radial direction.
High swirl numbers allow to spread temperature in radial direction. For this reason, in desired situations, the usage of high swirl numbers can provide a more stable temperature distribution in all combustor.

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