AN EXPERIMENTAL STUDY ON EFFECT OF SWIRL NUMBER AND GAS COMPOSITION ON COMBUSTION AND EMISSION BEHAVIOR OF PREMIXED H_2/CO/CNG BLENDING SYNTHETIC GAS FLAMES IN A NOVEL COMBUSTOR

Harun YILMAZ[1], Omer CAM[1], Ilker YILMAZ[2]
[1]Department of Airframes and Powerplants, Civil Aviation College, Erzincan University, Erzincan, 24100, Turkey
[2]Department of Airframes and Powerplants, Faculty of Aeronautics and Astronautics, Erciyes University, Kayseri, 38039 Turkey
Corresponding author: Harun YILMAZ, e-mail: hyilmaz@erzincan.edu.tr

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ABSTRACT

To answer worldwide energy demand in an environment friendly manner, extensive research has been done in the field of combustion, as fossil fuel combustion significantly increases emissions of NO_x, CO, CO_2 and unburned hydrocarbon. In this study, effect of swirl number (0.4, 0.8) and gas composition on combustion and emission behaviour of synthetic gases, which have important role in the future energy strategy was experimentally investigated in a novel, newly designed and fabricated laboratory scale combustor. 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. Results of this study revealed the great impact of swirl number on reaction zone distribution and so main combustion features such as temperature and species distributions. Additionally; gas composition was found to significantly alter dynamic flame behaviour and pollutant emissions, and to slightly alter centreline temperature distribution.

1. INTRODUCTION

Continuous increase in greenhouse gas emissions and depletion of fossil fuel resources are the motives of seeking renewable and sustainable energy sources [1]. Synthetic gas (or syngas) is a promising alternative fuel for its low pollutant emission levels (impurities in fuel are cleared before combustion), and is produced via gasification applications [2-3].

Gasification applications provide the potential of clean and effective energy usage and have been utilized more than a century for fuel (e.g., H_2, synthetic natural gas) and chemical production. These applications include production of synthetic gas from any kind of carbon containing feedstock such as coal, biomass and municipal waste etc. Depending on the reactor type, reactor atmosphere (oxygen level or air content, temperature, pressure) and type of heating (internal or external); synthetic gas composition varies. But it primarily consists of CO and H_2, and also slightly includes some inert components such as N_2 and CO_2. Synthetic gas can be used instead of natural gas to produce electricity or as raw material to produce liquid fuel and chemicals [4]. Nevertheless, heating value and Wobbe index (indicates interchangeability of fuel gases) of synthetic gases are very low compared to some of the conventional hydrocarbon fuels such as methane. Both variable gas composition and this situation make synthetic gases to be used in conventional burners problematic from flame stability (ignition and extinction limits, flame speeds, dynamic and static instabilities etc.) and combustion efficiency point of view [3, 5-6]. Motivated by these challenges and lack of understanding of synthetic gas combustion behaviour; many researchers investigated characteristics of synthetic gas flames both numerically and experimentally.

Arrieta et al. experimentally studied equimolar natural gas and syngas (3 different high hydrogen content syngas) mixture flames in radiant porous media burner by analysing effect of fuel composition, thermal power and fuel/air ratio on stability characteristics, emissions and radiant efficiency. They varied H_2/CO ratio between 1.5 and 3 and used results of 100 % natural gas combustion as a baseline case for comparison. The prominent impact of thermal power and fuel/air ratio on temperature patterns, exhaust gas emissions and radiant efficiency were demonstrated. Furthermore, it was shown that stable operating condition slightly varies with fuel composition by emphasizing the fuel gas interchangeability potential of burner of interest although flame stability characteristics change with fuel composition [5].

Synthetic gases can be mixed with hydrocarbon fuels to increase applicability of such gases in conventional burners. Park and Kim numerically investigated flame structure and emission characteristics of H_2/CO/CH_4 blending synthetic gases by examining 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 thermal, prompt and reburn routes in non-diluted counterflow non premixed synthetic gas flames; an increment in H_2 mole fraction in gas composition increases the peak NO_x amount; when fuel is diluted with N_2, NO formation rate increases with rising H_2 and CH_4, and decreasing CO amount; CH_4 decreases positive effect of N_2 dilution on NO decrement [6].

Dinesh et al. performed simulation studies to investigate characteristics of swirling H_2/CO diffusion flames in a TECFLAM burner model through LES (Large Eddy Simulation) technique. In their simulation studies, they used 2 different fuel compositions, namely H_2 rich (70%H_2-30%CO) and CO rich (30%H_2-70%CO). Results of their study revealed the significant importance of fuel composition on flow and scalar fields. High diffusion characteristics of H_2 was found to be responsible for thickening flame and enlarging vortex break down bubble in H_2 rich mixture, causing unsteady flame characteristics [7].

Askari et al. built an experimental setup to investigate synthetic gas (varying mole fraction of H_2 and CO mixture)/oxygen /helium premixed flame characteristics. They used two different kinds of chambers; cylindrical and spherical. For flame structure analysis, they used cylindrical chamber which had Schlieren system and was equipped with a CMOS camera. On the other hand, spherical chamber was used to measure laminar burning speeds of studied flames. It was shown that using He as a dilution agent instead of N_2 increases stability limits because of the helium's low molar heat capacity and high thermal conductivity (compared to nitrogen) properties. Lastly, laminar burning speeds were positively correlated with pressure [8].
Karyeyen and Ilbas designed and fabricated a laboratory scale combustor to examine low heating value and coal-derived synthetic gas combustion and emission characteristics. They fueled their combustor with hydrogen to improve combustion behaviour of investigated synthetic gases at a constant thermal power and equivalence ratio, and proved that low heating value synthetic gases can be burned in such burner in a stable manner. Results obtained from this experimental study showed that hydrogen addition increases peak temperature value; the amount of NO_x formed is very low for low heating value gases and this amount increases with hydrogen supply [9].

In addition to these studies summarized above, there can be found plenty of studies related to combustion, emission and stability characteristics of synthetic gases. For these purposes, many researchers investigated effect of fuel composition, operating conditions (temperature, pressure), type and amount of diluent (CO_2, N_2, steam, He etc.), hydrogen or hydrocarbon enrichment and other parameters that qualifies a combustion process such as thermal power, fuel/air ratio, mass flow rates etc. on fundamental flame properties [10-29].
To improve flame stability characteristics, the subject of introducing swirl into flow is an extensively investigated topic. Swirl is mainly used for flame stabilization via a

recirculation zone. It also reduces flame lengths and assures lower maintenance time and cost, and longer service life of the combustor. In a swirling flame; jet precession, vortex breakdown (VB), precessing vortex core (PVC) and recirculation are common flow properties. These properties can associate with the parameters that determine flame stability characteristics (also combustion and emission behaviour) such as dynamics of flow, interaction between heat release rate and acoustics [7]. As mentioned before, synthetic gas combustion in conventional burners may exhibit instable behaviour because of fuel composition diversity of such gases. Motivated by this, many researchers studied swirl stabilized synthetic gas flames [7, 30-33].

In this study, effect of swirl and fuel composition on combustion and emission behaviour of premixed synthetic gas/air flames is experimentally investigated in a newly designed and fabricated laboratory scale combustor.

2. EXPERIMENTAL SETUP

2.1. Burner

To effectively and environment friendly burn fuel, a burner must be compatible with combustor in which to be used. Thermal power, back pressure and dimensions of the combustor, operation mode of the burner (single or multi stage, or proportional) and characteristics of the fuel to be used are important parameters that must be considered during burner design. In addition, the burner must reduce exhaust gas emissions and ensure complete combustion with least amount of air throughout the entire operating range. Lastly, it must be such that flame diameter and length provide a uniform heat distribution within the combustor [34]. Taking all of these issues into consideration, we designed and manufactured a new type premixed burner and integrated it with a combustor. This burner can operate at thermal powers between 5 to 10 kW and top view of the burner can be seen in Fig. 1. In this figure; swirl vane, ionization electrode, pilot ignition system and thermocouples can also be seen.

Fig. 1. Top view of the burner.

2.2. Layout of the Overall Combustion System

Production of fuel supply lines are carried out based on heating value and density of each gas, and desired mass flow rate which is bound to thermal power. Each gas is supplied to combustor through a digital (thermal) mass flow controller (MKS-GE50A) and the amount of each gas is regulated by a vacuum system controller (MKS-946 Series). While designing burner, operation pressure is determined as 20 mbar. Pressure regulators and manometers in each gas line are arranged to bring the pressure value to the desired level and to monitor pressure value, respectively. Mechanical flow meters (which are calibrated for air) are assembled to gas lines to monitor mass flow rates (with appropriate gas correction factor) for control purposes. On the other hand, air supply line consists of an air source (compressor), a filter (for steam and oil removal), a digital mass flow controller (MKS-1579A), a manometer and a mechanical flow meter (float type). Lastly, solenoid valves are assembled to each supply line to electromechanically open and close these lines based on presence of flame which is detected by an ionization electrode. All equipment clarified above are mounted to each gas line by the same order. Diameter of each gas supply line is specified based on the density and heating value of each gas, and all lines are connected to a gas collector. The schematic view of the overall combustion system and experimental setup are demonstrated in Fig. 2, respectively.

20. Combustion chamber
21. Flue
22. Electrical connections
23. Gas supply lines

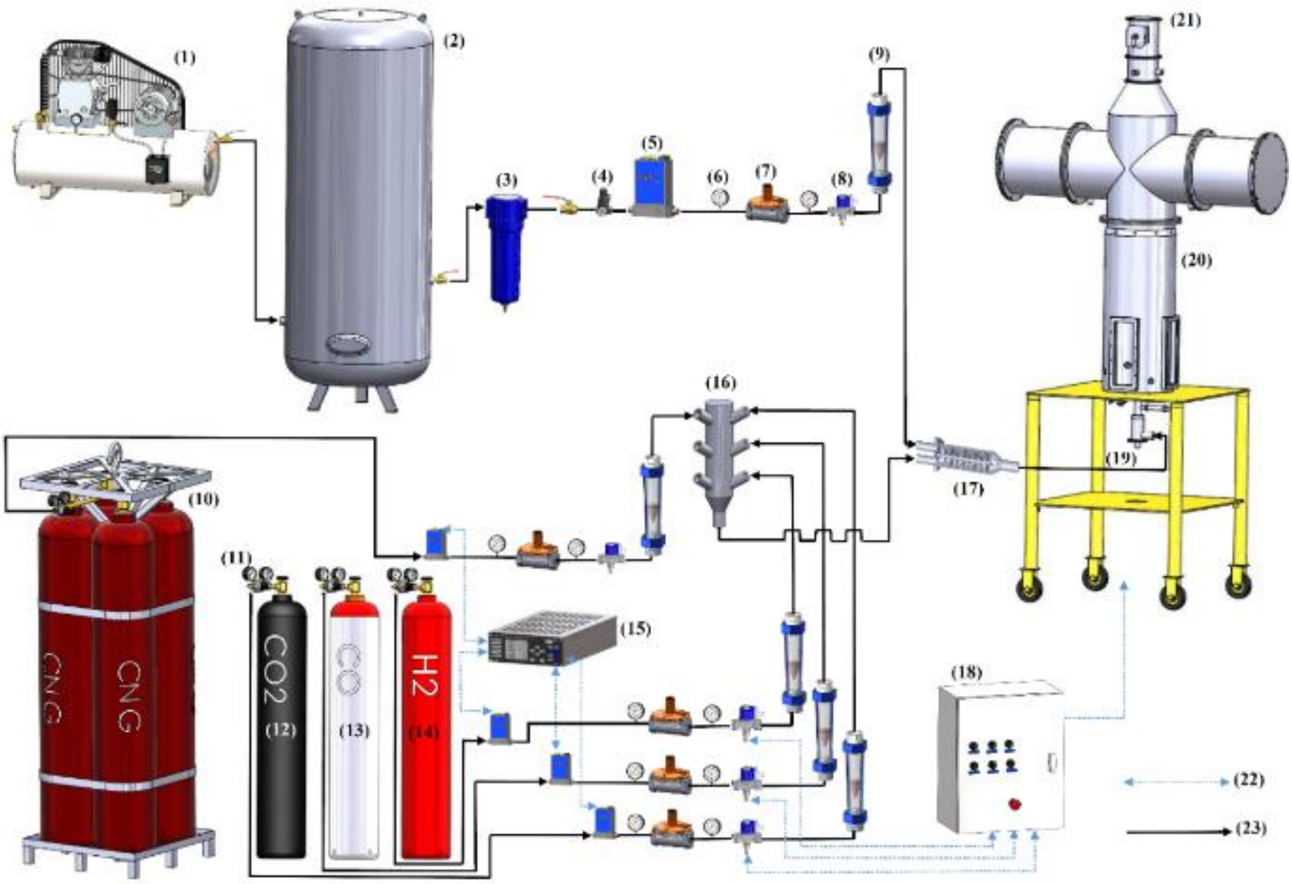

Fig. 2. Layout of the overall combustion system.

1. Air compressor
2. External air tank
3. Filter (for steam and oil removal)
4. Pressure regulator
5. Mass flow controller
6. Manometer
7. Pressure regulator
8. Solenoid valve
9. Float type flowmeter
10. CNG tank
11. Pressure regulator
12. CO_2 tank
13. CO tank
14. H_2 tank
15. Vacuum system controller
16. Gas collector
17. Fuel/air pre-mixer
18. Control Panel
19. Burner

In Fig. 3, designed and manufactured combustor can be seen. During combustor design; temperature, velocity, pressure and species distributions in the combustor at determined operating conditions (thermal power, gas compositions and operating pressure) were considered by numerical approaches and combustor geometry was optimized. Dimensions of the combustor are 1650 mm length, 320 mm inner diameter and 330 mm outer diameter. So thickness of the wall is 5 mm. For temperature and emission measurements, numerous slots are located on the combustor wall (at the side and behind, also on diverging chimney and side arms of the combustor). Thus, axial and radial measurements can be performed. There is also a cooling slot in which air is fed through an external air turbine around the circumference of the combustor. Tempered glasses which are located in front and side of the combustor make flame optically accessible and give chance to change swirl vane without removing burner. All metal components of the combustor are made of the stainless steel.

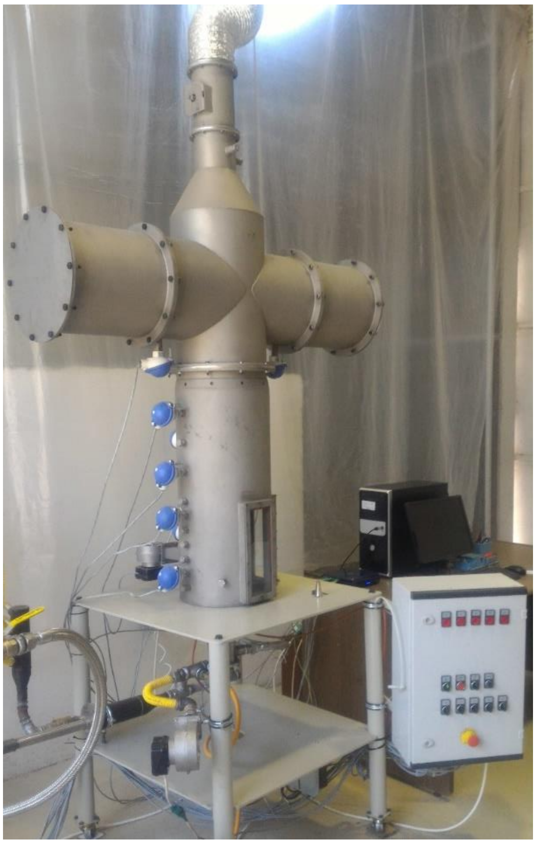

Fig. 3. Combustor.

To be able to ignite gas mixture, maintain a stable flame in all operating conditions and ensure reliable operation, a pilot ignition system is fabricated. This system comprises of fuel supply line (LPG), solenoid valve, air fan and burner. Furthermore, this combustor embodies a static fuel air pre-mixer equipped with a mechanical flashback arrestor.

2.3. Swirl Vanes

Swirling flows are preferred in most combustion applications because of their positive impact on flame stability, combustion intensity and consequently burner performance [35]. Most common parameter to characterize swirling flows is swirl number and defined as the ratio of axial flux of the tangential momentum (G_φ) to axial flux of the axial momentum (G_x).

$$Swirl\ Number = \frac{G_\varphi}{G_x R} \quad (1)$$

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

$$G_X = \int_0^R U\rho U 2\pi r dr \quad (3)$$

In these equations; U and W axial and tangential velocity components, R radius of the cross section plane, r radial coordinate [36].

For practical calculations, approximate swirl number can be expressed as;

$$Swirl\ Number = \frac{2}{3}\cdot\left[\frac{1-\left({d_h}/{d_o}\right)^3}{1-\left({d_h}/{d_o}\right)^2}\right].tan(\theta) \quad (4)$$

d_h, swirler hub diameter; d_o, swirler outer diameter; θ, swirl vane angle [37]. This approximate formulation has been used by many researchers [3, 38-42]. Besides, ${d_h}/{d_o}$ ratio is a widely varied and has extensively been studied parameter. Most of the researchers set this ratio as 0.5 and 0.3 [35, 41-46].

Regarding all of these issues and manufacturing facilities into consideration, swirl vanes with 0.333 ${d_h}/{d_o}$ ratio and swirl numbers (0.4 and 0.8) are fabricated.

2.4. Measurement Equipment

Each gas is supplied to combustor from a pressurized (200 – 300 bar) gas tank and pressure of the gas is reduced via a pressure regulator before entering mass flow controller. Desired mass flow rate is set through a vacuum system controller that governs digital mass flow controllers. For temperature measurement, ceramic coated K (Range: -200 – 1200C°) and B type (Range: 0 – 1800C°) thermocouples are used; in the flame region B type, outside the flame region K type. The data obtained from these thermocouples are converted to quantifiable parametric information via a data logger (Expert Key 200L) and stored in a computer. Emission measurements are performed via a portable flue gas analyzer.

2.5. Gas Compositions and Operating Conditions

The overall combustion system is fabricated to burn synthetic gases which have different gas compositions and to assess effect of gas composition and swirl number on combustion and emission behaviour of such gas mixtures. While determining amount of individual gas (H_2, CO, CH_4, CO_2 or N_2) in gas mixture, gas compositions from different gasification plants (PSI, Tampa, El Dorado, Pernis, Sierra Pacific, ILVA, Schwarze Pumpe, Sarlux, Fife, Exxon Singapore, Motiva Delaware, PIEMSA and Tonghua) are examined and synthetic gas compositions are specified at three different H_2/CO rates and at three different heating values (low, medium and high) [47]. Tested gas compositions are; 28%H_2-52%CO-20%CNG, 44%H_2-36%CO-20%CNG and 60%H_2-20%CO-20%CNG, in volume basis. To represent CH_4, 20 % CNG has been added to each gas mixture.

During experiments, thermal power of the combustor has been kept constant; 5 kW. Mass flow rate of each gas was specified based on the thermal power and gas composition. Fuel gases and air were premixed at room temperature in a pre-mixer before entering the burner. All experiments have been performed at the local atmospheric conditions of city of Kayseri, Turkey. Lastly, combustion takes place at 20 mbar (gauge pressure) and room temperature.

3. RESULTS

Among a variety of key parameters that characterize performance of a combustion process, flame temperature is of primacy for combustion efficiency, pollutant emissions and material selection. By taking this situation into consideration, we will first discuss effect of swirl number and gas composition on temperature distribution throughout the combustor.

All experiments were conducted at 0.4 equivalence ratio other than 28%H_2-52%CO-20%CNG mixture, because blowout occurred for this mixture at 0.4 equivalence ratio. Blowout is a phenomenon that takes place when the time required for chemical reaction to occur exceeds residence time. For respective mixture, lower hydrogen content (compared to other mixtures) causes flame speed to reduce, thus residence time shortens by making flame more prone to blowout [3]. On the other hand, mass flow rate of a lower heating value gas must be higher to keep thermal power constant, which in turn may cause to flame blowout at lower equivalence ratios. Therefore, equivalence ratio was set as 0.45 for 28%H_2-52%CO-20%CNG mixture. In Fig. 4, axial temperature distributions of 28%H_2-52%CO-20%CNG, 44%H_2-36%CO-20%CNG and 60%H_2-20%CO-20%CNG blending synthetic gas fuels at 0.4 swirl number can be seen. Temperature profiles show a good agreement in terms of trend and value. Irrespective of the gas composition, peak temperature values are in the flame zone and towards the outlet of the combustor, temperature values decrease depending on the heat losses to environment and heat absorption of combustor material. Maximum temperature values are 1064.6, 1078.52 and 1058.10 K for 28%H_2-52%CO-20%CNG, 44%H_2-36%CO-20%CNG and 60%H_2-20%CO-20%CNG mixtures, respectively. To clearly render effect of gas composition, temperature profiles of 44%H_2-36%CO-20%CNG and 60%H_2-20%CO-20%CNG mixtures must be examined. At the inlet of the combustor, measured temperature values of 44%H_2-36%CO-20%CNG mixture is higher than that of the 60%H_2-20%CO-20%CNG mixture, although heating value of latter mixture is higher. This may be because of the fact that volumetric heating value of CO is higher than that of H_2. But, starting from 300 mm away from combustor inlet, temperature profiles get closer. Similar studies of Ref. [48], it is revealed that H_2/CO ratio doesn't significantly change flame temperature but alteration of chemical, thermal and transport properties with fuel diversity substantially shifts reaction rate, burning velocity, heat release and flame shape (length, thickness and angle).

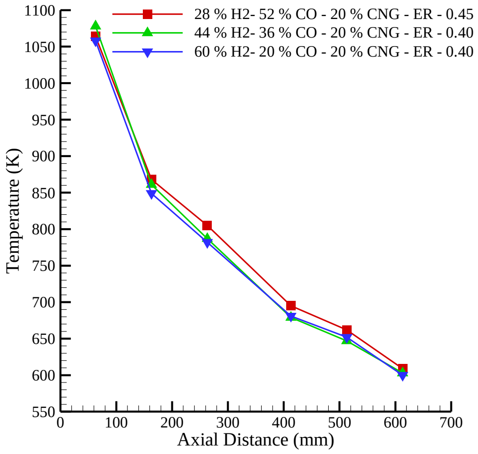

Fig. 4. Axial temperature distributions at different gas compositions.

In Fig. 5, flame images of 44%H_2-36%CO-20%CNG and 60%H_2-20%CO-20%CNG are illustrated. As a result of the lower equivalence ratio, i.e. burning in sufficient oxygen condition by leaving no UHC for soot formation, bluish flames were observed [3]. As the CO content in synthetic gas mixture increases, visible height of the flame increases based on the slow oxidation characteristics of CO [49]. On the other hand; as the H_2 content increases, visible flame height reduces and flame becomes wider. Because of the high diffusivity and reactivity of H_2, flames with high burning and luminous intensity arise.

To evaluate effect of swirl number on temperature field. Measured axial temperature values of 60%H_2-20%CO-20%CNG mixture at different swirl numbers (0.4 and 0.8) but at constant equivalence ratio (0.4) compared and demonstrated in Fig. 6. Temperature profiles show an agreement in terms of trend but in terms of value, there are differences. Temperature values are lower at high swirl number. The difference between these values is 153 K in the flame region and gradually decreases towards the outlet of the combustor (except for the point which is nearly 500 mm away from burner outlet).

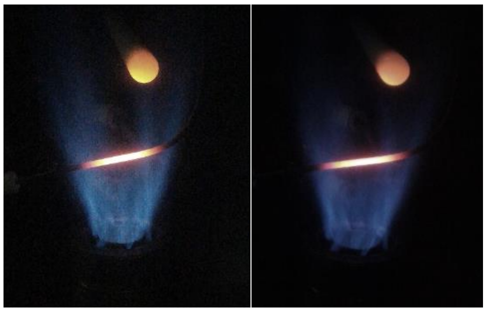
Fig. 5. Flame images. (On left: 44%H_2-36%CO-20%CNG, On right: 60%H_2-20%CO-20%CNG)

Activation energy of the reactions with hydroxyl radical are immensely lower than that of the reactions with atomic or molecular oxygen. Therefore, hydroxyl is a key intermediate species in determining completeness of a combustion process. An increment in H_2 fraction of a given mixture implicitly will increase net reaction rate (via increased OH fraction) [5]. Furthermore; as the swirl number increases, the place where chemical reactions take place shifts from inner annulus to radially outward and the OH mass fraction in the central region of the flame reduces due to the lower temperature values mainly rooted from characteristic features of highly swirling flows which are adverse pressure gradient, high shear stress and stretch rate [32]. Higher temperature distribution at low swirl number is attributed to this phenomenon.

At high swirl numbers; mixing condition of fuel air mixture improves, residence time of the mixture in hot temperature zone extends and heat radially diffuses better. Besides; flame expands radially outward, burns more steadily and intensively. Lastly, visible flame height reduces at high swirl numbers. At 0.4 swirl number, flame attaches both inner and outer annulus of the swirl vane. But, it only attaches inner annulus at 0.8 swirl number and propagates radially outward with increasing axial distance from burner outlet (Figure 7).

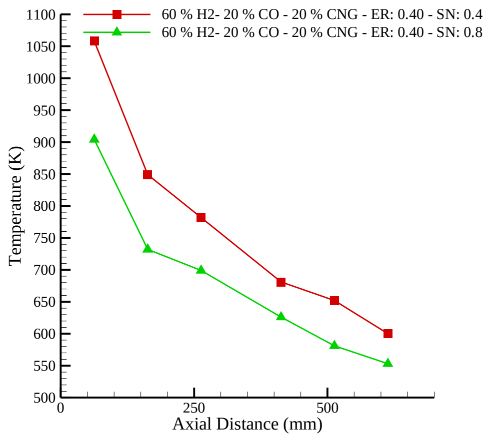

Fig. 6. Axial temperature distributions at different swirl numbers.

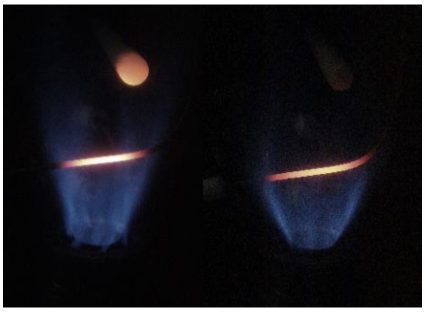

Fig. 7. Flame images of 60%H_2-20%CO-20%CNG mixture at different swirl numbers:
(Left) 0.4, (Right) 0.8.

In figure 8, CO_2 concentration profiles of 28%H_2-52%CO-20%CNG, 44%H_2-36%CO-20%CNG and 60%H_2-20%CO-20%CNG mixtures in percentage of total exhaust gases can be seen. Since we could not attain a stable value for 28%H_2-52%CO-20%CNG mixture, CO_2 emission measurements of this mixture are given in a range. Conversion rate of CO to CO_2 gets its highest value in the flame region and then decreases towards the outlet of the combustor except for the 28%H_2-52%CO-20%CNG mixture. CO_2 formation trend of this mixture shows an opposite behavior. Since all experiments were conducted under the same physical and atmospheric conditions, and at fuel lean equivalence ratio (near blowout limit) which is 0.45 for 28%H_2-52%CO-20%CNG mixture and 0.4 for other mixtures, this difference should have positive effect on conversion rate of CO to CO_2 in turn. But, CO_2 percentage gets its highest value further downstream for respective mixture. This opposite behavior is mainly rooted from different transport and chemical properties of the synthetic gas components. Hydrogen amount (implicitly, radicals that include H atom) in the synthetic gas mixture positively affects conversion rate of CO to CO_2 via modifying fast oxidation pathways (requires OH radical) of CO [3, 9, 49, 50]. Compared to 44%H_2-36%CO-20%CNG mixture, CO_2 percentage in exhaust gases in the flame region is higher for 60%H_2-20%CO-20%CNG mixture. But, it then sharply decreases with increasing axial distance. This decrement is slower for 44%H_2-36%CO-20%CNG mixture due to the higher CO content than former. For 28%H_2-52%CO-20%CNG mixture, CO_2 percentage increases towards the outlet of the combustor. This mixture has the highest CO content in all gas compositions tested. Because of the slow oxidation characteristics of CO and lack of H_2 (compared to other mixtures), combustion is completed further downstream and flame elongates (Figure 9) [49, 50].

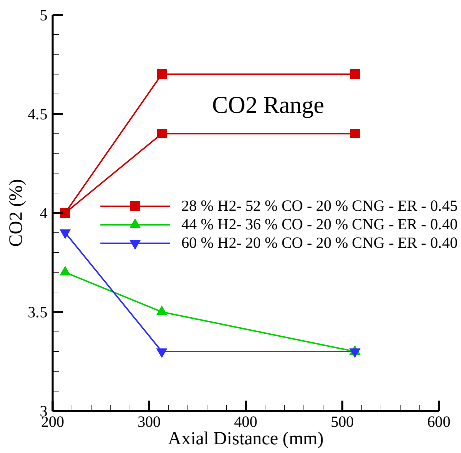

Fig. 8. Axial CO_2 concentration profiles at different gas compositions.

Fig. 9. Flame image of 28%H_2-52%CO-20%CNG mixture.

CO is an incomplete combustion product and highly sensitive to flame temperature as well as NO_x. The amount of CO formed is also controlled by residence time and oxygen availability [5, 49]. As mentioned before all combustion tests are conducted at 0.40 – 0.45 equivalence ratios and thus flow rates are very high, causing flame stretch in downstream and inhibiting CO oxidation. In other words, CO oxidation characteristics improve at higher temperatures [49]. Because of the low temperature values resulted from this phenomenon and the adiabatic flame temperature decrement with increased heat capacity of the mixture. CO emissions are very high for all compositions tested. Even it is out of upper measuring range (≥7000 ppm) of our flue gas analyzer for 28%H_2-52%CO-20%CNG mixture. This mixture also formed the highest CO_2 level and presence of CO_2 inhibits $H+O_2$ reaction and causes CO formation [3]. Highest CO level of respective mixture may originate from this situation. As the amount of CO in the gas mixture increases, CO emission increases (Figure 10). Because, CO augmentation affects both the amount of unburnt CO and burnt CO_2 in exhaust gases [48].

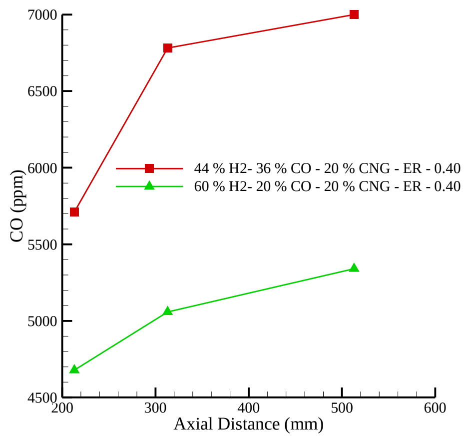

Fig. 10. Axial CO distributions at different gas compositions.

Swirl intensity is directly proportional to CO emissions. Low temperature values associated with high swirl reduces conversion rate of CO and so CO emissions significantly increase. As the emission values are out of upper measuring range, CO emission profiles at different swirl numbers are not illustrated in this paper. As stated earlier, reaction zone propagates radially outward as the swirl number increases and flame become wider. Depending on this propagation, the amount of CO_2 formed in the center of the flame reduces, which is 3.9 % (in the flame region) in all exhaust gases at 0.4 swirl number and is 3.6 % at 0.8 swirl number. Because of the low temperature values with regard to fuel lean conditions, absence of fuel bound nitrogen and unconventional combustion conditions (e.g. oxy-fuel or high pressure combustion), the amount of NO_x formed are 1-4 ppm levels for all synthetic gas compositions tested.

4. CONCLUSIONS

Although feedstock, and consequently product versatility (also depends on production method) of gasification processes seems an advantage, it brings in a difficult task of analyzing composition diversity and flame behavior of synthetic gases [48]. In this study effect of synthetic gas composition and swirl number on combustion and emission behavior of premixed 28%H_2-52%CO-20%CNG, 44%H_2-36%CO-20%CNG and 60%H_2-20%CO-20%CNG mixtures were experimentally investigated to better gain insight into synthetic gas combustion. Temperature distributions of tested compositions show a great agreement in terms of trend and value, irrespective of heating value of each mixture, which is highest for the 60%H_2-20%CO-20%CNG mixture. This may be because of the higher adiabatic flame temperature of CO than that of the H_2 and CH_4 (main constituent of CNG). CH_4 requires more oxidizer for stoichiometric combustion and this leads a more N_2 diluted mixture. On the other hand, oxygen requirement of H_2 and CO are the same, and molar heating value of CO is higher than H_2 [51]. Similar to studies of Ref. [49, 51], it is found that gas composition significantly affects flame shape because of the different characteristics of each synthetic gas component, which in turn will alter chemical and physical processes occurring in a combusting flow. Diffusivity of hydrogen and slow oxidation characteristics of

CO are found to be main determining factors for flame shape.

H_2 amount in the gas mixture is positively correlated with conversion rate of CO to CO_2. With decreased flame temperature (and combustion efficiency), synthetic gas oxidation rate decreases and this decrement causes incomplete combustion. As a result, emissions of CO increase.

Swirl intensity shifts reaction zone radially outward and so axial temperature distribution gets a lower value. Swirl intensity also has a great impact on flame shape (length, thickness, angle etc.), flame anchoring position and reaction zone distribution. At high swirl numbers; reaction zone uniformly expands, burning intensity increases, axial flame oscillations decrease, and flame becomes shorter (depending on the reduced convective time scale of hydrogen to flame front [3] and wider (indicating improved flame stability characteristics). Lastly, CO and CO_2 distributions alter with respect to modified reaction zone and temperature distributions.

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