ABSTRACT
The development of integrated gasification combined cycle (IGCC) systems provides cost-effective and environmentally sound options for meeting future coal-utilizing power generation needs in the world. The combustion of gasified coal fuel significantly influences overall performance of IGCC power generation. Experimental measurements are carried out on a non-premixed model combustor, equipped with a double-swirled syngas burner. Planar laser-induced fluorescence (PLIF) of OH radical measurement is adopted to identify main reaction zones and burnt gas regions as well. Together with the temperature and emission measurements during the exhaust section, some important characteristics of the syngas flame are investigated overall. In this paper, the effects of the CO/H$_2$ molar ratio consisting of syngas fuel are investigated under different humidity. With the increase of CO/H$_2$ ratios, the concentration field of OH radicals is gradually away from the nozzle exit, and the nozzle exit almost no existence of OH radicals, forming a typical lifted flame. In addition, fluorescent signal strength of OH radicals pronounced weakening, the flame gradually appeared W type distribution and more and more obvious with the increased of humidification amount. At the same time the average exhaust temperature of combustor CO and NO$_x$ missions almost no change. The study can provide a reliable database for high moisture gas turbine combustor design and combustion numerical simulation.

INTRODUCTION
The Integrated gasification combined cycle (IGCC), the humid air turbine (HAT) cycle, Integrated Gasification humid air (IGHAT) cycle and flow evaporative gas turbine cycle (PEvGT) are highlighted due to the interest in achieving high efficiency and low emission. With increasingly stringent environmental requirements on pollutant emissions, production of CO$_2$ and conservation of energy in the past several decades, there is a significnt increase of interest in IGCC and IGHAT cycle. In IGHAT and IGCC cycle, the gas turbine is powered by the combustion of "syngas" which is a hydrogen-rich mixture produced through the coal gasification. Giles et al.[1] reported typical syngas compositions that are in use in different power generation units. The composition of syngas obtained from different coal gasification plants can be summarized as 30–60% H$_2$–CO by volume with different CO/H$_2$ ratios. Thus, there is considerable variation in the composition of syngas due to various sources and processing methods, which would cause to the differences in the combustion properties of fuel including flame speed, heating-value and ignition-delay times (compared the natural gas). There is an big challenge in designing efficient gas turbine combustors to suit changes in fuel composition. A great deal of research has been conducted into syngas combustion[2-3]. The most recent investigation took advantage of laser diagnostic techniques to better understand the chemistry and fluid dynamics of syngas flows. And strong efforts are currently under-taken for the numerical simulation of syngas combustion flames with the intentional use for the design of improved GT combustors. The developments and applications of the CFD codes with reaction mechanism specific to syngas, call for detailed experimental validation under different operating conditions. The German Aerospace Center executed the HEGSA (High Efficient Gas Turbine with Syngas Application) project and wanted to establish such a dataset [4].
Another characteristics in gas turbine of IGHAT cycles is humid air combustion in combustors. The levels of moisture entering the combustors are considerably higher than the levels presently occurring in conventional combustion turbine cycles. This causes increasing the gas turbine efficiency without the need of an additional steam turbine. Besides this, the addition of steam into the combustion process reduces NOx emissions. It lowers the temperature peak by increasing the specific heat capacity and reduces oxygen concentration. Moreover, it alters the NOx formation pathways. A number of recent papers in the gas turbine literature have presented studies on the influence of water/steam addition on NOx and CO emissions[5]. They found that even at constant adiabatic flame temperatures, NOx is reduced with increasing humidity. The presence of steam leads to lower O-atom concentration which reduces “Zeldovich and N2O” NOx while higher OH-atom concentration reduces “Fenimore” NOx. In addition, steam injection allows operation with a variety of fuels, including hydrogen and hydrogen-rich fuels. Therefore, humid air combustor is an attractive solution for industrial application.

Now a promising way is to add steam into the combustion process at near stoichiometric conditions[6-7]. In the current study, the combustion process is investigated for significantly higher steam contents of up to 50%. This promises a further increase in efficiency and also allows for postcombustion CO2 capture at low cost, since the concentration of CO2 reaches the highest possible value for air breathing gas turbines after condensation of the steam. This causes a valid concern regarding combustion stability, efficiency and emissions of a combustor[8]. Additionally, for the IGHAT cycles, the combustor design is affected by both the different combustion characteristics of the coal gas fuel (composed primarily of CO H2 and CO2) and high moisture levels in the air which should require a combustor design that significantly deviates from conventional gas turbine experience.

The purpose of the present work is to report on an experimental study intended to examine the effect of CO/H2 molar ratio on flame structures and combustion emissions in a high humid air/syngas combustor. The study can provide a reliable database for high moisture gas turbine combustor design and combustion numerical simulation. The typical syngas fuel in this paper is simulated by a synthetic mixture of H2, CO, and CO2. Planar laser induced fluorescence (PLIF) measurement of OH radicals is adopted to yield useful insight into the chemical reaction zones and flame structures in humid air/syngas flame.

### NOMENCLATURE

- $D_a$ annular air-flow diameter
- $D_f$ central fuel-injection diameter
- $S$ swirl number, dimensionless
- $\Phi$ equivalence ratio
- $LHV$ Low heat value

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{V,\text{fuel}}$</td>
<td>volume flux of fuel at standard conditions</td>
</tr>
<tr>
<td>$Q_{V,\text{air}}$</td>
<td>volume flux of air at standard conditions</td>
</tr>
</tbody>
</table>

### EXPERIMENTAL SETUP

#### Apparatus and instruments

Fig. 1 shows a schematic of experiment setup. As shown in figure, syngas is confected by H2, CO, CO2and N2. The content of syngas fuel is adjusted by monitoring and controlling four mass flow controllers for four kinds of gases respectively, and is well mixed in a fuel mixer before going into the sprayer. The humid air is the mixture of steam and dry air. In experiment, steam is supplied by steam generators, and the amount of steam is controlled by flowmeter and regulating valve. The air flow rate is controlled by a flowmeter and transducer.

![Fig. 1. Schematic diagram of the experimental setup](image)

![Fig. 2. Structure of the double-swirled burner](image)
In this study, experiments are performed in an optically accessible combustion chamber, with the length of 200 mm and square section of 100*100 mm (Fig. 2). Two of three quartz windows are positioned at left and right sides for laser sheet, and the other window is placed on the top of the combustion chamber for signal capture. The chamber is convectively cooled with air-cooling passages around its radial direction. Upstream of the combustion chamber, there mounts the sprayer with double-swirled structure shown in Figure 1. The outer diameter of the sprayer is 42 mm. Air is supplied from a fan, and then delivered through the axial swirler before entering the combustion chamber test section. The air swirler is consisted of eight channels with the swirl number on the order of 0.8, based on its geometric dimension. The fuel flow is also swirled by an axial swirler with six 45° vanes. Leading to its swirl passages are co-swirling.

During experiment, planar laser induced fluorescence (PLIF) of OH radical is employed to detect reaction zone dimension and flame front position. The excitation laser derives from a pulsed Nd: YAG laser pumping a tunable dye laser with Rhodamine 6G as dye solution before going through a frequency double crystal. The output ultraviolet laser beam has the wavelength of 281.46 nm with pulse duration of 20 ns, and is used to excite OH radicals on the R1(9) line of the A^3Σ^+ ← X^2Π(v’=1, v”=0) transition. The ultraviolet laser beam is expanded by a set of spherical and cylindrical lenses, forming a laser sheet with the thickness less than 500 μm. The laser sheet is guided vertically through the center of the test section in the combustion chamber. The fluorescence is then collected around wavelength of 310 nm by an ICCD camera placed perpendicular to the laser sheet plane with Nikon UV lens, in front of which a combined UG11 and WG305 interference filter set is installed to suppress scattered laser light and background flame radiation. Timing delay of PLIF system is controlled by a pulse delay generator DG535. The gate width or exposure time of ICCD camera is set to 100 ns to include a complete OH fluorescence for each instantaneous laser shot. 500 single-shot OH-PLIF raw images are recorded for post-processing for each flame. PLIF measurement field, and 63.8*80 mm^2 rectangular test section, is fixed to the exit of the swirler. The resolution of each image is higher than 0.1 mm per pixel.

In addition to OH radical detection by PLIF technique, the temperature and CO emission at the exhaust section after the combustion chamber are measured by six thermal-couples and Siemens gas analyzer (ULTRAMAT 23), respectively. Six thermal-couples are disposed at six different radial positions, where the area of each rings is equal. The exhaust mean temperature is obtained by algebraically average of these six temperatures. The NOx and CO emission were converted to the concentrations at 15% O2 condition, with the O2 concentration recorded simultaneously, followed by Eq. 1 and Eq. 2.

\[
[CO]_{\text{measured}} = \frac{[CO]_{\text{measured}} \times 0.21 - [O_2]_{\text{measured}}}{0.21 - [O_2]_{\text{measured}}}
\]

\[
[NO]_{\text{measured}} = \frac{[NO]_{\text{measured}} \times 0.21 - [O_2]_{\text{measured}}}{0.21 - [O_2]_{\text{measured}}}
\]

**Operation conditions**

During experiment, the global equivalence ratio (Φ) is kept to 0.845 for all flames, and the air flow is fixed. The experimental conditions are as follow: P=1.0 atm, \(T_{\text{air, in}}=398K\), \(Q_{\text{fuel, in}}=288K\), \(Q_{\text{air, in}}=24.0\ Nm^3/h\), \(Q_{\text{fuel, in}}=10.08\ Nm^3/h\). There are two group operation codes in experiment. The first is to investigate on the influence of the humidity in syngas flame, as shown as in Tab. 1. The H2O/air molar ratio is from 0-50%. The second is to investigate on effects of the CO/H2 Ratio in humid air flames. There are two steam addition: 6 Nm3/h and 12 Nm3/h (the H2O/air molar ratios are 25% and 50% in humid air) in experiment. Test cases in experiment are summarized in Tab. 2.

<table>
<thead>
<tr>
<th>Fuel code</th>
<th>Syngas composition (by volume)</th>
<th>H2/O2/air molar ratio</th>
<th>CO/H2 molar ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-BZ0</td>
<td>36.9 H2, 47.6 CO, 15.5 CO2</td>
<td>0%</td>
<td>1.29</td>
</tr>
<tr>
<td>S-BZ1</td>
<td>36.9 H2, 47.6 CO, 15.5 CO2</td>
<td>10%</td>
<td>1.29</td>
</tr>
<tr>
<td>S-BZ1.5</td>
<td>36.9 H2, 47.6 CO, 15.5 CO2</td>
<td>15%</td>
<td>1.29</td>
</tr>
<tr>
<td>S-BZ2</td>
<td>36.9 H2, 47.6 CO, 15.5 CO2</td>
<td>20%</td>
<td>1.29</td>
</tr>
<tr>
<td>S-BZ2.5</td>
<td>36.9 H2, 47.6 CO, 15.5 CO2</td>
<td>25%</td>
<td>1.29</td>
</tr>
<tr>
<td>S-BZ3</td>
<td>36.9 H2, 47.6 CO, 15.5 CO2</td>
<td>30%</td>
<td>1.29</td>
</tr>
<tr>
<td>S-BZ4</td>
<td>36.9 H2, 47.6 CO, 15.5 CO2</td>
<td>40%</td>
<td>1.29</td>
</tr>
<tr>
<td>S-BZ5</td>
<td>36.9 H2, 47.6 CO, 15.5 CO2</td>
<td>50%</td>
<td>1.29</td>
</tr>
</tbody>
</table>

**Tab. 1 Operation conditions for the investigation on the Influence of the Humidity in syngas flame**

<table>
<thead>
<tr>
<th>Fuel code</th>
<th>Syngas composition (by volume)</th>
<th>H2/O2/air molar ratio</th>
<th>CO/H2 molar ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-BZ0CH75</td>
<td>49.3 H2, 37.0 CO, 13.7 CO2</td>
<td>0%</td>
<td>0.75</td>
</tr>
<tr>
<td>S-BZ0CH100</td>
<td>42.7 H2, 42.7 CO, 14.6 CO2</td>
<td>0%</td>
<td>1.29</td>
</tr>
<tr>
<td>S-BZ0CH129</td>
<td>36.9 H2, 47.6 CO, 15.5 CO2</td>
<td>0%</td>
<td>1.29</td>
</tr>
<tr>
<td>S-BZ0CH150</td>
<td>33.6 H2, 50.4 CO, 16.0 CO2</td>
<td>0%</td>
<td>1.5</td>
</tr>
<tr>
<td>S-BZ0CH90</td>
<td>27.7 H2, 55.5 CO, 19.8 CO2</td>
<td>0%</td>
<td>2.00</td>
</tr>
<tr>
<td>S-BZ0CH50</td>
<td>23.6 H2, 59.0 CO, 17.4 CO2</td>
<td>0%</td>
<td>2.5</td>
</tr>
<tr>
<td>S-BZ25CH75</td>
<td>49.3 H2, 37.0 CO, 13.7 CO2</td>
<td>25%</td>
<td>0.75</td>
</tr>
<tr>
<td>S-BZ25CH100</td>
<td>42.7 H2, 42.7 CO, 14.6 CO2</td>
<td>25%</td>
<td>1</td>
</tr>
<tr>
<td>S-BZ25CH129</td>
<td>36.9 H2, 47.6 CO, 15.5 CO2</td>
<td>25%</td>
<td>1.29</td>
</tr>
<tr>
<td>S-BZ25CH150</td>
<td>33.6 H2, 50.4 CO, 16.0 CO2</td>
<td>25%</td>
<td>1.5</td>
</tr>
<tr>
<td>S-BZ25CH200</td>
<td>27.7 H2, 55.5 CO, 19.8 CO2</td>
<td>25%</td>
<td>2.00</td>
</tr>
<tr>
<td>S-BZ25CH250</td>
<td>23.6 H2, 59.0 CO, 17.4 CO2</td>
<td>25%</td>
<td>2.5</td>
</tr>
<tr>
<td>S-BZ5CH75</td>
<td>49.3 H2, 37.0 CO, 13.7 CO2</td>
<td>50%</td>
<td>0.75</td>
</tr>
<tr>
<td>S-BZ5CH100</td>
<td>42.7 H2, 42.7 CO, 14.6 CO2</td>
<td>50%</td>
<td>1.29</td>
</tr>
</tbody>
</table>
**RESULTS AND DISCUSSION**

**The Influence of the humidity in syngas flames**

This experiment is finished in atmospheric condition. There are some differences between the experimental in atmospheric conditions and actual operative conditions. Bhargava et al[9] gives a review about the investigations on lean premixed combustion and performed an experimental and modeling investigation in order to determine the effect of pressure on emissions and the stability limit at lean conditions in 100~400 psi range with two different nozzle. If the influence of pressure on NO\textsubscript{x} emissions is expressed

\[
\left[\frac{\text{NO}}{\text{NO}_\text{x, atm}}\right] = p^n
\]

researchers have obtained different value for n varying from -0.77 to 1.6 which is related to equivalence ratio, unmixedness level, nozzle or combustor geometry and absolute pressure. Martelli et al[10] have experimentally investigated the pollutant emissions of a heavy-duty diffusion flame type, natural gas fuelled turbine combustor and its retrofitted version for reducing NO\textsubscript{x} emission under atmospheric and real gas turbine pressure conditions. They related the NO\textsubscript{x} emissions at atmospheric condition to those at full pressure and acquired the exponent n which is about 0.45 for both versions of combustor at full load. Cui et al[11] have investigated the effects of pressure on a gas turbine syngas combustor by numerical simulation. Their numerical results show that at the same fuel and air inlet temperature and the same equivalence ratio, the operation pressure has less effect on the flow fields, but its effect on temperature distribution and NO\textsubscript{x} emissions is obvious. The NO\textsubscript{x} emissions, the highest temperature in the combustor and the outlet temperature will increase with increasing operating pressure. Thus, the outlet temperature and NO\textsubscript{x} emissions in this experiment will lower than those in actual operative conditions.

Figure 3 is typical photographs of syngas flames under different humidification amounts in model combustor with dual-swirled burner. As shown in Figure 3a, there are double flame fronts at flame root region for 0% H\textsubscript{2}O. There are possibly three reasons contributing to the phenomenon of double flame fronts. Firstly, there are two shear layers on the both sides of the fuel swirling flow: one is the outer layer, between the fuel swirling flow and the air swirling flow; The other is the inner layer, between the fuel swirling flow and the high temperature recirculating gas, which can provide a stable ignition source. Secondly, the main contents of mid-calorific syngas are CO and H\textsubscript{2}, and the flame speed is high(\textit{the flame speed of H\textsubscript{2} and CO are 292cm/s and 43 cm/s). Lastly, the mid-calorific syngas has a high flame temperature. Thus, there is double flame fronts in mid-calorific syngas flame. As is shown in Figure3b-3c, the double flame structure disappear gradually with the increase of the steam additions. The region of the blue flame reduces continuously ,and flame’s color changes from sky blue to saffron with the increase of H\textsubscript{2}O content.

![PLIF measurement field](Image)

![Fig. 3 Photography of flames under different humidification amounts in model combustor (CO/H\textsubscript{2}=1.29)](Image)

![Fig. 4 OH radical distributions of flames burning syngas under different humidity](Image)
Fig. 5 average exhaust temperatures under different humidity

Fig. 6 outlet emissions under different humidity

Fig. 7 OH radical distributions of flames burning syngas under different CO/H\textsubscript{2} ratios with different steam additions

The ensemble images of mean OH-PLIF intensities of syngas flames with various CO/H\textsubscript{2} ratios under three moisture degree in the model combustor fueled through the burner with double-swirled structure after post-processing procedures, including average of 500 instantaneous images and shot-to-shot correction of laser energy, are shown in Fig.4. Air and fuel passages inside double-swirled burner are depicted on the left side of each image by the color of blue and red, respectively. The size of the burner and its position to the OH-PLIF test section are both in accordance with that during experiment after proper image processing. The legend is also shown in this figure, indicating the relative intensity of the OH radical fluorescence. The Fig.4
shows that with the increase of humidity: the region of the main reaction zone reduces continuously; the OH fluorescence intensity become weaker; the center of main reaction zone moves toward burner; the region of the main reaction zone on the head of combustor increases at first, then shrinks; a narrow area with low OH fluorescence intensity come out at the center of burner.

Fig.5 shows the average exhaust temperature under different humidity in syngas flames. As shown in figure, the average exhaust temperature declines with the increase of H2O content. Fig.6 is the combustor emissions under different humidity in syngas flame. The figure shows that the NOx emission will reduce quickly and the CO emission will increase continuously with increase of the H2O content in humid air. But when [H2O]>16.7%, the decrease speed of the NOx emission will reduce. And the CO emission will increase more quickly when [H2O]>23.1%

**The effects of the CO/H2 Ratio in humid air flames**

OH radical distributions of flames burning syngas for different CO/H2 ratios in humid air flame are shown in Fig.7. The OH intensity distribution shows that syngas is burnt in the shape of shuttle with CO/H2 ratio varies from 0.75 to 2.5. In regions close to the burner exit there exist two areas of very low OH intensity, representing the unburned swirling fuel near centerline and air on the upper left corner. The edge of flame root can be recognized as two parts of inner and outer ones. With the increase of CO/H2 ratio in syngas fuel, these two flame fronts tends to be merged together. Meanwhile, the distance between burner and the edge of flame root increases with higher CO/H2 ratio. As CO/H2 ratio increases, the content of CO out of syngas fuel increases with that of H2 decreases, leading to a fuel with more weight and less diffusivity. Since the chemical reaction speed of CO is much lower than that of H2, syngas with more CO and less H2 needs more time and space to complete reaction. As a result, the distance between burner and the edge of flame root increases with the higher CO/H2 ratio.

Fig. 7 also shows the the mean OH-radical distribution of syngas flames under various humid in air. As shown in Fig.4, the concentration of OH radicals becomes lower, and also strength of fluorescent signal is weakening clearly. At the same time, main reaction zone shrinks with the increase of H2O concentration. It can be seen from Fig.3b and Fig.3c that the lift-off height of the syngas flame with steam addition is smaller than that of the syngas flame without steam addition. Moreover, the syngas flame gradually appeared W type distribution and more and more obvious with the increased of humidification amount.

Fig.8 shows the average exhaust temperature in the exhaust section for syngas under different humidification amounts and different CO/H2 malor ratios. As shown in figure, the average exhaust temperature declines with the increase of H2O content. However, CO/H2 malor ratio influences the exhaust temperature a little. According to Table 1, the LHV of syngas keep constant in experiment though the CO/H2 malor ratios changes. Thus, heat release should be same for different fuel, and the average exhaust temperature changes little.

![Fig. 8 Effect of average exhaust gas temperatures under different humidification amounts and different CO/H2 ratio](image)

![Fig.9 Effect of CO emission under different humidification amounts and different CO/H2 ratios](image)

Fig.9 shows the effect of CO emission under different humidification amounts and different CO/H2 ratios. The relationship between CO emission and CO/H2 ratio under high humidification amounts is quite different from the low humidification amounts. When H2O/air ratio is 0 or 25%, CO emissions is small and change little with the variation of CO/H2 ratios. But CO emissions increase quickly with CO/H2 ratios increase monotonically when H2O/air ratio is 50%. As is shown in figure, CO emissions are all small for different humid air conditions when CO/H2 ratios is below 1.3. If CO/H2 ratios is bigger, the difference between low and high humidification amounts operation case increase.

The level of NOx emission in exhaust section of the test facility is reported in Fig.10 for syngas flame under different humidification amounts and different CO/H2 ratios. It can be seen from the figure that The level of NOx emission keep almost constant for different CO/H2 ratios. But The NOx emission
reduces with more and more steam added into combustor. The NO\textsubscript{X} emission gap between 50% \text{H}_2\text{O}/\text{air} ratio and 25% \text{H}_2\text{O}/\text{air} ratio is small. The syngas fuel used in experiment is the mixture of \text{H}_2, \text{CO}, and \text{CO}_2. When syngas combusts in model combustor, there are such compositions in flame: \text{H}_2, \text{H}, \text{OH}, \text{CO}, \text{CO}_2, \text{O}, \text{N}_2, \text{N}, \text{NO}, and \text{HO}_2. There is no \text{CH}, \text{CH}_2, or \text{C}_2\text{H}, which means the prompt \text{NO}_\text{X} formation does not exist [12]. So it is mainly caused by the temperature declination in reaction zones, which is desirable for suppressing the thermal \text{NO}_\text{X} formation.

CONCLUSIONS

In this paper, experimental results of a series test conditions regarding syngas in a model combustor with double-swirled structure burner are presented. The effects of the CO/H\textsubscript{2} molar ratio consisting of syngas fuel are investigated under different humidity.

1) With the increase of CO/H\textsubscript{2} ratios, the concentration field of OH radicals is gradually decreasing away from the nozzle exit, and at the nozzle exit almost no existence of OH radicals when CO/H\textsubscript{2} \geq 2.0, forming a typical lifted flame; the average exhaust temperature in reduce a little for different humidity operation conditions; NO\textsubscript{X} emission keep constant; the CO emission keep constant under low humidity condition, but increase under high humidity condition.

2) With the increase of H\textsubscript{2}O content in air, the concentration of OH radicals becomes lower, and main reaction zone shrinks; the lift-off height of high CO/H\textsubscript{2} ratios syngas flame reduce; the average exhaust temperature and \text{NO}_\text{X} emission declines.

ACKNOWLEDGMENTS

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REFERENCES


