Investigation of temperature and CO$_2$ concentration in converter gas flames by a combustion diagnostic system based on TDLAS

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Abstract. In this study, a novel combustion diagnostic system based on tunable diode laser absorption spectroscopy (TDLAS) was developed to simultaneously measure the temperature and CO$_2$ concentration in flames on a turbulent partly premixed burner. This system simulates harsh industrial combustion environment and enables in situ measurements of non-uniform temperature and CO$_2$ concentration distributions in converter gas-air flames. A mixture of CO, CO$_2$, and N$_2$ with the volume percentage ratio 80:15:5 was injected into the fuel stream to simulate effects of converter gas. Temperature and CO$_2$ concentration in flames along the axial direction at the burner centerline were simultaneously measured by online TDLAS. The flame temperature was compared with that obtained by thermocouple measurement. The CO$_2$ concentration was compared with those of samples taken from the flame. The results of online TDLAS measurements showed the same variation trend as temperature in the core of the flames measured using thermocouples and CO$_2$ concentration obtained from the analysis of samples. This work proved that non-uniform temperature and CO$_2$ concentration distributions in converter gas flames could be measured by this system and laid the foundation for further study about the effects of CO$_2$ and/or N$_2$ addition on converter gas/air flames.

1. Introduction

Converter gas [1] is generated during the process of oxygen converter steelmaking and contains approximately 80% carbon monoxide (CO), 15% carbon dioxide (CO$_2$) and 5% nitrogen (N$_2$). Converter gas is an important secondary energy resource and normally used as a fuel in hot-blast stoves, steel rolling heating furnaces, and power plants [2]. In order to get a primarily understanding of the combustion behavior of converter gas in harsh industrial environment, it is necessary to measure the fundamental parameters including temperature and species concentration in flames.

Tunable diode laser absorption spectroscopy (TDLAS) is a novel spectroscopic monitoring technique for temperature and species concentration measurement. Zhang et al studied two-dimensional temperature and CO$_2$ concentration distributions in methane co-flow diffusion flame [3]. Reconstruction technique based on TDLAS has been widely used for measuring temperature and species concentration distributions [4-7]. Ma et al in situ measured the non-uniform temperature, and H$_2$O and CO$_2$ concentration distributions in a premixed methane–air laminar flame by TDLAS [8]. Sebastian Bü rkle et al investigated the effects of oxy-fuel atmosphere on the temperature and H$_2$O, CH$_4$, OH and CO concentrations in methane flame [9]. TDLAS is useful for temperature and CO$_2$ concentration measurement in harsh ambient conditions.
The effects of CO\textsubscript{2} and/or N\textsubscript{2} addition on multi gas flames have been widely studied. Tu et al discussed MILD combustion and the flame characteristics of CH\textsubscript{4}/H\textsubscript{2} diluted by CO\textsubscript{2} [10,11]. The effect of CO\textsubscript{2} addition on CH\textsubscript{4}-air flames was a major subject investigated in combustion and energy [12-18]. Xi et al investigated the effects of CO\textsubscript{2} addition on temperature and soot formation in ethylene/air flame [19]. The effect of CO\textsubscript{2} and/or N\textsubscript{2} addition on the structure and temperature of some other hydrocarbon fuel flames has been discussed [20-22].

Based on the outcome of previous studies, a combustion diagnostic system based on TDLAS was developed for simultaneously measuring the temperature and CO\textsubscript{2} concentration in converter gas-air flames. The non-uniform temperature and CO\textsubscript{2} concentration in the flames along the axial direction at the burner centerline were simultaneously measured by online TDLAS. The online TDLAS was compared to thermocouple measurement and sampling analysis.

2. Experimental

2.1. Combustion diagnostic system based on TDLAS

The simplified schematic of the combustion diagnostic system is shown in figure 1.

![Schematic of the combustion diagnostic system](image)

This system consists of CO, N\textsubscript{2}, and CO\textsubscript{2} gas cylinders, pressure relief valves, an air compressor, mass flow controllers (MFCs), a mixing chamber, digital manometers, an operation screen, a ball valve, pressure stabilizing valves, a gas solenoid valve, digital manometers, a butterfly valve, a partly premixed burner, a fire controller, a combustion chamber, laser diode controllers, DFB lasers, a splitter, laser probes, extension tubes, a detector, a computer, a displacement platform, an Ar gas cylinder, a pressure relief valve, and LZB gas flow meters.

CO, N\textsubscript{2}, and CO\textsubscript{2} gas cylinders and air compressor provide fuel gas and air. The supplied CO, N\textsubscript{2}, and CO\textsubscript{2} gases from Praxair have a purity of 99.9%, 99.999%, and 99.9%, respectively. The gas flow rates are controlled by mass flow controllers. The fuel gas and air are transferred through the ball valve, pressure stabilizing valves, the gas solenoid valve, digital manometers, and the butterfly valve into the partly premixed burner and ignited in the combustion chamber finally. The temperature and CO\textsubscript{2} concentration in flames are measured by online TDLAS and compared to thermocouples and sampling.
The laser diode controllers (ILX 3724C) exactly control the current and temperature. Two DFB lasers (NEL KELD1G5BAAA) generate two tunable continuous-waves. The splitter splits the light sources into three laser probes corresponding to three measurement positions. The light is emitted by laser probe and passes through the extension tube and flame. The detector receives the light and converts it into an electrical signal. The signal is transmitted to the data acquisition card in the computer and demodulated by LabView-based software. The extension tube is placed on the laser probe and connected to an Ar gas cylinder, a pressure relief valve and LZB gas flow meters, which is aimed to blow off the air inside the tube. The laser detection device is supported by a displacement platform, which is controlled to move along the axial and radial directions by UartAssist software in the ranges 0-500 mm and 0-400 mm.

This study utilized two-line scanned-wavelength direct absorption spectroscopy to measure the temperature and CO₂ concentration in converter gas flames. Two tunable continuous-waves near 1996 and 2004 nm were employed as the light sources. A spectral simulation of the selected absorption lines using the HITRAN database was plotted, as shown in figure 2. The strong absorbance of CO₂ and high temperature sensitivity were chosen to guarantee high signal-to-noise ratio (SNR) and minimal interference from ambient water vapor.

![Absorbance vs Wavelength](image.png)

**Figure 2.** Simulation of the CO₂ and H₂O absorption lines at different temperatures. The total pressure and path length were set at 1 atm and 45 mm, respectively.

### 2.2. Operating conditions and the analysis of data

| Table 1. Combustion conditions of the converter gas. |
|-----------------------------------------------------|
| Converter gas pressure | Air pressure | CO volume flow rate | CO₂ volume flow rate | N₂ volume flow rate | Air volume flow rate |
|------------------------|--------------|---------------------|----------------------|---------------------|----------------------|
| Unit | kPa | kPa | L/min | L/min | L/min | L/min |
| 1 | 0.88 | 0.32 | 33.4 | 6.2 | 2.1 | 302.4 |
| 2 | 0.88 | 0.31 | 33.4 | 6.2 | 2.1 | 302.3 |
| 3 | 0.88 | 0.32 | 33.4 | 6.2 | 2.1 | 302.4 |
| 4 | 0.88 | 0.33 | 33.4 | 6.2 | 2.1 | 302.5 |
Table 1 lists the measurement conditions of the experiments. CO, CO₂, and N₂ with a volume percentage of 80:15:5 were injected into the fuel stream. The representative measurements (Plot 0) of the absorption spectra of CO₂ along with the corresponding Voigt-fitting profiles (Plot 1) and residuals (Plot 2) of the two lines are presented in Labview software, which is shown in figures 3 and 4.

![Figure 3. Measured absorption spectra of CO₂ near 1996 nm. The Voigt fit to the experimental data is plotted for comparison along with the residual.](image)

![Figure 4. Measured absorption spectra of CO₂ near 2004 nm. The Voigt fit to the experimental data is plotted for comparison along with the residual.](image)

Nine positions in total were selected for temperature and CO₂ concentration measurement. S-type platinum rhodium thermocouples (wrp-100) were used for temperature measurement in the core of the flames. The thermal response time of thermocouple is ~150 s, and the limit of intrinsic error is ±0.25%. Six of the nine measurement positions were chosen for thermocouple measurement because of the long thermal response time. A black box, a sampling tube, a laser diode controller, a DFB laser, a laser probe, a detector and a computer were utilized for the detection of samples taken from the
flames. The process of detection is shown in figure 5. The black box was completely evacuated before each measurement, and the whole process lasted for 180 s. Six of the nine measurement positions were chosen for the sample detection, because the sampling process needed too much time.

Figure 5. The process of sampling detection based on TDLAS.

3. Results and discussions

3.1. Temperature

Figure 6 shows the online TDLAS temperature measurements and the temperature measured using thermocouples as a function of distance along the centerline axis, which are processed by software Origin Lab. In the entire flame area (ca. 80 mm along the axial direction), the TDLAS temperature remained constant between 600 K and 1400 K, while the thermocouple temperature remained constant between 800 K and 1500 K. The temperature uncertainty for all the points was ≤40 K. The variation trends of the results measured by the two methods agree well.

Figure 6. The two methods for temperature measurements in flames. Temperature measured by online TDLAS at 9 positions along the axial direction at the burner centerline is compared with thermocouple measurement at 6 positions.

The measurement area was divided into the flame end part (axis 0-10 mm along the center line), the flame center part (axis 35-45 mm along the centerline) and the flame tip part (axis 70-80 mm along the centerline). In the flame end part, the TDLAS temperature ranged 681-719 K, while the thermocouple
temperature ranged 882-917 K. In addition, the thermocouple temperature values were approximately 200 K higher than those of TDLAS. In the central part of the flame, the temperature measured by TDLAS ranged 753-774 K, while the thermocouple temperature ranged 938-958 K. The temperature measured by thermocouples was approximately 180 K higher than those of TDLAS. As the flame was kept at a distance from the burner exit, both the fuel and air gradually mixed well, leading to a rapid increase in the temperature, and the temperature fluctuations remained initially flat, which then increased with the increasing axial distance. In the flame tip part, the TDLAS temperature ranged from 1158 K to 1331 K, while thermocouple temperature ranged 1259-1478 K. The thermocouple temperatures were approximately 110 K higher than those measured using online TDLAS. Due to a good mixing between the fuel and air, the temperature of the flame rapidly increased to a maximum (1331 K for TDLAS and 1478 K for thermocouple) in the beginning. Then, the temperature decreased and temperature fluctuations increased as the horizontal flame turned upward under the action of updraft in the tip.

3.2. $\text{CO}_2$ concentrations

The results of $\text{CO}_2$ concentrations along the axial direction at the centerline measured by online TDLAS and sampling are processed by software Origin Lab and shown in figure 7. In the detection area, the distribution of $\text{CO}_2$ concentrations measured using the online TDLAS remained constant within 15.6 mol%, whereas the results obtained from analyzing the samples were within 16.0 mol%. The results measured by analyzing the samples were the average concentrations in the detection device after sampling. In this section, mol% was defined as the mole percentage of the measured $\text{CO}_2$ concentration passing through the laser lights. The uncertainty in the $\text{CO}_2$ concentrations for all the points was $\leq 0.96$ mol%.

![Figure 7. The two methods for $\text{CO}_2$ concentration measurements in flames. $\text{CO}_2$ concentration measured by online TDLAS at 9 positions along the axial direction at the burner centerline is compared with sampling TDLAS measurement at 6 positions.](image)

The $\text{CO}_2$ concentrations measured using the online TDLAS ranged from 6.2 mol% to 15.6 mol%, while those obtained from the analysis of samples ranged 7.1-16.0 mol%. The results from the analysis of samples were 0.47 mol% to 0.96 mol% higher than those obtained using the online TDLAS. The $\text{CO}_2$ concentrations initially remained low, and then increased with the axial distance to a maximum. Finally, it decreased rapidly with the appearance of upward flame.
4. Conclusions
In conclusion, a novel combustion diagnostic system based on tunable diode laser absorption spectroscopy (TDLAS) was developed and successfully built to simultaneously measure the temperature and CO$_2$ concentration in converter gas/air flames on a turbulent partly premixed burner. The temperature and CO$_2$ concentration in converter gas flames along the axial direction at the burner centerline were simultaneously measured by online TDLAS. The flame temperature was compared with that measured using thermocouples. The CO$_2$ concentration was compared with those of samples taken from the flame. The results indicate that this newly developed system achieved in situ measurements of non-uniform temperature and CO$_2$ concentration in converter gas flames. The results of online TDLAS measurements showed the same variation trend as temperature in the core of the flames measured using thermocouples and CO$_2$ concentration obtained from the analysis of samples. The updraft in the tip of the horizontal flames affected the temperature and CO$_2$ concentration fluctuations. This study laid the foundation for further studying the effects of CO$_2$ and/or N$_2$ addition on converter gas/air flames.

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