

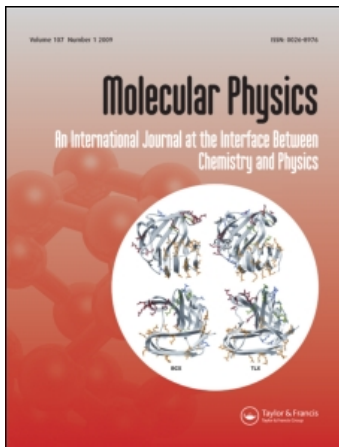
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Diode laser measurement of line strengths and air-broadening coefficients of CO₂ and CO in the 1.57 μm region for combustion diagnostics

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RESEARCH ARTICLE

Diode laser measurement of line strengths and air-broadening coefficients of CO₂ and CO in the 1.57 μm region for combustion diagnostics

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Spectral measurements of two line pairs of CO₂ and CO in the temperature range 300–1000 K at 1.573 μm were performed using a fiber-coupled distributed feedback (DFB) diode laser. The two line pairs can be used in a tunable diode laser (TDL) absorption sensor for simultaneously detecting CO₂ and CO gas in a single scan of the diode laser. The spectral parameters (line strengths, air-broadening coefficients and the temperature exponent n) of the two pairs are presented. The measured data agree well with existing databases (HITRAN 2004 and HITRAN 2008), the discrepancies being less than 5% for most of the probed transitions. Although the HITRAN database is a useful tool for sensor design, we found that laboratory measurements of the spectroscopic data for the line pair selected for high-temperature sensors are necessary for establishing the uncertainty for accurate measurements.

Keywords: CO₂ and CO; high temperature; line strength; air-broadening coefficients

1. Introduction

Sensors based on tunable diode laser absorption spectroscopy (TDL sensor) have been employed for more than two decades to provide non-intrusive *in situ* measurements of temperature, pressure, species concentration, and flow velocity in a variety of environments [1–5]. Accurate values of certain spectroscopic parameters, such as line strength and line broadening coefficients, are very important in the development of a TDL sensor. In particular, the diagnosis of high-temperature combustion environments with a TDL sensor requires line strength and collisional broadening coefficients as a function of temperature.

Studies of carbon dioxide and carbon monoxide have always been of immense importance in combustion. CO₂ and CO are attractive target gases for hydrocarbon-fueled systems and their concentrations can be interpreted to indicate combustion efficiency. The TDL sensors used to detect CO₂ or CO have been developed in the mid- and near-infrared [6–15]. The information (temperature, gas species concentration, velocity, density, mass flux, pressure, etc.) provided by such sensors can be useful in the development of modern propulsion and combustion systems, e.g. to facilitate design advancements, improve efficiency, and

reduce pollutant emissions. Although the absorbances of the second overtone and combination band in the near-infrared are relatively weak compared with the fundamental bands in the mid-infrared, the advances in detection methods (e.g. wavelength modulation spectroscopy, frequency modulation spectroscopy) over the past decade have greatly increased the sensitivity of diode laser absorption spectroscopy measurements, such that detection of fractional absorbances on the order of 10⁻⁶ or better can be achieved [16,17]. In addition, robust, compact, fiber-coupled, mW, single-mode, telecommunications-grade diode lasers in the near-infrared are commercially available.

CO₂ and CO have been extensively studied in all infrared bands [18–28], and a large set of line parameters may be found in the HITRAN database [29]. However, only a few of these parameters have been measured at high temperature [30–32]. As the standards of efficiency and emissions of combustion have become more and more strict, the study of molecular spectra at higher temperatures has become crucial. This paper presents precise measurements of line strengths and air-broadening coefficients of two pairs of CO₂ and CO (6357.312 and 6357.814 cm⁻¹, 6361.250 and 6361.344 cm⁻¹) in the 1.57 μm region.

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Temperature exponents of the pressure-broadening coefficients are also given. Each line pair is of particular interest owing to their use in the TDL absorption sensor for measuring CO₂ and CO gas concentrations simultaneously in a single scan of the diode laser. The measured parameters in the present study are compared with published data from HITRAN 2004 and HITRAN 2008. The results are valuable for transition selection and evaluation of the uncertainty of accurate measurements of CO₂ and CO gas concentrations in the development of high-temperature sensors.

2. Theory

The transmission coefficient $\tau(\nu)$ of monochromatic radiation through a uniform medium can be obtained from the Beer–Lambert relation

$$\tau(\nu) = \left(\frac{I_t}{I_0}\right)_\nu = \exp[-\alpha(\nu)], \tag{1}$$

where I_t and I_0 are the transmitted and incident laser intensities, respectively, and $\alpha(\nu)$ represents the spectral absorbance. For an optically thin sample ($\alpha(\nu) < 0.1$),

$$\tau(\nu) = \exp[-\alpha(\nu)] \approx 1 - \alpha(\nu) = 1 - PxL \sum_j S_j(T)\varphi_j(\nu), \tag{2}$$

where P (atm) is the total pressure, x is the mole fraction of the absorbing species, L (cm) is the path length, S_j (cm⁻²atm⁻¹) is the line strength of the transition, $\varphi_j(\nu)$ (cm) is the shape function which is normalised such that $\int \varphi_j(\nu)d\nu \equiv 1$, the subscript j denoting the j th absorption feature, and T (K) is the gas temperature.

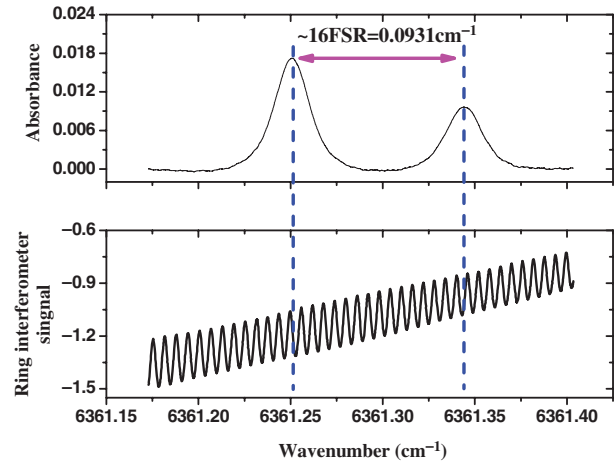


Figure 2. Top: Absorption spectrum of CO₂ and CO at 6361.250 and 6361.344 cm⁻¹, respectively. Bottom: Ring interferometer signal.

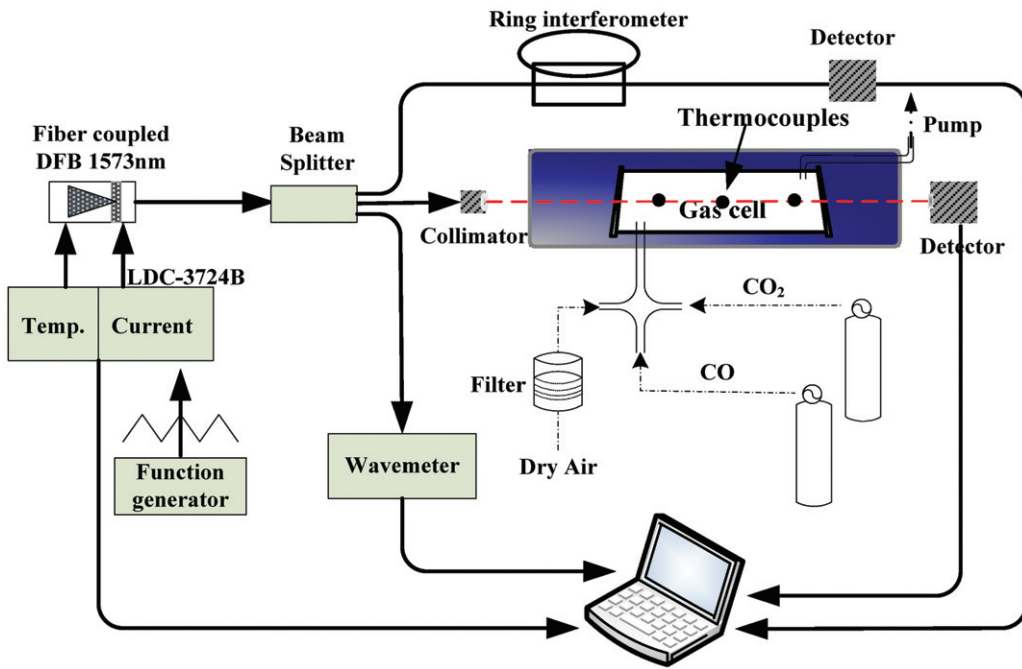


Figure 1. Schematic of the experimental setup.

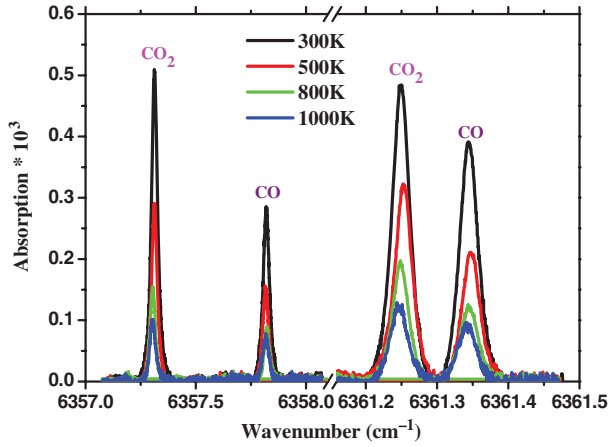


Figure 3. Measured spectra of the selected transitions in pure gas at different temperatures with 25.19 Torr of CO₂ and 19.29 Torr of CO. The y axis is the integrated absorption $-\ln(I_t/I_0)/L$.

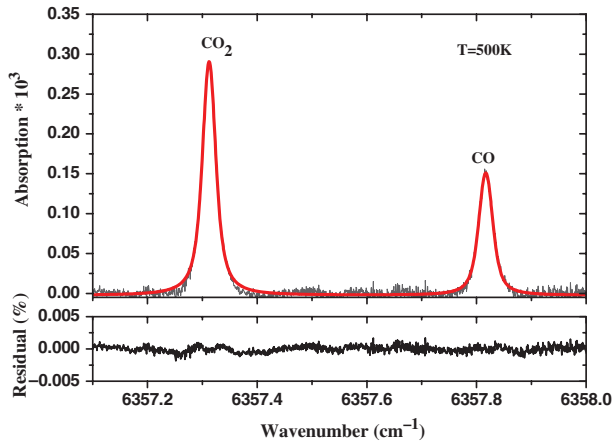


Figure 4. Comparison between the experimental line shape and the fit Voigt function for the selected transitions at 6357.312 and 6357.814 cm⁻¹ with 25.19 Torr of CO₂ and 19.29 Torr of CO at a temperature of 500 K. The y axis is the integrated absorption $-\ln(I_t/I_0)/L$. The lower part shows the residual obtained from the least-square fitting.

The integrated absorbance (cm⁻¹) can be expressed as

$$A = \int_{-\infty}^{+\infty} \alpha_\nu d\nu = PxS(T)L. \quad (3)$$

The temperature-dependent line strength at an arbitrary temperature T is related to the known line strength at reference temperature T_0 by

$$S(T) = S(T_0) \frac{Q(T_0)}{Q(T)} \left(\frac{T_0}{T}\right) \exp\left[-\frac{hcE''}{k} \left(\frac{1}{T} - \frac{1}{T_0}\right)\right] \times \left[1 - \exp\left(\frac{-hcv_0}{kT}\right)\right] \left[1 - \exp\left(\frac{-hcv_0}{kT_0}\right)\right]^{-1}, \quad (4)$$

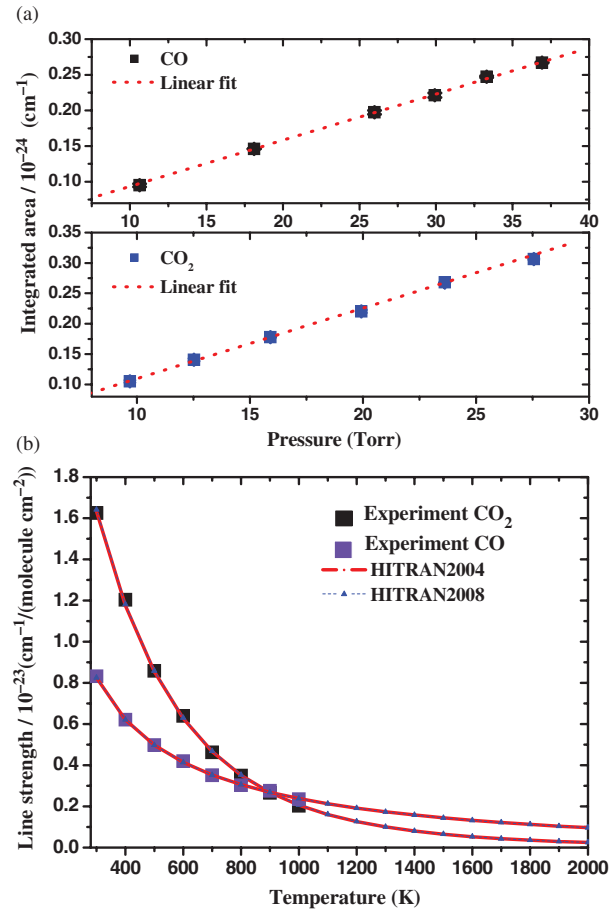


Figure 5. Line strength measurements for the transitions at 6357.312 and 6357.814 cm⁻¹. (a) Measured integrated absorbance versus pressure at $T=500$ K, and the linear fit used to infer the line strength. (b) Comparison between the measured line strength and the HITRAN database value.

where $Q(T)$ is the molecular partition function, h (J s⁻¹) is Planck's constant, c (cm s⁻¹) is the speed of light, k (J K⁻¹) is Boltzmann's constant and ν_0 (cm⁻¹) is the line-center frequency of the transition.

The line-shape function in Equation (2) is usually represented by a Voigt profile [33] when both Doppler and collisional broadening are considerable as in many combustion applications. The Doppler full width at half maximum (FWHM) of a molecule with molecular weight M (g mol⁻¹) at temperature T (K) is given by

$$\Delta\nu_D = (7.1623 \times 10^{-7}) \nu_0 \sqrt{\frac{T}{M}} \quad (5)$$

The collisional FWHM $\Delta\nu_C$ is proportional to the system pressure,

$$\Delta\nu_C = P2\gamma = P \sum_i x_i 2\gamma_i, \quad (6)$$

where γ_i (cm⁻¹ atm⁻¹) is the collisional broadening coefficient of the absorbing species for perturber i with

Table 1. Comparison of the measured results for the line strength and the HITRAN database values for the two pairs of CO₂ and CO transitions.

| ν_0 (cm ⁻¹) | S_M | S_{H04} | σ (%) | S_{H08} | σ (%) | S_M | S_{H04} | σ (%) | S_{H08} | σ (%) |
|-----------------------------|-------|-----------|--------------|-----------|--------------|-------|-----------|--------------|-----------|--------------|
| | | | 300 K | | | | | 400 K | | |
| CO ₂ 6357.312 | 16.25 | 16.33 | -0.49 | 16.41 | -0.97 | 12.04 | 11.76 | 2.38 | 11.82 | 1.86 |
| CO 6357.814 | 8.325 | 8.255 | 0.85 | 8.255 | 0.85 | 6.214 | 6.217 | -0.5 | 6.217 | -0.5 |
| CO ₂ 6361.250 | 16.76 | 16.94 | -1.06 | 16.91 | -0.88 | 13.29 | 13.30 | -0.07 | 13.28 | -0.07 |
| CO 6361.344 | 12.09 | 12.09 | 0 | 12.09 | 0 | 9.177 | 9.187 | -0.11 | 9.187 | -0.11 |
| | | | 500 K | | | | | 600 K | | |
| CO ₂ 6357.312 | 8.583 | 8.542 | 0.48 | 8.583 | 0 | 6.389 | 6.275 | 1.81 | 6.305 | 1.33 |
| CO 6357.814 | 4.979 | 4.978 | 0.02 | 4.978 | 0.02 | 4.199 | 4.138 | 1.47 | 4.138 | 1.47 |
| CO ₂ 6361.250 | 10.16 | 10.18 | -0.19 | 10.16 | 0 | 7.651 | 7.743 | -1.18 | 7.730 | -1.02 |
| CO 6361.344 | 7.424 | 7.396 | 0.37 | 7.396 | 0.37 | 6.131 | 6.172 | -0.66 | 6.172 | -0.66 |
| | | | 700 K | | | | | 800 K | | |
| CO ₂ 6357.312 | 4.622 | 4.667 | -0.96 | 4.690 | -1.44 | 3.493 | 3.515 | -0.63 | 3.532 | -1.10 |
| CO 6357.814 | 3.511 | 3.527 | -0.45 | 3.527 | -0.45 | 3.035 | 3.059 | -0.78 | 3.059 | -0.78 |
| CO ₂ 6361.250 | 5.905 | 5.904 | 0.02 | 5.894 | 0.18 | 4.417 | 4.530 | -2.49 | 4.522 | -2.32 |
| CO 6361.344 | 5.201 | 5.274 | -1.38 | 5.274 | -1.38 | 4.511 | 4.584 | -1.59 | 4.584 | -1.59 |
| | | | 900 K | | | | | 1000 K | | |
| CO ₂ 6357.312 | 2.653 | 2.679 | 0.97 | 2.692 | -1.44 | 2.028 | 2.065 | -1.79 | 2.075 | -2.26 |
| CO 6357.814 | 2.752 | 2.688 | 2.38 | 2.688 | 2.38 | 2.352 | 2.386 | 1.43 | 2.386 | -1.43 |
| CO ₂ 6361.250 | 3.540 | 3.503 | 1.05 | 3.497 | 1.22 | 2.613 | 2.732 | 4.28 | 2.727 | -4.18 |
| CO 6361.344 | 4.090 | 4.034 | 1.38 | 4.034 | 1.38 | 3.432 | 3.585 | -4.27 | 3.585 | -4.27 |

Notes: S_M , measured line intensity (10^{-24} cm⁻¹/(molecule cm⁻²)); S_{H04} , line intensity in HITRAN 2004 (10^{-24} cm⁻¹/(molecule cm⁻²)); S_{H08} , line intensity in HITRAN 2008 (10^{-24} cm⁻¹/(molecule cm⁻²)); σ , $(S_M - S_H)/S_H$.

mole fraction x_i . The temperature dependence of the collisional broadening coefficient γ_i can be expressed in terms of the temperature exponent n as

$$\gamma_i(T) = \gamma_i(T_0) \left(\frac{T_0}{T} \right)^n. \quad (7)$$

3. Experimental details

A schematic of the laboratory experimental arrangement used to study the spectroscopic parameters is shown in Figure 1. A heated static cell (20 cm long with wedged (1.5°) windows to avoid residual etalon fringes), equipped with a temperature controller (type SKW), was used for measurements at temperatures as high as 1000 K. The cell has a total path length of 38 cm and an inner diameter of 3.5 cm. Three type K thermocouples with an accuracy of $\pm 1\%$ were attached to the middle and both ends of the absorption cell to monitor the temperature of the gas. The maximum temperature deviation along the path length was measured to be less than 1%. The gas pressures were measured by a vacuum pressure gauge with an accuracy of $\pm 1\%$. After the heated cell was evacuated to the order of 10^{-4} Torr using a mechanical pump and a molecular pump, CO₂ and CO gases of 99.99% purity

were delivered into the cell. When the air-broadening coefficients were measured, dry air (filtered with a 1 μ m diameter filter) was charged into the heated cell using a perturber gas. Before each measurement, the gas sample was allowed to stabilise thermally for a sufficient time. The total sample pressures were known to be better than 0.4%.

The DFB laser (NEL NLK1E5GAAA) used in the experiments can produce ~ 10 mW of stable output power near 1.573 μ m. The laser was placed in a commercial laser mount (ILX Lightwave LDM-4980) and driven using a modular diode-laser controller (ILX Lightwave LDC-3724). The laser beam was coupled to a single-mode fiber optic cable using bulk optics. A 1 \times 3 fiber splitter divides the laser output into three beams. The main beam ($\sim 90\%$ of the power) is collimated by a fiber collimator and directed to the heated cell containing pure or mixed gas at known temperature and pressure. The transmitted laser beam exiting the heated cell is detected by a Ge photo-detector (New Focus 2011). A ring interferometer (RI) with a free spectral range (FSR) of 0.00601 cm⁻¹ (Figure 2) receives the secondary beam (8% of the power), which is monitored by another similar photo-detector for wavelength calibration, and the remaining beam is focused on the probe of a wavemeter

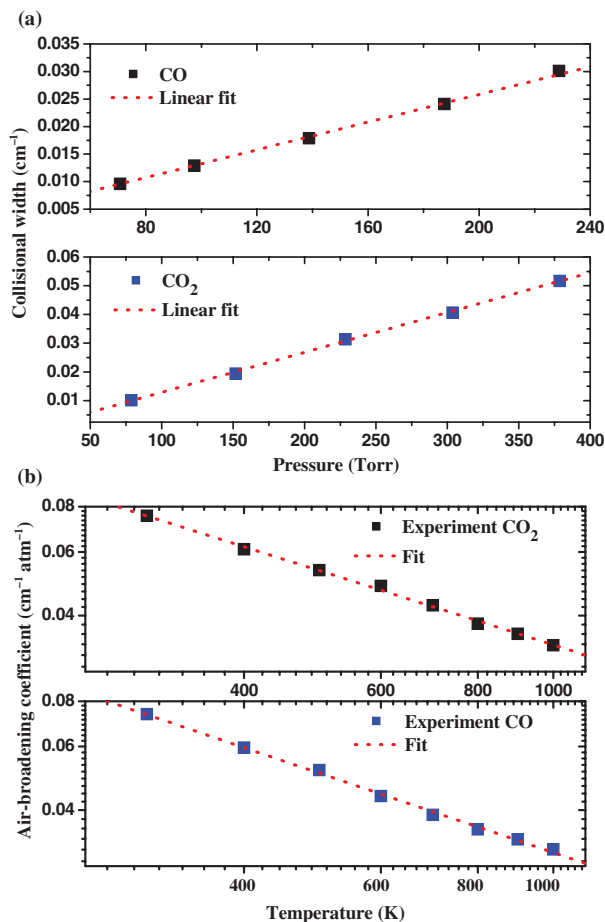


Figure 6. Air-broadening coefficient measurements for the transitions at 6357.312 and 6357.814 cm⁻¹. (a) Collisional HWHM for various pressures determined by Voigt fits, $T = 500$ K. (b) The measured air-broadening coefficients versus temperature, and the fit used to infer the temperature exponent n .

(Burleigh, WA-1500-NIR, with an accuracy of about ± 0.001 cm⁻¹) to record the absolute wavelength.

The system error was estimated to be better than 2%, based on uncertainties in the pressure, the uncertainty of the FSR of the RI, the error of calibration of the heated cell, etc. Further details concerning the experimental apparatus, sample pressures and sample temperature monitoring, calibration procedures and experimental precautions taken to minimise systematic errors have been discussed previously [34,35].

4. Spectroscopy results and discussion

Figure 3 shows the measured spectra of the selected transitions in pure gas at different temperatures with 25.19 Torr of CO₂ and 19.29 Torr of CO. At this pressure, the line shape function of gaseous molecule absorption was fitted using a Voigt function where

both Doppler and pressure broadening are considered. Here, all the recorded spectra are fitted with standard Voigt line profiles in order to determine the line strengths and air-broadening coefficients of CO₂ and CO transitions. During the fitting process, the amplitude, the collisional (Lorentz) width, the line center frequency and the magnitude of the background are varied, while the Doppler width is maintained fixed at the theoretical value. Figure 4 presents the experimental line profile fitted with the Voigt function and residual for the transitions at 6357.312 and 6357.814 cm⁻¹ recorded at a temperature of 500 K.

4.1. Measurements of line strength

The line strength measurement procedure is illustrated in Figure 5 and is similar to that used in [36]. For each temperature, the integrated absorbance area is first measured at six different pressures from 5 to 40 Torr. At each pressure, five measurements are made, and the average value of the integrated absorbance and its standard deviation are extracted and plotted in Figure 5(a) (the error bars are too small to be identified in this figure). These data are fitted to a line to eliminate any systematic error in the zero of the pressure gauge. The line strength and its statistical precision at this temperature can be inferred from the slope of the linear fit to the data. Line strength measurements are made at eight different temperatures from 300 to 1000 K. The measured line strength and the statistical precision of the CO₂ and CO transitions near 6357.312 and 6357.814 cm⁻¹ at each temperature are plotted in Figure 5(b). The good agreement (most within 1%) between the measured and HITRAN databases value confirms the spectroscopic assignment in HITRAN. The measured results of the two pairs of CO₂ and CO transitions are compared with the HITRAN 2004 and HITRAN 2008 databases in Table 1. For most lines, the difference between the measured line strength and the HITRAN database value is about $\pm 1\%$.

4.2. Measurements of the air-broadening coefficient

To infer the air-broadening coefficients for the selected transitions, the absorption spectra of CO₂- and CO-air mixtures at pressures of 50–400 Torr were measured at a series of temperatures between 300 and 1000 K. The collisional width can be obtained by the Voigt fit of the measured absorption. In order to remove the contribution of self-broadening, the pure CO₂ and CO spectra were recorded before dry air was added to the heated cell and the collisional width obtained from the

Table 2. Comparison of the measured results for the air-broadening coefficient and the HITRAN database values for the two pairs of CO₂ and CO transitions.

| ν_0 (cm ⁻¹) | γ_M | γ_{H04} | σ (%) | γ_{H08} | σ (%) | γ_M | γ_{H04} | σ (%) | γ_{H08} | σ (%) |
|-----------------------------|------------|----------------|--------------|----------------|--------------|------------|----------------|--------------|----------------|--------------|
| | | | 500 K | | | | | | | 600 K |
| CO ₂ 6357.312 | 0.0755 | 0.0755 | 0 | 0.0773 | -2.32 | 0.0610 | 0.0619 | -1.45 | 0.0632 | -3.48 |
| CO 6357.814 | 0.0737 | 0.0741 | -0.54 | 0.0741 | -0.54 | 0.0596 | 0.0597 | -0.17 | 0.0597 | -0.17 |
| CO ₂ 6361.250 | 0.0728 | 0.0715 | 1.82 | 0.0729 | -0.13 | 0.0558 | 0.0576 | -3.13 | 0.0602 | -7.30 |
| CO 6361.344 | 0.0700 | 0.0702 | -0.28 | 0.0702 | -0.28 | 0.0561 | 0.0567 | -1.06 | 0.0567 | -1.06 |
| | | | 500 K | | | | | | | 600 K |
| CO ₂ 6357.312 | 0.0534 | 0.0531 | 0.57 | 0.054 | -1.11 | 0.0483 | 0.0468 | 3.21 | 0.0476 | 1.47 |
| CO 6357.814 | 0.0516 | 0.0505 | 2.18 | 0.0505 | 2.18 | 0.0437 | 0.0440 | -0.68 | 0.0440 | -0.68 |
| CO ₂ 6361.250 | 0.0482 | 0.0487 | -1.03 | 0.0518 | -6.94 | 0.0428 | 0.0425 | 0.71 | 0.0458 | -6.55 |
| CO 6361.344 | 0.0481 | 0.0481 | 0 | 0.0481 | 0 | 0.0431 | 0.0420 | 2.61 | 0.0420 | 2.61 |
| | | | 700 K | | | | | | | 800 K |
| CO ₂ 6357.312 | 0.0427 | 0.0421 | 1.43 | 0.0427 | 0 | 0.0380 | 0.0384 | -1.04 | 0.0389 | -2.31 |
| CO 6357.814 | 0.0388 | 0.0392 | -1.02 | 0.0392 | -1.02 | 0.0354 | 0.0355 | -0.28 | 0.0355 | -0.28 |
| CO ₂ 6361.250 | 0.0362 | 0.0379 | -4.49 | 0.0413 | -12.34 | 0.0331 | 0.0343 | -3.49 | 0.0378 | -12.43 |
| CO 6361.344 | 0.0378 | 0.0375 | 0.81 | 0.0375 | 0.81 | 0.0340 | 0.0340 | 0 | 0.0340 | 0 |
| | | | 900 K | | | | | | | 1000 K |
| CO ₂ 6357.312 | 0.0356 | 0.0354 | 0.68 | 0.0358 | -0.55 | 0.0331 | 0.0329 | 0.61 | 0.0333 | -0.60 |
| CO 6357.814 | 0.0332 | 0.0325 | 2.15 | 0.0325 | 2.15 | 0.0311 | 0.0300 | 3.67 | 0.0300 | 3.67 |
| CO ₂ 6361.250 | 0.0323 | 0.0314 | 2.65 | 0.0349 | -7.44 | 0.0295 | 0.0290 | 1.75 | 0.0326 | -9.50 |
| CO 6361.344 | 0.0313 | 0.0311 | 0.64 | 0.0311 | 0.64 | 0.0273 | 0.0288 | -5.20 | 0.0288 | -5.20 |

Notes: γ_M , measured air-broadening coefficient (cm⁻¹ atm⁻¹); γ_{H04} , line intensity in HITRAN 2004 (cm⁻¹ atm⁻¹); γ_{H08} , line intensity in HITRAN 2008 (cm⁻¹ atm⁻¹); σ , $(\gamma_M - \gamma_H)/\gamma_H$.

pure CO₂ and CO spectra was subtracted from that for CO₂- and CO-air mixtures. At a selected temperature, the air-broadening coefficient can be determined from the slope of the linear fit to the measured collisional width at various pressures of CO₂- and CO-air mixtures, as shown in Figure 6(a) (again the error bars are too small to be identified in this figure). It can be seen from the figure that the linearity is excellent, and suggests a negligible Dick narrowing effect within the plotted pressure range [37–39]. The temperature exponent n of the air-broadening coefficient can be inferred from the fit of the measured air-broadening coefficient at various temperatures, as illustrated in Figure 6(b). The measured results for the air-broadening coefficient and the temperature exponent n are compared with HITRAN 2004 and HITRAN 2008 databases in Tables 2 and 3, respectively. It is found that the discrepancies are less than 5% for most of the probed transitions.

The estimated uncertainties of our measured line strength and air-broadening coefficients are typically no more than 5%, resulting from the measurement uncertainties of 1% in the temperature, 1% in the pressure, 0.5% in the path length, 2% in the area or width for the Voigt fit, and less than 1% in the standard deviations for multiple measurements. To our knowledge, the measurements presented here are the first of their kind at temperatures as high as 1000 K.

Table 3. Comparison of the measured results for the temperature exponent n and the HITRAN database values for the two pairs of CO₂ and CO transitions.

| ν_0 (cm ⁻¹) | n_M | n_{H04} | σ (%) | n_{H08} | σ (%) |
|-----------------------------|-------|-----------|--------------|-----------|--------------|
| CO ₂ 6357.312 | 0.678 | 0.69 | -1.739 | 0.7 | -3.142 |
| CO 6357.814 | 0.729 | 0.75 | -2.80 | 0.75 | -2.80 |
| CO ₂ 6361.250 | 0.767 | 0.75 | 2.267 | 0.67 | 14.49 |
| CO 6361.344 | 0.753 | 0.74 | 1.757 | 0.74 | 1.757 |

Notes: n_M , measured temperature exponent n ; n_{H04} , temperature exponent n in HITRAN 2004; n_{H08} , temperature exponent n in HITRAN 2008; σ , $(n_M - n_H)/n_H$.

Although the HITRAN database is a useful tool for sensor design, it focuses on atmospheric conditions, where temperatures range from 200 to 350 K. For high-temperature diagnostics applications, especially those with temperature variations between 300 and 1000 K, we suggest using our measurement results presented here since the HITRAN database is optimised for low-temperature applications.

5. Conclusion

High-resolution absorption spectra of two pairs of CO₂ and CO (6357.312 and 6357.814 cm⁻¹, 6361.250 and 6361.344 cm⁻¹) were recorded in a heated cell as a function of temperature and pressure. Each line pair

can be used in the TDL absorption sensor for detecting CO₂ and CO gas simultaneously in a single scan of the diode laser. Line strengths, air-broadening coefficients and the temperature exponent of the two pairs were inferred from the measured spectra and compared with the HITRAN 2004 and HITRAN 2008 databases. Small discrepancies (<5%) between the measurements and databases are identified for most of the probed transitions. The measurement results are very useful for the design of a combustion diagnostics sensor used to monitor the emission of CO₂ and CO.

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References

- [1] J.A. Silver and D.J. Kane, *Measure. Sci. Technol.* **10**, 845 (1999).
- [2] K. Chan, H. Ito, H. Inaba and T. Furuya, *Appl. Phys. B* **38**, 11 (1985).
- [3] A. Rocco, G. Natale, P. De Natale, G. De Gagliardi and L.A. Gianfrani, *Appl. Phys. B* **78**, 235 (2004).
- [4] L.C. Philippe and R.K. Hanson, *Appl. Opt.* **32**, 6090 (1993).
- [5] D. Richter, D.G. Lancaster and F.K. Tittel, *Appl. Opt.* **39**, 4444 (2000).
- [6] D.M. Sonnenfroh and M.G. Allen, *Appl. Opt.* **36**, 3298 (1997).
- [7] L. Joly, B. Parvitte, V. Zeninari and G. Durry, *Appl. Phys. B* **86**, 743 (2007).
- [8] J.B. Jeffries, C. Schulz, D.W. Mattison, M.A. Oehlschlaeger, W.G. Bessler, T. Lee, D.F. Davidson and R.K. Hanson, *Proc. Comb. Inst.* **30**, 1591 (2005).
- [9] J. Wang, M. Maiorov, J.B. Jeffries, D.Z. Garbuzov, J.C. Connolly and R.K. Hanson, *Measure. Sci. Technol.* **11**, 1576 (2000).
- [10] R.M. Mihalcea, D.S. Baer and R.K. Hanson, *Appl. Opt.* **36**, 8745 (1997).
- [11] M. Gabrysch, C. Corsi, F.S. Pavone and M. Inguscio, *Appl. Phys. B* **65**, 75 (1997).
- [12] B.L. Upschulte, D.M. Sonnenfroh and M.G. Allen, *Appl. Opt.* **38**, 1506 (1999).
- [13] A. Farooq, J.B. Jeffries and R.K. Hanson, *Appl. Phys. B* **90**, 619 (2008).
- [14] R.A. Engelbrecht, *Spectrochim. Acta A* **60**, 3291 (2004).
- [15] V. Weldon, J. O'Gorman, P. Phelan, J. Hegarty and T. Tanbun-Ek, *Sensors Actuators B* **29**, 101 (1995).
- [16] J.A. Silver, *Appl. Opt.* **31**, 707 (1992).
- [17] J. Reid and D. Labrie, *Appl. Phys. B* **26**, 203 (1981).
- [18] I. Pouchet, V. Zeninari, B. Parvitte and G. Durey, *J. Quant. Spectrosc. Radiat. Transfer* **83**, 619 (2004).
- [19] L. Ozanne, J.-P. Bouanich, R. Rodrigues, J.-M. Hartmann, G. Blanquet and J. Walrand, *J. Quant. Spectrosc. Radiat. Transfer* **59**, 337 (1998).
- [20] C. Corsi, F. D'Amato, M. De Rosa and G. Modugno, *Appl. Phys. B* **70**, 879 (2000).
- [21] C. Corsi, F. D'Amato, M. De Rosa and G. Modugno, *Eur. Phys. J. D* **6**, 327 (1999).
- [22] J.S. Li, K. Liu, W.J. Zhang, W.D. Chen and X.M. Gao, *J. Quant. Spectrosc. Radiat. Transfer* **109**, 1575 (2008).
- [23] T. Hikida, K.M.T. Yamada, M. Fukabori, T. Aoki and T. Watanabe, *J. Molec. Spectrosc.* **232**, 202 (2005).
- [24] J. Henningsen and H. Simonsen, *J. Molec. Spectrosc.* **203**, 16 (2000).
- [25] M. De Rosa, C. Corsi, M. Gabrysch and F. D'Amato, *J. Quant. Spectrosc. Radiat. Transfer* **61**, 97 (1999).
- [26] V.M. Devi, D.C. Benner, M.A.H. Smith, L.R. Brown and M. Dulick, *J. Quant. Spectrosc. Radiat. Transfer* **76**, 393 (2003).
- [27] J.W.C. Johns, *J. Molec. Spectrosc.* **134**, 433 (1989).
- [28] J.W.C. Johns and J. Vander Auwera, *J. Molec. Spectrosc.* **140**, 71 (1990).
- [29] L.S. Rothman, D. Jacquemart, A. Barbe, D. Chris Benner, M. Birk, L.R. Brown, M.R. Carleer, C. Chackerian Jr, K. Chance, L.H. Coudert, V. Dana, V.M. Devi, J.-M. Flaud, R.R. Gamache, A. Goldman, J.-M. Hartmann, K.W. Jucks, A.G. Maki, J.-Y. Mandin, S.T. Massie, J. Orphal, A. Perrin, C.P. Rinsland, M.A.H. Smith, J. Tennyson, R.N. Tolchenov, R.A. Toth, J. Vander Auwera, P. Varanasi and G. Wagner, *J. Quant. Spectrosc. Radiat. Transfer* **96**, 139 (2005).
- [30] X.S. Song, X.D. Yang, Y.D. Guo, J. Wang, X.L. Cheng and R.F. Ling-Hu, *Commun. Theor. Phys.* **47**, 892 (2007).
- [31] R.M. Mihalcea, D.S. Baer and R.K. Hanson, *Appl. Opt.* **37**, 8341 (1998).
- [32] L. Rosenmann, S. Langlois, C. Delaye and J. Taine, *J. Molec. Spectrosc.* **149**, 167 (1991).
- [33] E.E. Whiting, *J. Quant. Spectrosc. Radiat. Transfer* **16**, 611 (1976).
- [34] W.X. Zhao, X.M. Gao, L.H. Deng, T. Huang, T. Wu and W.J. Zhang, *J. Quant. Spectrosc. Radiat. Transfer* **107**, 331 (2007).
- [35] L.H. Deng, X.M. Gao, Z.S. Cao, W.D. Chen, W.J. Chen and Z.B. Gong, *J. Quant. Spectrosc. Radiat. Transfer* **103**, 402 (2007).
- [36] H.J. Li, A. Farooq, J.B. Jeffries and R.K. Hanson, *J. Quant. Spectrosc. Radiat. Transfer* **109**, 132 (2008).
- [37] R.H. Dick, *Phys. Rev.* **89**, 472 (1953).
- [38] S. Langlois, T.P. Birbeck and R.K. Hanson, *J. Molec. Spectrosc.* **163**, 27 (1994).
- [39] V. Nagali, S.I. Chou, D.S. Baer and R.K. Hanson, *J. Quant. Spectrosc. Radiat. Transfer* **57**, 795 (1997).