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FTIR emission spectroscopy methods and procedures for real time quantitative gas analysis in industrial environments

Jimmy Bak and Sønnik Clausen

Optics and Fluid Dynamics Department, OFD-128, PO Box 49, DK-4000 Roskilde, Denmark

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Abstract
Diagnostic tools for real time and direct gas analysis have been developed. The simultaneous measurements of gas and particle temperatures (280–330 °C) and gas concentrations (CO, CO_2, HCl, H_2O) are demonstrated in a hot particle-laden flue gas with a fibre-optic probe connected to a Fourier transform infrared spectrometer. The gas temperature is found from the thermal radiation at the 2350 cm^{-1} CO_2 fundamental band, whereas the gas concentrations are determined by comparing the measured transmittance spectra with a spectroscopic database and validation measurements using the Hotgas facility at Risø. Measurement uncertainties are discussed. The measured local gas temperatures and concentrations are in good agreement with measurements made with conventional equipment.

Keywords: gas analysis, gas temperature, emission spectroscopy, FTIR, Hitemp, high-temperature gas cell, incinerator plant

1. Introduction

Infrared spectroscopic diagnostic methods, which have been designed for making rapid measurements of key parameters in harsh industrial systems, are valuable when detailed knowledge is required about the process inside the systems on a short timescale. Deeper insight into the chemical reactions taking place within the system can be achieved if robust methods are available which are able to measure both temperature and the most important gaseous species simultaneously and rapidly inside the process. More information about the process on a shorter timescale enables even more precise control of the process. This will yield both economic and environmental benefits. The disadvantage in using conventional gas analysers based on sampling and thermocouples for temperature measurements is the extended time of measurement, which results in integrated mean values. Time delays of 1–5 min are not unusual. In addition, the separate measurements of gas concentrations and temperature make it difficult to correlate relative changes in gas composition and variations in temperature. A literature review reveals that papers reporting *in situ* infrared spectroscopic measurements in industrial systems without sampling are very rare [1, 2].

In the EU project Aeroprofile, the Hotgas facility was developed at Risø National Laboratory. The facility comprises a heated gas cell, a blackbody source, an FTIR spectrometer and gas mixing equipment. Aeroprofile was designed to develop methods for profiling FTIR spectrometry, which could be used to investigate the spatial distribution of temperatures and simultaneously chemical species in aircraft exhaust engines. The Hotgas test facility was used to validate the methods developed in the Aeroprofile project. In a newly begun EU project entitled MENELAS, the Hotgas facility will be used to calibrate and validate the performance of gas analysers based on diode lasers. Analytical procedures, which have been presented recently, can be used to determine the gas temperatures based on combined emission–transmission measurements [3, 4].

In the work presented in this paper we shall demonstrate how the experience gained with the experimental methods developed in the Aeroprofile project with minor modifications can be used to determine the temperature and gas concentrations simultaneously in harsh industrial environments. This is exemplified by a particle-laden hot-gas flow in an incinerator plant. The temperatures and concentrations will be extracted from the measurements by

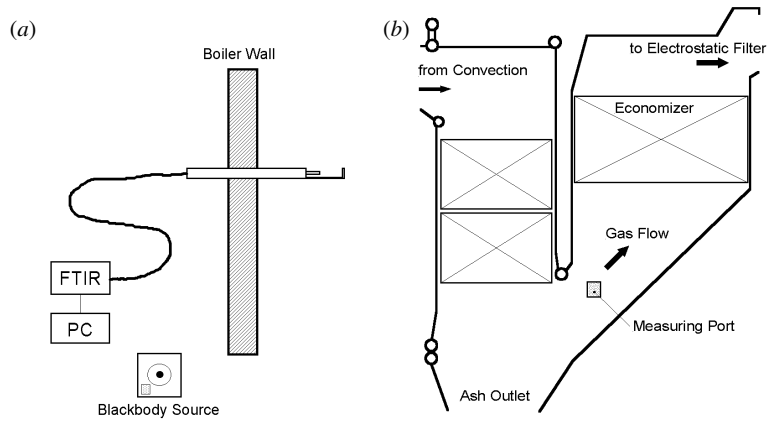

Figure 1. Experimental set-up at the site and schematic diagram of the rear part of the waste incinerator. (*a*) The fibre-optic probe is inserted through the boiler wall with the probe head approximately 0.5 m into the hot-gas flow. (*b*) Position of the measuring port used during experiments.

applying the analytical procedures developed earlier. A fibre-optic probe was developed in order to measure the thermal radiation inside the hot-gas flow. The probe was designed in such a way that it could be considered as a heated gas cell. Assuming that the gas behaves as a uniform slab of gas over a set pathlength, and choosing this pathlength sufficiently long that the fundamental bands of carbon dioxide saturate (ca 0.1 m with 6% CO_2 at 300 °C), measured spectra can then be compared with those calculated by the Hitemp database [5, 6]. The determination of gas species is relatively simple, giving the experimentally determined gas temperature as input. In addition, the carbon dioxide concentration was checked by reference measurements at the Hotgas facility. Finally, the temperatures and concentration were compared with the values measured by the staff at the plant using conventional techniques.

The experimental work presented below was initiated in order to demonstrate the close link between measurements carried out at our Hotgas laboratory facility and in harsh industrial environments. In an earlier work [3, 4], we showed that it was possible to relate radiance and transmittance data of CO_2 measured at our hot-gas cell taking into account the response of almost all radiating parts in the experimental set-up. As a result of this, the gas temperature is determined by fitting a Planck blackbody curve to measured CO_2 radiance bands. In order to test these ideas in practical environments, we developed a water-cooled probe, which resembles a gas cell, i.e. a fixed pathlength exists between the probe optics and a cold plate in the background. Probe performance tests were carried out at a Danish incinerator plant near Copenhagen.

2. Experiment

The experiments were performed on a waste incinerator, furnace no 4, at Vestforbrænding I/S located in a suburb west of Copenhagen.

A schematic drawing of the experimental set-up is shown in figure 1(*a*). The instrumentation comprises a water-cooled fibre-optic probe connected to an FTIR spectrometer, a purge generator, a blackbody calibration source and a computer for collecting, processing and storing spectra.

The flue gas composition was measured with the conventional infrared gas analysers of the plant on gas extraction after the electrostatic filter.

The measuring port was located between the convection unit and economizer (see figure 1(*b*)). At this position the flue gas is cooled to approximately 300 °C.

2.1. Fibre-optic probe

The design of the fibre-optic probe presented in this work is based on our experience obtained earlier with a probe designed for accurate gas temperature measurements in large flames and boilers [7]. In a similar way, the present probe is intended to be used in large systems over 1 MW thermal power. A cross-sectional view of the modified fibre-optic probe head is shown in figure 2. The tip of the protection tube in front of the optical mount and a beam stop defines the optical path. The beam stop is water cooled in order to stabilize the temperature, and reflections are reduced as the surface is grooved and coated with high-emissivity paint.

The probe is designed to minimize disturbances of the temperature profile along the optical path. This is achieved by an un-cooled probe tip in front of the collimating lens that stabilizes the protection tube (figure 2) quickly at the process temperature, and applying the probe with a gas flow direction towards the optical path as indicated in figure 2. The temperature profile is expected to be flat due to its fairly short pathlength compared with the dimensions of the boiler unit (2–15 m) and hence the internal flow patterns.

The fibre-optic probe was made of stainless steel and is water cooled (see figure 2). The distance (0.35 m) between the stainless steel probe tip and a cold plate in the background defines the optical pathlength. A small purge flow from a Balston purge generator was used to prevent the deposition of dust on the optics and distortions of the shape of the CO_2 band due to self-absorption effects from cold CO_2 at the lens.

The fibre-optic probe was connected with a 5 m mid-infrared chalcogenide fibre, 0.76 mm in diameter of type C2, obtained from Amorphous Materials, to the emission port of the FTIR spectrometer, Bomem model MB155, mounted with a liquid-nitrogen-cooled InSb detector. The cooled InSb detector is necessary due to the relatively weak thermal

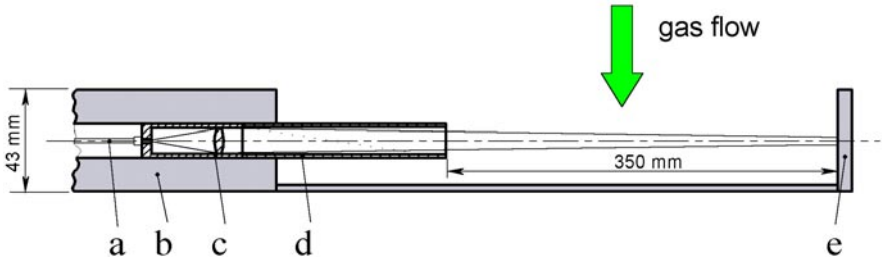

Figure 2. A cross-sectional view of the probe head: a, infrared fibre; b, water-cooled stainless steel probe; c, optical mount; d, protection tube; e, water-cooled beam stop. The optical path (dotted line) and optimum flow direction towards the measuring volume is indicated. The arrow illustrates the desired gas direction with minimum disturbance of the measuring volume conditions in front of the probe tip.

(This figure is in colour only in the electronic version)

radiation at gas temperatures about 300 °C and the small optical throughput of the infrared fibre ($A = 0.45$ mm^2). The data presented in this work are measured at a spectral resolution of 4 or 1 cm^{-1}, and ten or 100 interferograms are collected and averaged, respectively.

A two-point calibration procedure of the FTIR spectrometer is required due to the strong background thermal radiation signal from the instrumentation [8]. This procedure requires two blackbody calibration sources. The fibre optic probe was calibrated at 375 °C with a portable blackbody source, Mikron model M360, and at room temperature with a piece of cardboard.

2.2. Hot-gas cell facility

The design and performance test of a new and improved high-temperature gas cell is described in detail elsewhere [9].

The new cell is characterized by having a flat (less than ±1.0 °C at 300 °C) and stable (0.1 °C) temperature profile along the optical pathlength. This was achieved by changing the design and improving the heating and temperature control system. The hot-gas cell facility was developed as a part of the EU project Aeroprofile for testing and validating an advanced system for spatial aircraft emission measurements [10].

3. Results and discussion

3.1. Analysis of spectra

The measured radiation signal includes radiation from the gas, particles, background and spectrometer. The radiation from the ash particles in the gas is composed of two major parts, thermal emitted radiation from the particles and scattered light. The temperature field around the measuring volume is fairly uniform at the position of measurements, i.e. a simple grey-body approximation is adequate to describe the particle radiation term in this application. The measured signal from the different terms, using a complex formulation, is given by

$$\begin{aligned} f_1(\tilde{\nu}) = R(\tilde{\nu})\mathrm{e}^{\mathrm{i}\phi(\tilde{\nu})}\big[&\underbrace{\varepsilon_\mathrm{g}(\tilde{\nu}, T_\mathrm{g})L(\tilde{\nu}, T_\mathrm{g})(E - E_\mathrm{p})}_{\text{gas radiation}} \\ &+\underbrace{\varepsilon_\mathrm{p}L(\tilde{\nu}, T_\mathrm{p})E_\mathrm{p}}_{\text{particles}} + \underbrace{\tau\,\varepsilon_\mathrm{b}L(\tilde{\nu}, T_\mathrm{b})E}_{\text{background}} + \underbrace{G(\tilde{\nu}, T_\mathrm{i})E_\mathrm{i}\mathrm{e}^{\mathrm{i}\psi(\tilde{\nu})}}_{\text{instrument}}\big] \end{aligned} \tag{1}$$

where f_1 is found from the measured interferogram as described in [2], $R(\tilde{\nu})$ is the spectral response function of the spectrometer, $\phi(\tilde{\nu})$ is the phase response of the instrument, $\varepsilon_\mathrm{g}(\tilde{\nu}, T_\mathrm{g})$is the spectral emissivity of the gas, $E = A\Omega$ (area of fibre core multiplied by solid angle of incident light from lens) is the throughput, $L(\tilde{\nu}, T)$ is the radiance from a blackbody at temperature T (index g for gas, p for particles and b for background) and ε_b and ε_p are the effective emissivities of the background and particle, respectively. τ is the transmitted radiation from the background, $\psi(\tilde{\nu})$ is the phase response for internal instrument radiation and $G(\tilde{\nu}, T_\mathrm{i})$ is the offset from instrument emission, referred to input. A reflection term from the beam stop is not included, as the beam stop of the probe has been designed with $\varepsilon_\mathrm{b} \approx 1$. The offset term $G(\tilde{\nu}, T_\mathrm{i})\,E_\mathrm{i}\mathrm{e}^{\mathrm{i}\psi(\tilde{\nu})}$ is eliminated from equation (1) by subtracting a measurement at ambient ($f_2(\tilde{\nu})$) prior to the Fourier transformation and phase correction of the measured signal (interferogram):

$$f_2(\tilde{\nu}) = R(\tilde{\nu})\mathrm{e}^{\mathrm{i}\phi(\tilde{\nu})}[\varepsilon_\mathrm{b}L(\tilde{\nu}, T_\mathrm{b})E + G(\tilde{\nu}, T_\mathrm{i})E_\mathrm{i}\mathrm{e}^{\mathrm{i}\psi(\tilde{\nu})}]. \tag{2}$$

It is required that the radiation received from the instrument and beam stop of the probe must remain stable, e.g. the beam stop should have a high emissivity to avoid encountering a contribution from reflected radiation and a stable temperature. This procedure is identical to the two-temperature method used to eliminate both 'background effects' and phase correction problems. The background term vanishes only if $\tau = 1$; however, the term can be neglected in the present application as the error is small, i.e. the maximum error ($\tau = 0$) is 0.4% at the 2350 cm^{-1} band of CO_2 at 300 °C, which is equal to an error on the gas temperature measurement of less than 1 °C.

The emittance spectrum is then given by the measured signal in equation (1) after subtracting a measurement at ambient temperature in equation (2):

$$\begin{aligned} f_{12}(\tilde{\nu}) = f_1(\tilde{\nu}) - f_2(\tilde{\nu}) = R(\tilde{\nu})\mathrm{e}^{\mathrm{i}\phi(\tilde{\nu})} \\ \times[\varepsilon_\mathrm{g}(\tilde{\nu}, T_\mathrm{g})L(\tilde{\nu}, T_\mathrm{g})(E - E_\mathrm{p}) + \varepsilon_\mathrm{p}L(\tilde{\nu}, T_\mathrm{p})E_\mathrm{p}]. \end{aligned} \tag{3}$$

The term $R(\tilde{\nu})E$ must be found from a calibration of the measuring system with a blackbody source, and the phase response of the instrument disappears after correcting for phase. Equation (3) is the basic equation for determining the gas temperature, gas composition and particle temperature. The gas concentration can be found from the emissivity spectrum of the gas given by equation (3), if a nonlinear least-squares fitting algorithm for simultaneously estimating all parameters is applied. If the gas temperature and the signal from the particles are known or determined first, a simpler, robust and more direct approach can be followed. This approach will follow in this work.

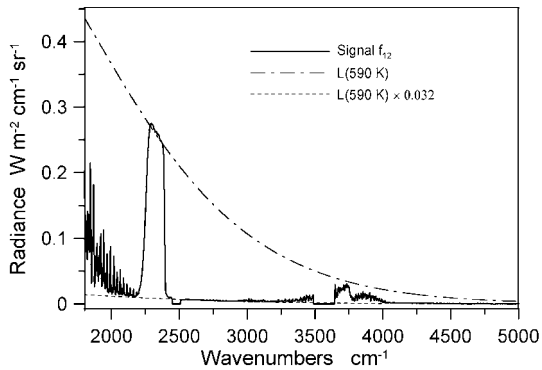

Figure 3. Retrieval of gas temperature from emittance spectrum (solid curve) from best match of the major band of CO_2 at 2350 cm^{-1} with a Planck curve (dot–dashed curve) and particle temperature to a grey body (dashed curve). Both temperatures are estimated as 317 °C from the spectrum. Water lines/bands are seen at approximately 1750–2200 cm^{-1} and 2800–4100 cm^{-1} overlaid with the 3700 cm^{-1} band of CO_2. Regions with strong absorption bands of the optical fibre are truncated. The spectral resolution is 4 cm^{-1} and ten scans were collected.

Quantitative information from the spectra was extracted using the method described in the following. The mean particle temperature can be found from the emittance spectrum from a best fit with a grey body in regions without gas bands (figure 3). The effective particle emissivity over the pathlength can then be found by

$$\varepsilon_{p,\mathrm{eff}} \equiv \frac{\varepsilon_\mathrm{p} L(\tilde{\nu}, T_\mathrm{p}) E_\mathrm{p}}{L(\tilde{\nu}, T_\mathrm{p}) E} = \frac{\varepsilon_\mathrm{p} E_\mathrm{p}}{E}. \tag{4}$$

Similarly, the gas temperature is found directly from a comparison with a Planck curve to the peak of the very strong 2350 cm^{-1} band of CO_2 where $\varepsilon_\mathrm{g} \geqslant 0.99$. This condition is in practice fulfilled for a CO_2 concentration over 3% with a pathlength of 0.35 m at 200–400 °C. However, it is possible to validate that this condition is fulfilled for each measurement from the shape of the CO_2 band when it is saturated. It should be noted that the CO_2 band gas temperature method in reality is less sensitive to the presence of particles than is indicated in equation (3). This is due to the limitation in penetration depth in the range from 2300 to 2350 cm^{-1} to a fraction of the optical pathlength and $E_\mathrm{p} \ll E$, i.e. in this situation $E - E_\mathrm{p} \to E$. Therefore, the gas temperature can be found directly from the emittance spectrum without knowing E_p. Gas concentrations can now be determined by comparing the measurement with a transmittance spectrum calculated from a spectroscopic database. The measured transmittance spectrum can be found from the measured absorptivity or emissivity:

$$\tau_\mathrm{g}(\tilde{\nu}, T_\mathrm{g}) = 1 - \alpha_\mathrm{g}(\tilde{\nu}, T_\mathrm{g}) = 1 - \varepsilon_\mathrm{g}(\tilde{\nu}, T_\mathrm{g}) \tag{5}$$

where Kirchhoff's law expressed as

$$\varepsilon_\mathrm{g}(\tilde{\nu}, T_\mathrm{g}) = \alpha_\mathrm{g}(\tilde{\nu}, T_\mathrm{g}) \tag{6}$$

has been used.

Solving for ε_g in equation (3) and inserting the result in equation (5) and then substituting ε_p for $\varepsilon_{p,\mathrm{eff}}$ and using $\varepsilon_\mathrm{p} \approx 1$ gives

Table 1. 10 min averaged data measured with conventional infrared gas analysers and thermocouple.

10 Feb. 99 Time	CO_2 (vol%) (wet)	CO_2 (vol%)	H_2O (vol%)	CO (mg m^{-3})	Temperature (°C)
14:15	5.5	6.5	14.9	3	291
14:25	6.4	7.6	15.4	3	294
14:35	6.0	7.2	16.7	3	295
14:45	*6.8*	*8.1*	*17.1*	*3*	*293*
14:55	*5.9*	*7.1*	*17.5*	*5*	*292*
15:05	*5.6*	*6.7*	*16.2*	*6*	*297*
15:15	*6.4*	*7.7*	*16.2*	*4*	*292*
15:25	7.1	8.7	18.4	4	286
15:35	6.1	7.5	18.5	4	294

$$\tau_\mathrm{g}(\tilde{\nu}, T_\mathrm{g}) = 1 - \frac{\left[\frac{f_{12}(\tilde{\nu})}{R(\tilde{\nu})E} - \varepsilon_{p,\mathrm{eff}} L(\tilde{\nu}, T_\mathrm{p})\right]}{L(\tilde{\nu}, T_\mathrm{g})\left(1 - \frac{E_\mathrm{p}}{E}\right)}$$
$$\approx 1 - \frac{\left[\frac{f_{12}(\tilde{\nu})}{R(\tilde{\nu})E} - \varepsilon_{p,\mathrm{eff}} L(\tilde{\nu}, T_\mathrm{p})\right]}{L(\tilde{\nu}, T_\mathrm{g})(1 - \varepsilon_{p,\mathrm{eff}})}. \tag{7}$$

Equation (7) is used to calculate the transmittance spectrum to be compared with the simulated spectrum from the database or calibration spectra in order to determine gas concentrations.

The use of common chemometrics methods for multi-component analysis to retrieve gas temperature and concentrations is not possible due to the fact that both the temperature and concentration values vary at the same time. In this case a chemometric model which relates absorbance and concentration is difficult to obtain. Software based on a least-squares approach must be developed and used if the principles described in this paper should be used routinely for gas analysis. Absorption cross sections read from a database and convolved with a lineshape function taking into account the gas temperature and overall pressure must be retrieved. Next these data are convolved with an instrumental lineshape function. Finally, these simulated data can be compared with the measured ones. An optimal match between measured and calculated spectra is found when the sum of squared differences is minimal. A more detailed description of this method can be found in the literature [11].

3.2. Validation

The CO_2 and water vapour concentrations determined by the use of the fibre-optic probe and the gas cell data and Hitemp simulations are compared with those measured by the process instrumentation at the incinerator plant. The concentrations measured at the plant are shown in table 1. It should be noted that the main part of CO in the flue gas at this position has been converted to CO_2 and is therefore below the detection limit (approximately 50 ppm). The signature of HCl (g) can be seen faintly in figure 3 at around 2750 cm^{-1}, and the content can be determined if needed. HCl (g) parameters are not included in the Hitemp database. More important, the concentration of HCl is not measured by the staff at the plant close to the place for our measurements. Under these circumstances it would be difficult to judge the quality of the measured concentration values. In principle it is possible to find the concentration using the hot-gas cell following a procedure as described below for CO_2. Similar, the hot-gas cell can be used to obtain calibration

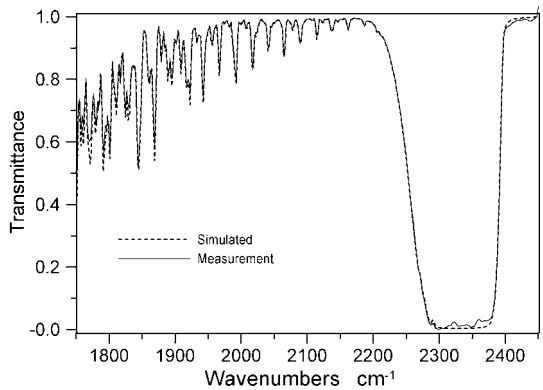

Figure 4. Transmission spectrum simulated with Hitemp database (dashed curve) and calculated from the measured emittance spectrum (solid curve) using the gas temperature and particle signal found in figure 3.

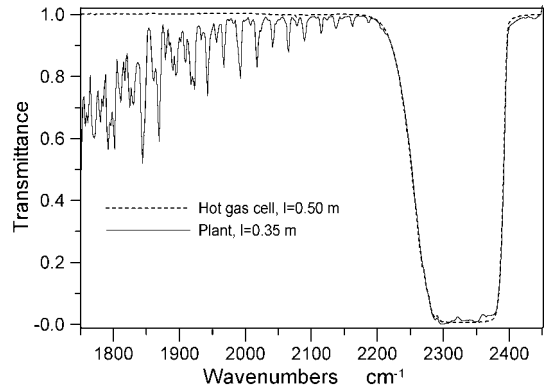

Figure 5. The measured transmittance spectrum from the incinerator plant is compared with measured spectrum from the hot gas facility with 5.18% CO_2 at 317 °C.

spectra of other gases such as NO, N_2O and SO_4 that are not included in the spectroscopic database.

Some of the spectra measured by the probe inside the plant were analysed quantitatively using the data analytical procedures described above and the Hitemp database and our hot-gas cell. The temperature and gas concentrations found were next compared with the values measured by conventional methods by the staff. Since these values are averaged over a long period of time, and measured closer to the flue gas exit, a perfect match between the values obtained by the probe and the conventional ones is not expected. A comparison is, however, relevant, because no dramatic change in the gas concentrations is anticipated. If the compared values show a high degree of resemblance, the probe method can be justified as a useful way to measure gas instantaneously at different places inside the plant. A determination of the accuracy of the analytical procedures for obtaining the data cannot be based solely on these investigations due to our lack of knowledge of the exact local gas temperature and concentration data. The data analytical procedure presented here has been validated earlier with specified temperature and gas samples and this subject is treated in more detail in [3, 4].

The gas temperature inside the plant was determined on the basis of the measured radiance spectrum from the height of the CO_2 band at 2350 cm^{-1}. Next the Hitemp database was run with that temperature (590 K) and carbon dioxide (7.5 vol%) and water vapour (17 vol%) concentrations close to those measured by the staff (see table 1). In figure 4 one of the measured spectra is compared with a simulated spectrum based on Hitemp parameters. A good correspondence between the spectra is observed. Deviations below 1800 cm^{-1} are due to noise in the InSb detector. This result shows that the quantitative content of the measured spectral data is close to the conditions which existed in the gas at that time.

Another way to compare the values is to fill the high-temperature gas cell described in the experimental section with carbon dioxide equal to the concentration given above, heat up the gas to 590 K and then measure the transmittance spectrum. Figure 5 shows the transmittance spectra from the cell and probe. The carbon dioxide concentration injected into the cell (5.18 vol%) was found by multiplying the carbon dioxide concentration, 7.40 vol%, by the optical pathlength ratio of the probe and gas cell (0.35/0.50). A reasonably good match between the two spectra is observed.

The above validation measurements indicate that spectral data measured by the probe set-up can be used to measure the gas temperatures and concentrations in a shorter timescale than by conventional methods. This subject will be demonstrated in the next section.

3.3. Discussion

The 10 min averaged data shown in the table are measured with conventional infrared gas analysers. The measurement point is in between the flue gas clean-up and the exit to the chimney. The data in italics in table 1 should be compared with the probe data. We observed a fairly good agreement between the concentrations measured by the staff and those measured by us using the fibre-optic probe. It is difficult to make a comparison between the data measured at the exit of the gas clean-up system and those measured at the position between the convection and economizer parts. First, the data are measured at different positions in the plant. Second, our measurements are local and more or less instantaneous. The data taken by the staff at the plant are non-local and averaged values. Third, the water vapour concentrations predicted by the Hitemp database are expected to be too high due to the lack of line data in the database.

Trend curves on gas temperature and water vapour concentration are plotted in figure 6 for a period of 18 min. The gas temperature varies from 287 to 323 °C and the water concentration from 13.5 to 21% during this period, whereas plant measurements varied from 292 to 297 °C and approximately 16.5 to 17.4% in the same period. The agreement of the probe measurements with plant data is reasonable taking into account the slow response time of the plant sensors, different position of sensors and the 10 min averaging of plant data. Details on the state of the combustion process of the waste on the grate are unveiled from the variations and correlation of the gas temperature and water trend curves, for example the water concentration is expected to increase with a drop in gas temperature during the drying process of the fuel (see table 2). All process states in table 2, except stationary and stable combustion for a longer period, can be identified from the trend curves in figure 6. Information

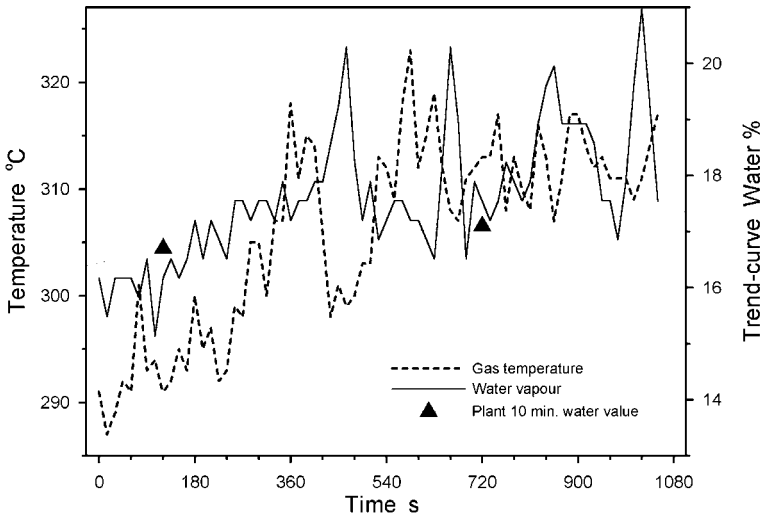

Figure 6. Trend curves of gas temperature and water vapour over 18 min calculated from spectra averaged over ten scans and collected with 15 s time separation. 10 min values on water vapour from the plant are shown with triangles. 120 s on the x-axis is equal to measured plant values at 14:45 in table 1.

Table 2. Overview on simplified process conditions for a grate-fired boiler.

Process state[a]	Gas temperature	Water vapour concentration
Stationary combustion	Stable, minor variations	Stable, minor variations
Drying of fuel	Decrease	Increase
Call for fuel, load decreased	Decrease	Decrease
Load increased	Increase	Decrease
Combustion of dry pyrolysed fuel	Increase	Decrease

[a] Fixed water content of fuel.

about the instant state of the combustion process might be used for an improved control and regulation of the process.

The gas temperature must basically be known in order to extract gas concentrations from the emission spectra as expected and shown in the analysis of spectra. The accuracy of the gas temperature measurement is therefore critical. It depends on the following factors: blackbody source (1.7 °C), IR fibre bending effects (2%), instrument stability (1%) and disturbance of the temperature field by the water-cooled probe (2 °C). The error in the transmittance spectrum calculated from the emittance spectrum is determined from Planck's radiation law:

$$\frac{\Delta\tau}{\tau} = \frac{\Delta\varepsilon}{\varepsilon} \approx \frac{\Delta T\ C_2\,\tilde{\nu}}{T^2} \tag{8}$$

where C_2 is the second radiation constant (1.4388 cm K) and T the temperature in kelvin. The error decreases with temperature level and increases with wavenumber according to equation (8). The combined error in the transmittance measurement is 3.3% at 2300 cm^{-1}, which is equal to 3.5 °C (63% confidence level) on the gas temperature for the actual conditions.

4. Conclusion

A fibre-optic probe has been developed and interfaced to an FTIR instrument for simultaneous and rapid measurements of gas temperature and gas composition. The performance of the probe was demonstrated by measurements in an incinerator plant at about 300 °C. Gas temperatures and concentrations of carbon dioxide and water vapour have been determined using Hitemp data and reference gas cell measurements. The Hotgas facility at Risø or a similar set-up is useful for accurate gas calibration and validation measurements. It was shown that the values obtained by the probe measurements were in agreement with values measured at the plan with conventional methods. A series of measurements over a period of time conducted by the probe set-up revealed that fluctuations in water vapour concentrations and gas temperatures were correlated to the state of the combustion process. This information cannot be retrieved when conventional measuring methods are applied. This improved knowledge about the state of the combustion process might be used for a better control and regulation of the process in order to obtain a smoother operation and thereby a higher conversion rate of the fuel and/or a reduced outlet of hazard chemical substances to the environment.

The temperature range where the fibre-optic probe can be applied might be extended up to 1100–1700 °C with few modifications in the design, which will allow mapping of flame temperatures and gas concentration with a measuring time down to a fraction of a second. Alternatively, the measuring principle can be used in an open-path configuration with an infrared sensor in the wall for rapid simultaneous measurements of gas conditions.

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