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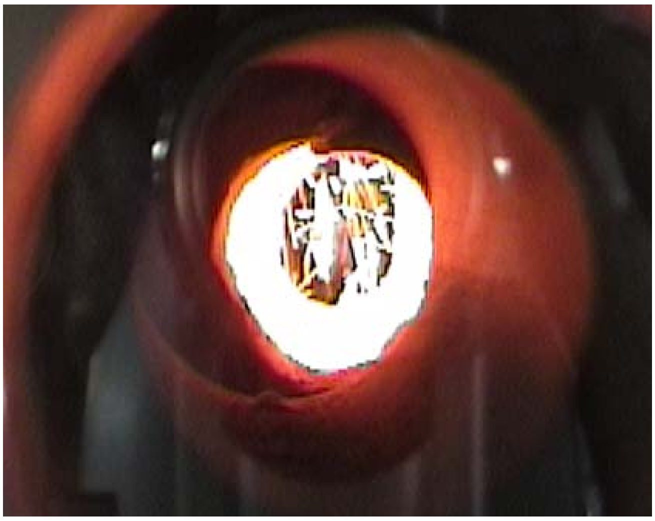

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Abstract (max. 2000 char.):

Particle and gas temperature measurements were carried out in experiments on VTTs entrained flow reactor with 5% and 10% oxygen using Fourier transform infrared emission spectroscopy (FTIR). Particle temperature measurements were performed on polish coal, bark, wood, straw particles, and bark and wood particles treated with additive. A two-color technique with subtraction of the background light was used to estimate particle temperatures during experiments.

A transmission-emission technique was used to measure the gas temperature in the reactor tube. Gas temperature measurements were in good agreement with thermocouple readings. Gas lines and bands from CO, CO_2 and H_2O can be observed in the spectra. CO was only observed at the first measuring port (100 ms) with the strongest CO-signal seen during experiments with straw particles. Variations in gas concentration (CO_2 and H_2O) and the signal from solid particles reflects variations in particle feeding rates during the experiments.

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Picture taken with digital camera of burning bark particles at first measuring port (100 ms). Small flames (soot) around the bark particles are seen indicating ignition.

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Contents

1 Introduction, methods, experimental setup and results

Particle and gas temperature measurements were carried out 26-30 August 2002 and 13-14 Marts 2003 on VTTs EFR using Fourier transform infrared emission spectroscopy (FTIR). Equipment was shipped from Risø by flight to VTT before the experiment. The measurement technique is based on the detection of thermal radiation from gas and fuel particles located in the field of view of a fibre optic sensor connected to a FTIR spectrometer.

The experimental setup is illustrated in figure 1. Five quartz windows at position TI6, TI7 and T8 (260, 460 and 810 mm from the fuel inlet feeding tube) were replaced by sapphire windows in order to extend the lower spectral limit from approx. 2.7 to 6 microns. 5 flanges with ø50.8 mm and 5.0 mm thick sapphire windows was designed and machined at Risø and thereafter mounted on VTTs PEFR before the experiments.

Position	Distance from inlet	Residence time
TI6	260 mm	100 ms
TI7	460 mm	185 ms
TI8	810 mm	325 ms

Table 1 Position of windows and residence time calculated for a particle velocity of 2.5 m/s.

The extended spectral range allows remote optical gas temperature measurements using the emission-transmission method on the strong absorption band of CO_2 at 4.3 µm and particle temperature measurements can be performed using the 3.9 µm region free from gas linies. A blackbody source at 800ºC was use for the transmission measurement and calibration of the fiber optic sensor. The field of view (FOV) of the sensor is illustrated in figure 1 with dashed lines. The measuring volume is approx. 6.5 cm^3, i.e. the sensor sees normally a few particles. Single particle temperature measurements by an FTIR technique could in principle be performed, but it would require a lower particle feeding rate and an optical setup without fiber optics, which would increase the experimental costs.

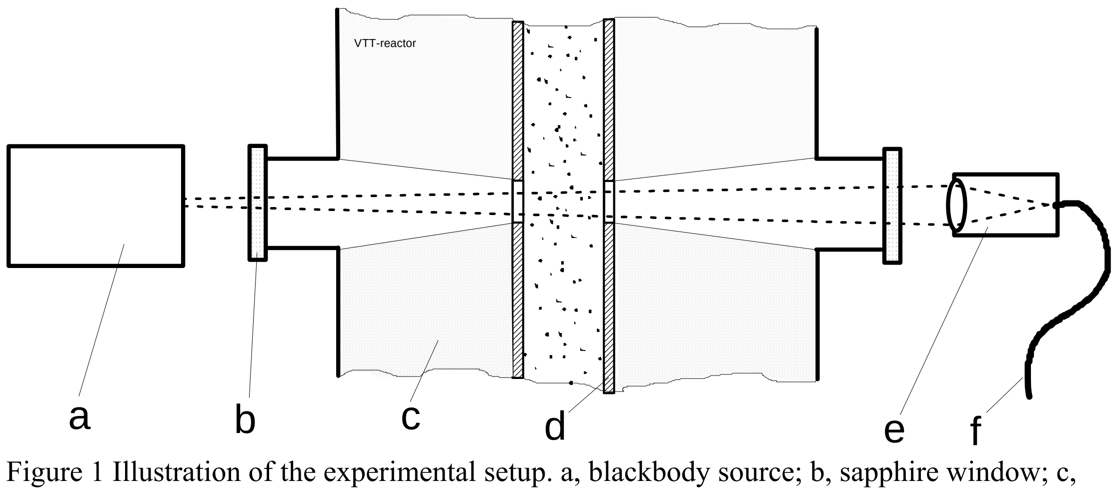

Figure 1 Illustration of the experimental setup. a, blackbody source; b, sapphire window; c, window section of PEFR at VTT; d, ceramic tube with a diameter of 60 mm; e, optical sensor; f, mid IR fiber connected to FTIR spectrometer. The field of view of the optical sensor is carefully aligned to avoid radiation from the walls of the ceramic tube.

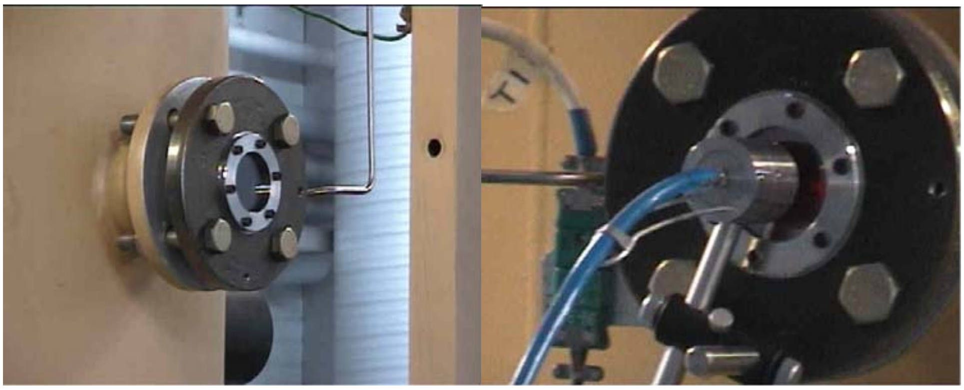

Figure 2 Left is shown a sapphire window mounted in a window section of the VTT-PEFR. Right the aligned optical sensor is mounted with a mid IR fiber that is connected to the FTIR spectrometer is shown.

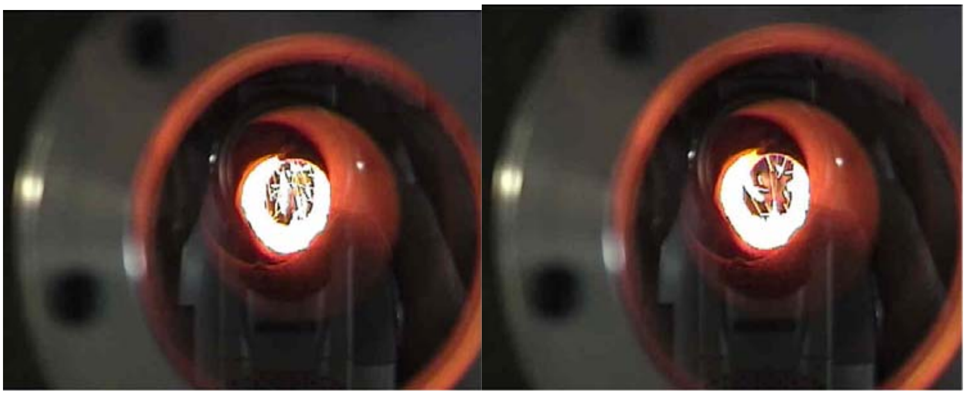

Figure 3. Ignition of bark particles after around 100 ms observed in position TI6 (flames/soot). Right a picture with a few particles and left a picture with several particles is shown. Light tracks reflect complex flow patterns of particles. Some particles are surrounded by a flame/soot .

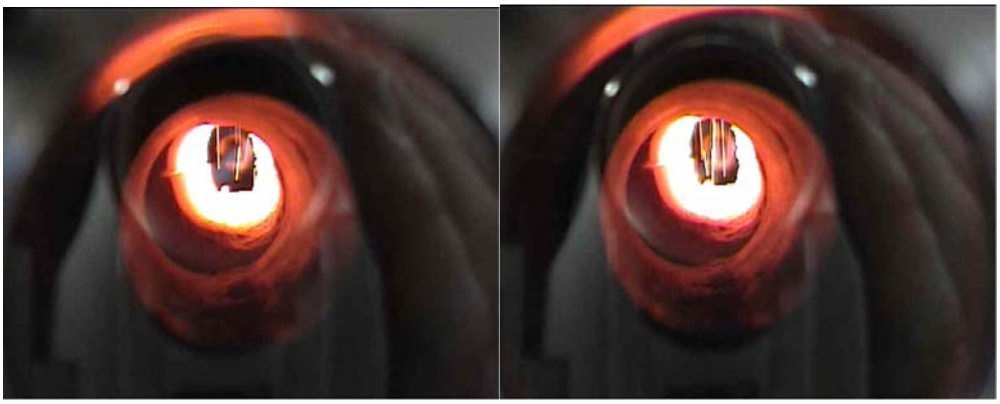

Figure 4. Burning bark particles after around 325 ms observed in position TI8. Light tracks from burning particles are at this position straight lines. No flame or soot around particles.

Pictures in Figure 3 and 4 illustrate differences in movement of fuel particles at position TI6 (first port) and TI8 (last port). Soot around particles is observed at position TI6.

A simple two-color technique is used to estimate the mean group particle temperature, see figure 5. Single particle measurement methods, see references, would be time consuming as the particle feeding rate should be lowered significantly and a special feeding system should be arranged.

The fuel-feeding rate was adjusted to about 0.02 – 0.03 g/s. Variations in the particle-feeding rate can be observed looking at series of single scan spectra. The fuel-feeding rate is expected to be proportional with the signal from the particles. Therefore, variations in the fuel-feeding rate can be monitored from the measured intensity in selected spectral regions (figure 6). Large fluctuations in the particle feeding rate is observed in experiment 4D, and the particle temperature appears to vary too, which can be seen from the fact that the signal in two bands are not constant. The particle temperatures appear to decrease in some periods with high particle feeding rate (figure 6).

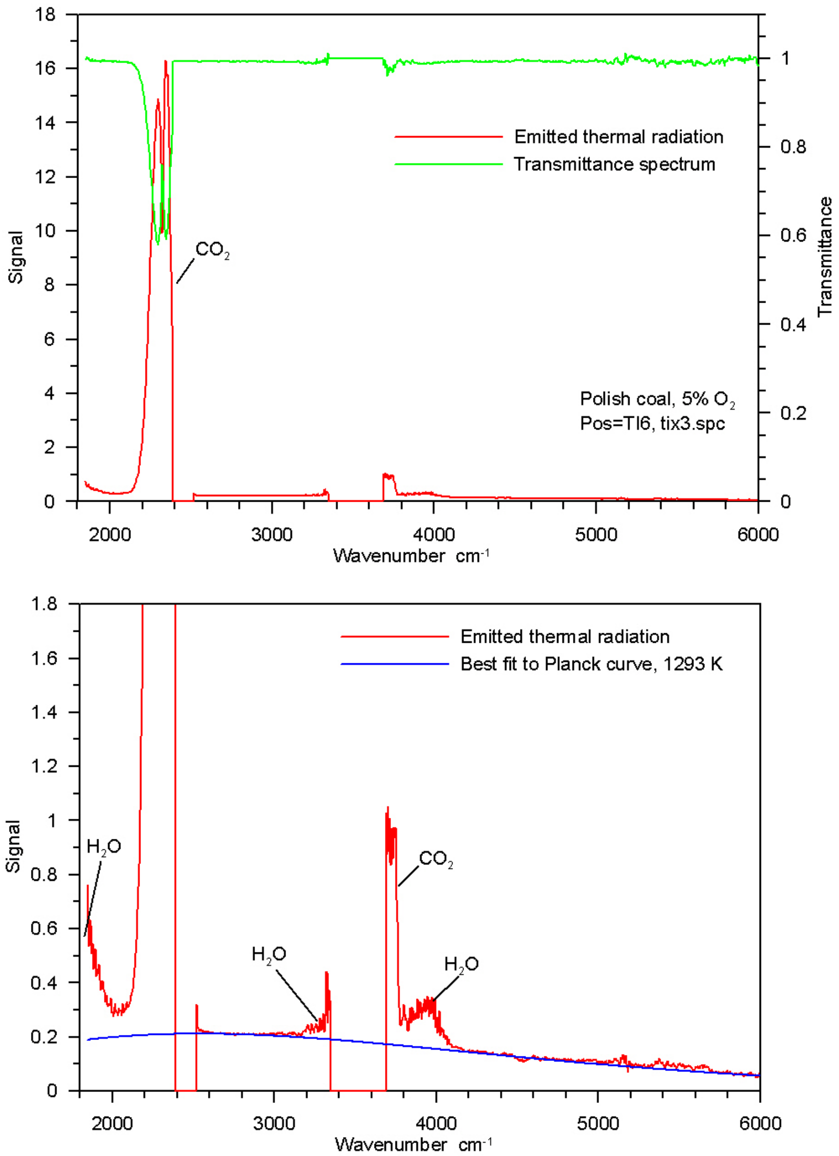

Figure 5 Measurement on Polish coal at 1000˚C 5% O_2 window position TI6. Upper curves: example of emittance and transmittance spectrum. The gas temperature can be found using the emissivity ($\varepsilon = 1 - \tau \approx 0.4$) of the CO_2 band and the intensity of the CO_2 peak. Lower curves: best fit of emittance spectrum with a Planck curve using two bands at 2580 – 2840 cm^{-1} and 4250 – 4650 cm^{-1} outside regions where

gas absorption appears. Measurements average of 50 scans at 8 cm^{-1} (approx. 1 minute). Wavenumber (ν) = $1/\lambda$, e.g. 2000 cm^{-1} equals 5.0 µm.

The gas temperature can be calculated from the transmittance and emittance spectrum of CO_2 at 2300 cm^{-1}, e.g. the gas temperature is calculated using Planck's equation for a blackbody to 1000˚C ± 15˚C from the hot (left side) of the CO_2 band in figure 2, which is in good agreement with thermocouple measurements and the settings of the PEFR. The optical gas temperature measurement is dependent on the stability of the fuel-feeding rate, i.e. the gas temperature can only be measured with good precision when the fuel feeding is similar during the measurement of the emittance as well as the transmittance spectrum over 2-3 minutes.

The particle-feeding rate is not constant in time, figure 6. This behavior is observed for all fuels, but the effect is more pronounced in some experiments. A graphical overview is given in appendix A. A pull action solenoid used to prevent blocking of the fuel feeding line with particles might be the source to the feeding variations.

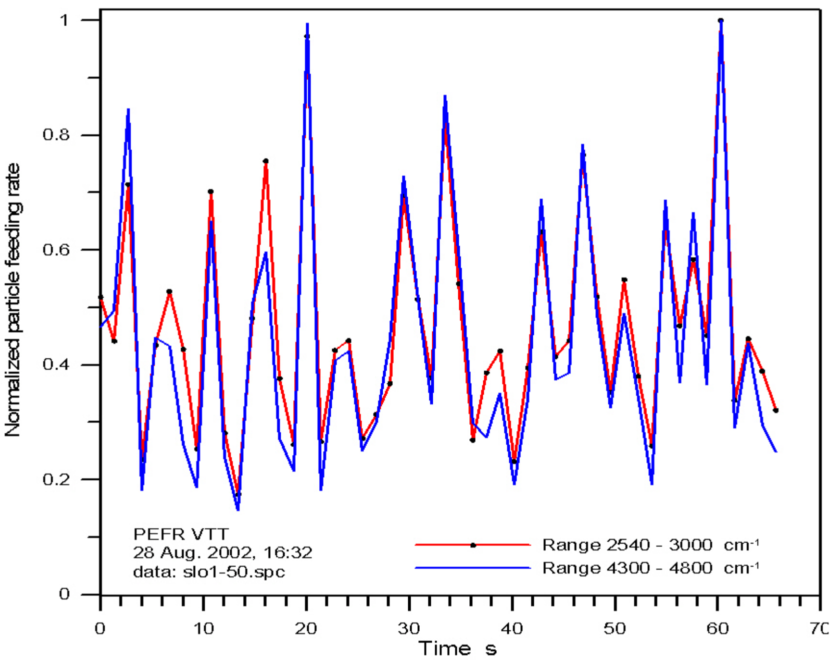

Figure 6 Variation in particle feeding rate during experiment 4D with bark (data: slo1-50.spc) calculated for two different spectral regions (blue and red curve). The two curves should overlap if the particles mean temperature is constant during the experiment (two-color method), whereas the temperature is increased when the blue curve is above the red and decreased when red is above the blue curve. The particle-feeding rate is estimated to vary from 0.008 to 0.050 g/s with a mean feeding rate of approx. 0.022 g/s in this experiment. Measurements (dots) are all single scan, i.e. the measuring time is few ms. Particle temperatures are included in plots Appendix A.

From Plancks radiation law we know that the emitted thermal radiation at shorter wavelengths (range 4300 – 4800 cm^{-1}, approx. 2.2 µm) will increase faster than at longer wavelengths (range 2540 – 3000 cm^{-1}, approx. 3.6 µm) for a raise in temperature, e.g. the blue curve is below the red at time 16 s in figure 6 which indicate a lower particle surface temperature than at time 20 s. The blue and red curve in figure 3 should overlap if the particle temperature were constant.

Spectra was usually measured with a resolution of 8 cm^{-1}, however, in some experiment spectra were measured with a higher resolution, 2 cm^{-1}, in order to see lines from CO in the spectra as seen in figure 7.
CO was only detected at position TI6 as might be expected from flames/soot seen at this position (figure 3). The CO concentration can in principle be estimated by comparison of the transmittance spectrum and a simulated CO spectrum using a spectroscopic database. Thereby, the CO/CO_2 ratio can be determined directly from a transmittance measurement, e.g. the spectrum in figure 7 for straw.

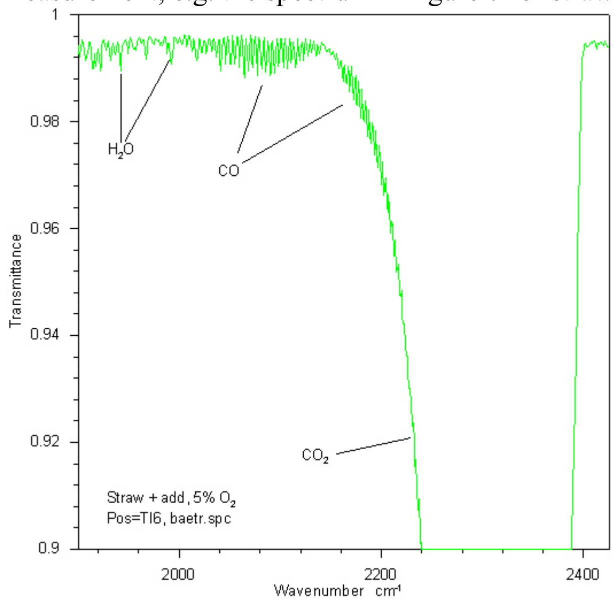

Figure 7 Example of transmittance spectrum with features from CO lines seen as fine lines in the range 2000 – 2250 cm^{-1} and with a center at 2150 cm^{-1}. The strongest CO-signal is seen from straw.

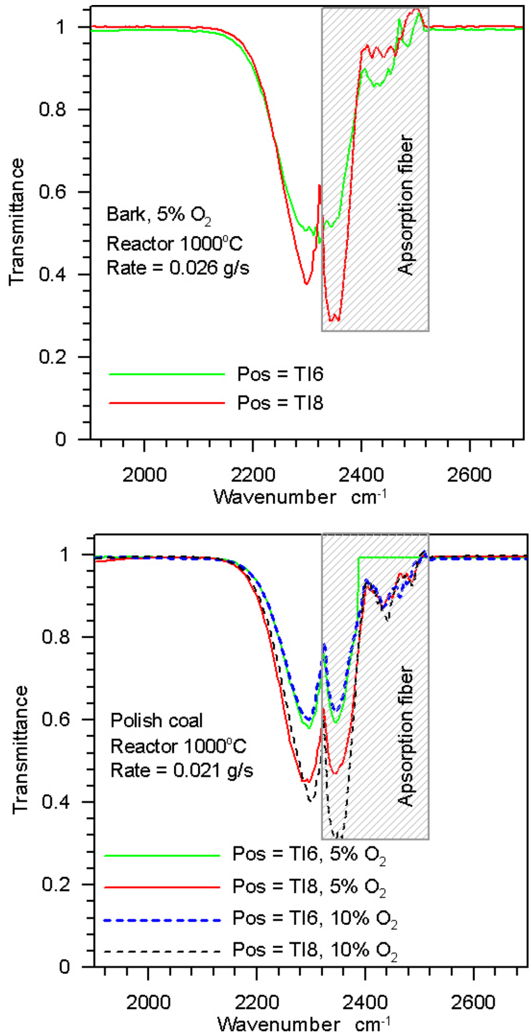

Figure 8 Comparison of transmittance spectra for Bark and Polish coal. Right side of CO_2 band is noisy due to strong absorption of light in the infrared fiber. It is remarkable that only a small change in the CO_2 band is observed changing the oxygen concentration. Spectra averaged over 50 scans, 8 cm^{-1} spectral resolution.

Measured CO_2 transmittance spectra for bark and coal is compared in Figure 8. The content of carbon in Polish coal is 44% larger than of bark, whereas bark has more than 100% volatiles than Polish coal. The area of the CO_2 band reflect the concentration, therefore, the CO_2 concentration appears to be the similar for coal at 5% and 10% oxygen level, i.e. the same carbon mass loss (no CO is observed, assuming constant fuel-feeding). A minor change in the CO_2 concentration (from the CO_2 bands in figure 8) is observed for bark between position TI6 (100 ms) and TI8 (325 ms) compared to coal as expected. A detailed analysis of the measured transmittance spectra suffers from the uncertainty in the fuel-feeding rate during experiments.

Table 2 : Measured particle and gas temperatures

Fuel type	File	Oxygen	Position	Mean ˚C	Min ˚C	Max ˚C	Std. ˚C	T_{gas} ˚C
Polish coal	Tax	5%	TI6	986	875	1080	45	1000±15
Polish coal	Tio, tbo, tco	5%	TI8	1070	894	1401	85	983±34
Polish coal	Ttj, ttg	10%	TI6	1160	994	1384	82	1075±15
Polish coal	Tbt, tut	10%	TI8	1129	874	1385	111	>=1000
Bark + add	Suo, syo	5%	TI6	1213	885	1699	167	1010±7
Bark	Tro, tso	5%	TI6	1210	994	1711	111	-
Bark	Tko	5%	TI8	1010	811	1582	170	-
Bark	Sjo, smo	10%	TI6	1250	985	1677	127	-
Wood + add	Njx, nlx	5%	TI6	1191	893	1771	170	-
Wood	Njp, nmp	5%	TI6	1356	944	2005	200	-
Wood	Mjx, mlx, mmx	10%	TI6	1232	854	1823	160	-
Straw *	Bah	5%	TI6	906	694	1340	141	-

*: Note: problems with background variations.

The gas temperature was 800 ˚C in experiments with straw and 1000˚C in all other experiments.

Table 2 Found particle temperatures for single scan measurements (examples, see Appendix A).

TI6: (260 mm, 100 ms), TI7: (460 mm, 185 ms), TI8: (810 mm, 325 ms)

The measured gas temperatures in the experiments, where Polish coal was tested are in good agreement with VTT’s thermocouple measurements. Small flames seen around the coal particles can explain the approx. 75˚C higher gas temperature with Polish coal, 10% oxygen at position TI6. Long flames and flame pulses were observed in the experiments with wood, which might help to explain why some particles are very hot.

2 Discussion of temperature measurements

The FTIR particle temperature measuring method requires a stable background measurement in order to subtract thermal radiation from other sources (reflected radiation from window surfaces, FTIR instrument, etc.) than the burning particles from the measurement. The reactor actually stabilise at a slightly higher temperature due to the heat release from the burning particles, e.g. 30 - 70˚C at position TI6. This effect might cause an offset in measured particle temperature that is estimated to be less than 100˚C. This effect is critical at window position TI7, where the temperature change of the opposite ceramic wall (only one window at this position) is too large, i.e. it is not possible to separate radiation from the fuel particles from the change in thermal radiation from the reactor wall. A solution to this problem would be to lower the fuel-feeding rate, however, this would require more time to carry out the experiments. Small particles due to fragmentation might have an influence on the results.

Background variations are a problem for measurement of the straw particle temperature at the second visit to VTT. A new more sensitive IR-fiber with 40% larger diameter seems to be the main problem as it was not possible to align the sensor to look through the ceramic reactor tube without a small fraction of the field of view sees the edge of the hole.

Table 3: Overview particle temperature measurements compared to the gas temperature. $\Delta T = T_{par} - T_{gas}$

Fuel type	**Oxygen**	**t_p (ms)**	**T_{gas} ˚C**	**ΔT ˚C**	**ΔT_{min} ˚C**	**ΔT_{max} ˚C**
Polish coal	5%	100	1000±15	-14	- 125	80
Polish coal	5%	325	983±34	+87	- 89	418
Polish coal	10%	100	1075±15	+85	- 81	309
Polish coal	10%	325	>=1000	+129	- 126	385
Bark + CAP	5%	100	1010±7	+213	- 125	689
Bark	5%	100	≡ 1000	+210	- 6	711
Bark	5%	325	≡ 1000	+10	- 181	582
Bark	10%	100	≡ 1000	+250	- 15	677
Wood + CAP	5%	100	≡ 1000	+191	- 107	771
Wood	5%	100	≡ 1000	+356	- 56	1005
Wood	10%	100	≡ 1000	+232	- 146	823
Straw *	5%	100	≡ 850	+56	-156	490

*: Note: problems with background variations.
t_p: Particle residence time
The gas temperature was 800 ˚C in experiments with straw and 1000˚C in all other experiments.
Table 3 Found particle temperatures for single scan measurements (examples, see Appendix A).

Particle temperatures are similar for bark with and without CAP, which indicate that CAP does not change reactivity. Biomass particle temperatures are significant higher than for Polish coal, i.e. approximately +200ºC for bark and wood at 5% O_2 and 100 ms residence time. Very high peak temperatures (Δt_{max}) are measured for biomass particles during the experiments, i.e. 490ºC - 1005ºC above the gas temperature. The particle temperature peaks is typically observed at high signal (high particle density), see appendix A.

3 Conclusion

Particle and gas temperature measurements have been carried out at VTTs entrained flow reactor for coal, bark, wood and straw particles. The optical ports were mounted with sapphire windows that are transparent at wavelengths where signatures from CO and CO_2 can be found in the measured spectra. It is shown that the CO/CO_2 ratio might be measured directly. Gas temperatures found from measured spectra of thermal radiation are found to be in good agreement with thermocouple measurement.

Biomass particle temperatures are significant higher than for Polish coal at similar conditions (100 ms residence time). Particle temperatures variations are found to be broader for biomass particles than for coal particles. The strong volatile release for biomass particles seem to smear out a simple picture of the particle temperature behavior, i.e. pulsating flames were observed for wood. Very high peak temperatures are measured for biomass particles during the experiments. The maximum particle temperature is typically observed at high particle density, i.e. fluctuations in the particle-feeding rate influence results.

The experimental conditions for optical particle and gas measurements by the FTIR technique was not optimum due to the fuel-feeding rate was fluctuating during experiments, i.e. the experimental conditions change from none, single to many particles in the field of view of the sensor. The interpretation of the measurements become therefore complex and results less accurate. The change of reactor wall temperature when fuel particles are injected cause problems when extracting straw particle temperatures. The straw particles appeared visually close to the reactor wall temperature at position TI8 ($m/m_o < 10\%$). The feeding of straw particles was highly unstable, i.e. many stops and even blocking of the feeding line.

Additional detailed information on particle temperatures can be measured with a suitable infrared camera, however, this technique was not though to be applicable at VTTs reactor at the time experiments in this project were carried out. Risøs infrared camera, Radiance PM, has been demonstrated in later work with success for measurement of particle temperatures in a laboratory facility (DTU) and of straw particles in a power plant. The infrared camera technique could have been used on VTTs reactor for particles larger than about 50 μm if the optics of the infrared camera is modified. Individual particle temperature and particle size measurements can be extracted from snap shot thermal pictures.

Thanks to Martti Aho and Kari Paakkinen for help and assistance during the experiments at VTT. The work is part of PSO project ”Biomass dust firing”, FU 2203, supported by Elkraft System.

4 References

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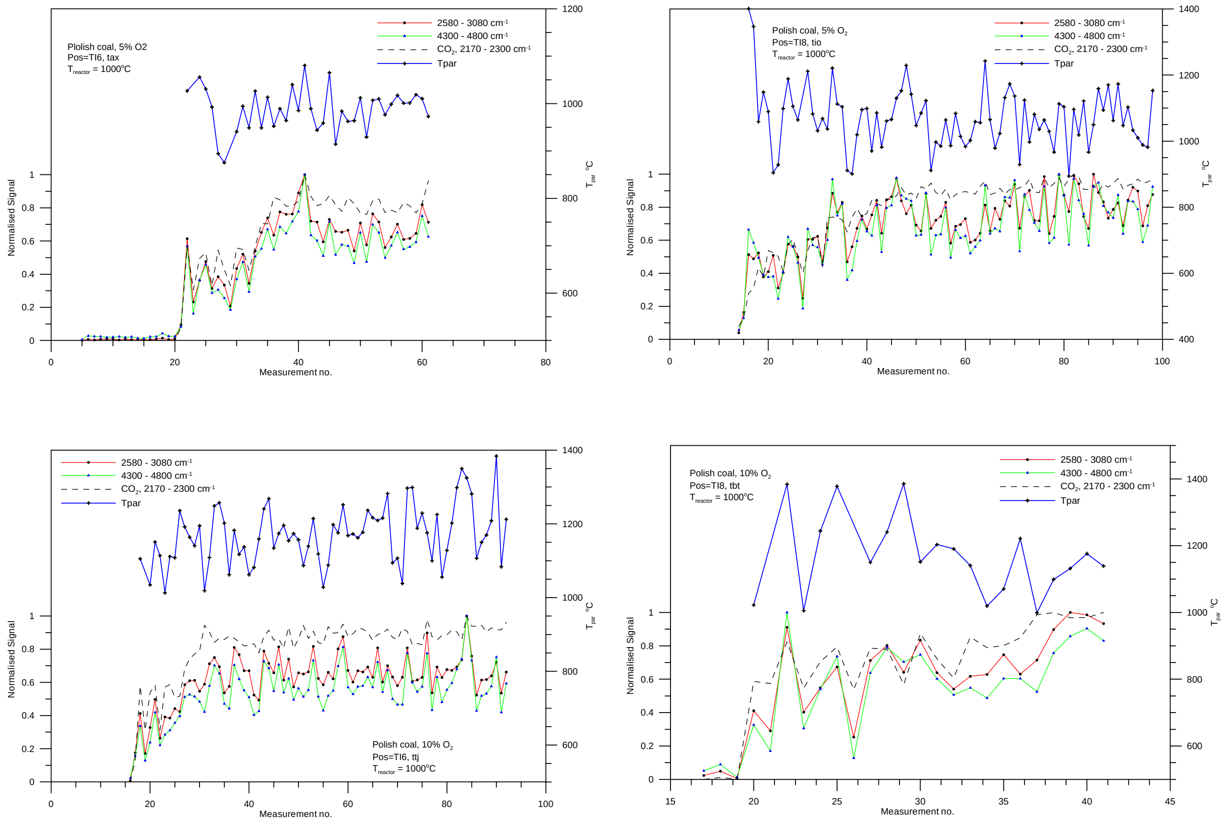
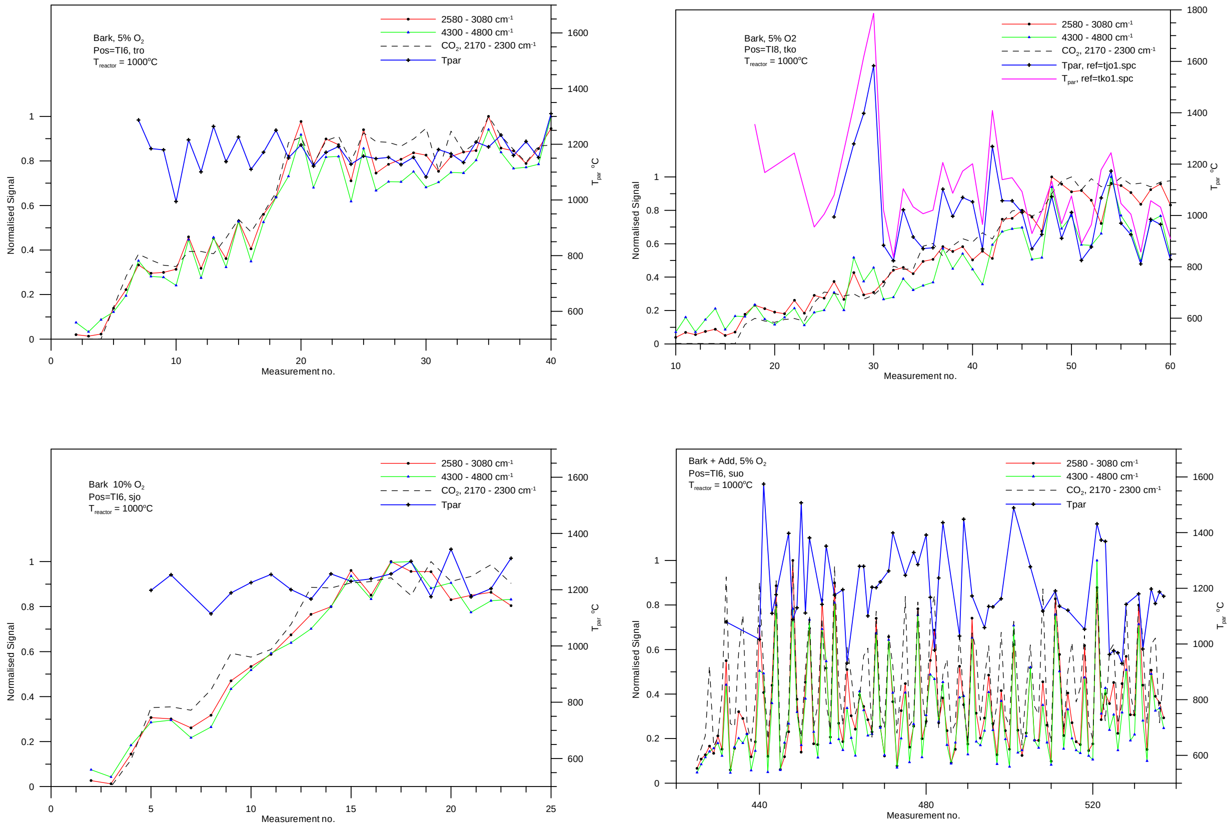
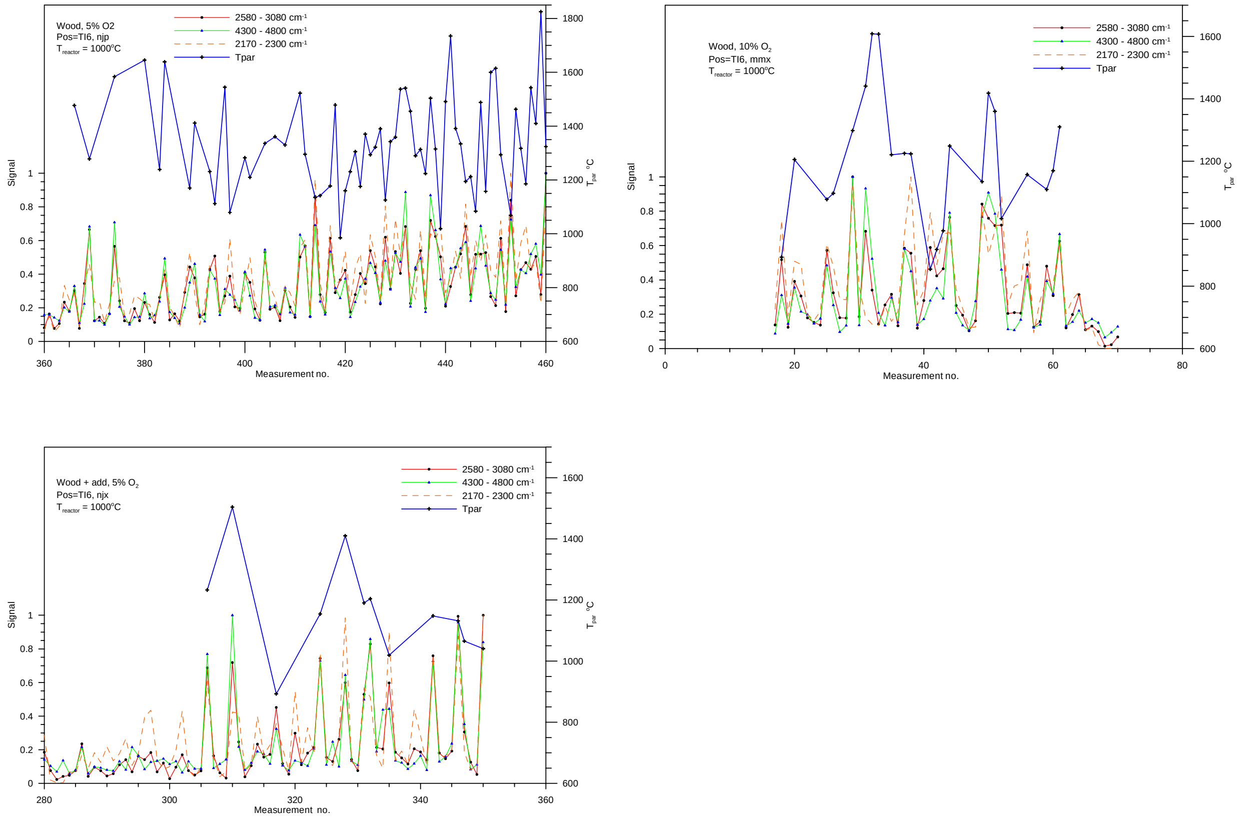
Appendix A. Measured signals and particle temperatures



Polish coal. Example of measurements at the beginning of feeding fuel particles into the reactor. The dashed lines show the signal from the gas (CO_2). Particle temperatures are only calculated for signals larger than 0.2 to avoid large uncertainties. Measurements are averaged over 10 scans (approx. 5 s), i.e. fluctuations in the fuel-feeding rate appear less pronounced.



Bark, Bark + add. Examples of single scan measurements at the beginning of feeding fuel particles into the reactor. The dashed line shows the signal from the gas (CO_2). Particle temperatures are only calculated for signals larger than 0.2 to avoid large uncertainties at weak signals.



Wood, wood + add. Example of measurements at the beginning of feeding fuel particles into the reactor. The dashed line show the signal from the gas (CO_2). Particle temperatures are only calculated for signals larger than 0.2 to avoid large uncertainties for weak signals.

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