1. Introduction

Temperature has always been a central parameter within catalysis studies. In fact, the very essence of catalysis, lowering the activation energy of a reaction, is inherently linked with lowering the temperature needed for the reaction to take place. Temperature directly controls reaction speed, and central properties of a catalyst, such as activation energy, can be derived from a correlation between sample temperature and catalytic activity [1]. Thus, accurate and comprehensive temperature data for both the catalyst sample itself, as well as the reactants and products, are crucial for a full interpretation of experimental results.

Over the last decades, the focus of heterogeneous catalysis research has shifted increasingly towards the use of so-called operando techniques where active catalysts are probed in situ, while being exposed to as realistic operating conditions as possible. These conditions usually entail that the sample is studied in a flow reactor at high pressures [2, 3]. The reason is evident from several studies, which show that the behavior of catalysts may be fundamentally different when the surface is exposed to higher pressures [3, 4]. Traditionally, atomic surface sensitivity and high surrounding gas pressure have often been mutually exclusive. However lately, with methods such as ambient pressure x-ray photoelectron spectroscopy (AP-XPS) [5], atmospheric pressure surface tunneling microscopy (AP-STM) [6], and High energy surface x-ray diffraction (HESXRD) [7], an ever-increasing repertoire of techniques compatible with higher pressures is at the surface scientist’s disposal.

While the terms operando and ‘high pressures’ are not always coherently defined, their definition does generally entail that the gas surrounding the catalyst plays a role in the reaction, and is analyzed in conjunction with the catalyst surface [8]. Further, with higher gas flows, and higher catalytic activities, it can no longer be assumed that the gas properties are homogeneous throughout the reactor, as turbulent gas conditions may occur [9]. The gas flow itself can also affect the...
temperature of the sample. In some experiments, for example, the sample itself is not heated directly. Instead, the gas supplying the reaction is brought to an elevated temperature to heat the catalyst. Other experiments use a cold gas flow combined with a heated sample; in this case, the sample may be cooled down by the gas flow.

In experiments where the gas temperature around the catalyst is probed, which in itself is not commonplace, the gas temperature can be measured by placing a thermocouple in the gas, or by a quartz leaking orifice, commonly used for point measurements of gas concentration by MS, the opening of which is temperature dependent [10]. These techniques, however, only provide point measurements, which requires moving the probes to obtain 2D data. It is further not possible to obtain 2D data during transient processes as the probing takes time. Also, both of these probe types, when placed in the gas flow, will cause disruptions in the flow.

Knowledge of the gas temperature is also important for techniques such as x-ray photoelectron spectroscopy (XPS), as the mean-free-path of electrons in a gas is temperature dependent [11]. Another motivation for accurate and non-intrusive temperature data of the gas phase is to facilitate theoretical modeling of the reactor and the catalytic processes within. Theoretical models of reactors also provide gas temperature information as output data [12]; as such, experimental gas temperature data could be very valuable to verify these theoretical models.

In this work, we report on various methods to measure the temperature of the gas surrounding the catalyst sample in a typical heterogeneous catalysis experiment scenario. We also present ways to measure the sample temperature itself, without the need to spot-weld any thermocouples.

2. Method

This section will briefly treat the methods used in this paper, focusing on how to determine absolute temperature values from the raw data. The experimental details will be provided in the next section.

Laser based techniques have been widely used to measure e.g. gas temperature in combustion scenarios [13]. In principle, these techniques rely either on a change in number density with temperature according to the ideal gas law, or in a change in the population of vibrational or rotational energy states as the thermal equilibrium is shifted. While many methods exist, planar laser induced fluorescence (PLIF) and Rayleigh scattering excel at providing 2D information [14]. Rayleigh scattering, however, is difficult to perform in enclosed reactors, as any scattered light will be many orders of magnitude more intense than the signal, and the enclosed nature of a reactor together with the proximity to the sample surface render it difficult to avoid scattering. It is also impossible to discriminate the scattered light by time-gating or filtering, as Rayleigh scattering is an elastic instantaneous process, where the signal will be of the same wavelength as the incident beam. While scattering can be minimized using filtered Rayleigh scattering, where a very narrow-band filter is used to remove any scattered light, this approach is technically challenging [15].

Instead, techniques based on PLIF are desired. While these techniques can be experimentally challenging—a laser with the right wavelength must be available and substantial post-processing is required to obtain absolute concentration information—they provide a much stronger signal which can be discriminated from the background by spectral filtering or time-gating. In short, PLIF is a non-intrusive laser-based technique which gives a 2D map of molecular number density in a slice of gas above the sample, from which temperature information can be derived. PLIF is widespread within combustion diagnostics, but has also been used for catalysis studies on several occasions [16, 17].

There are two approaches to thermometry using PLIF. Two-line fluorescence thermometry (TLFT) and single-line fluorescence thermometry (SPLIF). While not as commonly used as TLFT, SPLIF is useful when the gas concentration can be known at a point in time, and has been used in combustion when it has been possible to seed known gas concentrations into the area to be probed [18, 19]. Since we can control the gas situation in our reactor, SPLIF is a good choice. Hence, in this work, we primarily use SPLIF to visualize the temperature. An adaption of TLFT, which we will henceforth refer to as spectral measurement, will also be presented as proof-of-concept. Here, instead of looking at two lines, two larger parts of the fluorescence spectrum are measured. The fluorescence in these regions is then integrated and compared to simulations to obtain absolute temperature data.

To accurately measure the sample temperature without the need to spot-weld a thermocouple, we present a combination of thermographic phosphors [20], thermocouple data and in situ calibrated infrared camera imagery [21]. This combination provides accurate absolute temperature readings while also being sensitive to small changes in sample temperature. We will further compare the temperature of the gas in the direct vicinity to the catalyst with that of the sample itself, to show that the different methods give coherent results.

2.1. Sample temperature

2.1.1. Thermocouple. As discussed, temperatures of heating elements in catalysis research are commonly monitored using thermocouples. However, the construction of many low pressure reactors does not permit the use of a continuous stretch of chemically suitable thermocouple material from the readout location to the point to be measured. This introduces uncertainties in the readout accuracy. In our case, a type D thermocouple is used outside and inside the reactor, while a steel pass-through is used to feed the thermocouple leads into the reactor volume. Further, the thermocouple is connected with a screw to the heating element side, a few millimetres away from the sample location. A calibration of the thermocouple reading is thus necessary to achieve accurate results.
2.1.2. Phosphor thermometry. Phosphor thermometry is a remote temperature sensing technique that utilizes sensor materials known as thermographic phosphors. Thermographic phosphors have sensing range that extends from cryogenic temperatures up to 1800 K and their temperature sensing capabilities are used in various applications such as industrial, biological, and combustion to name few [22]. When subjected to a temperature change, thermographic phosphors exhibit a change in their luminescence characteristics. Every thermographic phosphor has its individual sensitivity range and thus calibration of its luminescence features as function of temperature is necessary to extract temperature data from the detected luminescence. Two common methods are used to retrieve temperature information from thermographic phosphors, the temporal and the spectral ratio method [20, 23]. The temporal method exploits the reduction of the luminescence decay time as function of temperature after excitation with pulsed excitation radiation. While the spectral ratio method utilizes the ratio of two or more bands of the emitted luminescence to obtain the temperature of the phosphor.

For the catalyst heater calibration presented in this work, the temporal method is selected due to its inherent superiority to the spectral method in terms of accuracy and precision. After excitation with a pulsed optical radiation source, typically using a pulsed laser system, the thermographic phosphor emits a red-shifted luminescence known as phosphorescence. The decay of the phosphorescence intensity as function of time can be estimated by a mono-exponential decay function

\[
(t, T) = I_0(T) \cdot \exp (-t/\tau(T)).
\]

The decay time, represented as \(\tau\) in equation (1), usually decreases several orders of magnitude over the temperature sensitivity range of the thermographic phosphor. The high sensitivity of the decay time as function of temperature range makes thermographic phosphors an accurate remote temperature sensing method. The single shot accuracy of phosphor thermometry is around \(\pm 2\) K within the corresponding temperature sensitivity range.

In this work, the thermographic phosphors technique has been used to create a calibration between the actual sample holder temperature and the temperature reported by the thermocouple.

2.1.3. IR camera. Since the InSb IR-camera used for the PLIF measurements is sensitive in the mid-IR range, it can be used as a heat camera. While it is difficult to obtain absolute temperature values in this way due to differences in emissivity, it is possible to follow the temperature evolution of the sample as it is heated, given that the temperatures at the endpoints are known. The calibrated thermocouple data is then used to calibrate the IR-camera in situ.

2.2. Gas temperature

2.2.1. Using the ideal gas law. The number density of molecules in a volume of gas at constant pressure changes with temperature according to the ideal gas law (IGL). Thus, any technique to map the number density of a gas can, in principle, be used to measure temperature. As discussed in the introduction, PLIF is a technique which can non-intrusively measure that quantity. Once gas molecules have been excited using a laser targeting a transition, and the resulting fluorescence from molecular relaxation has been imaged by a camera, the resulting PLIF intensity \(S_{PLIF}\) in each pixel can be described using

\[
S_{PLIF} = \eta_e E_g(T) f(T) \sigma_0(T) \frac{\chi_{abs} P}{k_B T} \phi,
\]

where \(\eta_e\) is the collection efficiency of the camera, \(E\) the laser energy, \(g\) the overlap between the laser excitation envelope and the spectrum of the molecule to be probed at temperature \(T\), \(f\) the Boltzmann fraction describing how many electrons are occupying the probed energy levels as function of temperature \(T\), \(\sigma_0\) is the absorption cross section of the species to be probed, \(\chi_{abs} P / k_B T\) is the number density of the molecule to be probed. In this fraction, \(\chi_{abs}\) is the molar fraction of the probed gas, and \(P\), \(k_B\) and \(T\) are the pressure, Boltzmann constant and temperature respectively.

It is assumed that \(\eta_e\), \(E\), \(P\), \(\chi_{abs}\) are constant while \(g\), \(f\), and \(\sigma_0\) depend on the gas temperature \(T\). Hence, the PLIF signal intensity can be written as \(S_{PLIF} = i(T)/i(T)\), where \(i(T)\) is the combined effect of \(g\), \(f\), and \(\sigma_0\) while the reciprocal \(T\)-factor originates from the IGL. To find \(i(T)\), the CO \(_2\) spectrum is simulated at different temperatures. The part overlapping with the laser wavelength envelope is then used to find \(i(T)\).

By taking both of these factors into account, the imaged fluorescence can be used to calculate the temperature for every pixel by comparing the PLIF intensity originating from a reference image with homogeneous gas distribution at room temperature, with another acquired with the sample at an elevated temperature.

The advantage of this technique is that it only requires two instantaneous fluorescence images, one at a known temperature, the other at an unknown temperature.

2.2.2. Sample temperature as calibration. Another method, henceforth referred to as calibration method, to determine the temperature using PLIF is to assume that the temperature of the gas in the very near vicinity of the sample surface is equal to that of the sample. With that assumption, the loss in fluorescence intensity in the gas just above the sample is mapped to the sample temperature, which was determined by the methods mentioned above. The resulting curve may then be used to map the temperature loss as detected in every pixel to a temperature, which gives a full temperature map of the reactor.

The resulting temperature map by this method is similar to that given by the IGL method, which suggests it gives accurate results. However, the method requires fluorescence data to be available for the entire range of temperatures expected to be found, in order to construct the calibration curve. Further, the method assumes accurate temperature data is available for the sample surface.

2.2.3. Spectral measurement. Since the population distribution of vibrational and rotational levels is highly temperature sensitive, it is possible to determine gas temperature by investigating the spectrum of a gas. In this study, the CO \(_2\) infrared
spectrum was simulated for a numbers of temperatures using the HITRAN database [24, 25]. By making an excitation scan over a spectral region, it is then possible to acquire spectrally resolved images of the entire gas distribution.

3. Experiment

3.1. The reactor

The reactor used in the experiment is a 23 ml high-pressure (1 mbar to 1 bar) flow reactor for catalysis with a boracite heating element onto which the sample is placed, similar to the one presented in [26], but without the UHV capability. A cube-shaped enclosure, which is equipped with CaF2 windows on all sides, defines the reactor volume and surrounds the cross-shaped heating element, which enables optical access to the sample from all four sides. The gas supply of the reactor was regulated through a set of mass flow controllers (Bronkhorst EL-FLOW), and a pressure regulator (Bronkhorst EL-PRESS), which allowed for fine adjustments of the individual gas flows. This way, the system supports flows through the reactor ranging from a few mln min$^{-1}$ to around 500 mln min$^{-1}$, at pressures between a few mbar and 1 bar.

3.2. Flow geometries

The reactor top has five ports where windows can be placed for optical access, four on the sides and one on the top. In the default flow configuration, where the gas flow comes from below, three of the side ports and the top are equipped with windows while the fourth side port is equipped with a stainless steel cover, which has been coated with graphite on the inside to reduce background. For laser diagnostics, two opposite side ports are used as entry and exit windows, while one of the windows perpendicular to the beam is used to image the fluorescence. This configuration (without the stainless steel cover) is shown in figure 2(a), and a more artistic render of the default flow configuration with a sample in place is shown in figure 1. The latter also shows how the laser beam traverses the reactor and where the signal image is generated.

It is also possible to replace the windows in the ports with pipes used as gas inlet or outlet. In a configuration which we henceforth will refer to as stagnation flow, the top window is replaced with a pipe for the gas inlet, which leads to a well defined gas flow impinging onto the sample from above (figure 2(b)). This configuration makes it easy to compare results with simulations, as the flow is well defined and perpendicular to the sample surface [27]. However, a downside is the incompatibility with techniques that require access to the sample from the top, which the case for techniques such as STM, XPS or AFM, where the surface is probed from above.

Further, the reactor can be configured to mimic a channel flow reactor by placing the inlet and outlet pipes on the sides of the reactor (figure 2(c)). The laser is then travelling through the same pipes as the gas. This configuration is sometimes used in simulations or flow experiments which motivates its use [27, 28].

To calibrate the heating element surface temperature, a thermographic phosphor, Mg$_3$F$_2$GeO$_4$ : Mn, mixed with a magnesium aluminum silicate (HPC) binder, was applied to the heating element in positions (a)–(c) as shown in figure 3. Here (a) is on the thermocouple attachment screw itself, (b) is on top of a 10 mm × 10 mm, 2 mm thick stainless steel dummy sample used to simulate real catalyst samples, and (c) is on the heating element, where the center of the sample would end up when placed on the heating element.

The temperature of the phosphors is then determined by measuring the decay time of the phosphorescence upon excitation. To this end, a pulsed, frequency quadrupled Nd:YAG-laser (Quantel Brilliant-B) at 266 nm operating at an repetition rate of 10 Hz and with a pulse length of 6 ns was used to excite the phosphor. The laser energy was approximately 5.3 ± 1.9 µJ per pulse. An iris was used to reduce the beam diameter to 1 mm. The iris also created a top-hat profile from the Gaussian laser beam profile by cutting off the edges of the beam. Two dichroic mirrors (266 nm) were used to direct the beam to the sample holder inside the chamber. The second mirror blocked the laser light from passing through while allowing the phosphorescence signal to reach a focusing lens (f = 50 mm). The phosphorescence could then be focused into a photomultiplier tube (Hamamatsu H11256-20-NF), passing through an OG-570 long-pass filter and a bandpass interference filter with a center wavelength of 656.3 ± 3 nm (Andover Corp. FS03). The signal output was fed into an Oscilloscope (LeCroy HDO 6054) using a 50 Ω termination with a 10 Hz collection rate, synchronized to the triggering of the laser. The measured decay times are then compared with the calibration curve of Mg$_3$F$_2$GeO$_4$ : Mn to obtain the final absolute temperature. Since the calibration range of the phosphor is from around 100 °C–500 °C, the measurements are only to be considered valid within that range. The gas
conditions during the temperature calibrations were a flow of 100 ml min$^{-1}$ Ar at 150 mbar total pressure, with the reactor in the default flow configuration as presented above.

### 3.4. PLIF gas temperature measurements

All techniques to perform gas temperature characterization were derived from data acquired with PLIF. During all gas temperature measurements, a Pd(100) sample was in the positions discussed in above, and the gas flow was set to 100 ml min$^{-1}$ which resulted in around 150 mbar. The flow was 2% CO$_2$ and 98% Ar. For the PLIF measurements, a pulsed 1064 nm Nd:Yag laser operated at 10 Hz with a per-shot energy of 300 mJ was used to pump an optical parametric oscillator (OPO). This non-linear optical device can split the incoming beam into two components, a signal beam, and an idler beam. By rotating the non-linear BBO medium in the OPO with respect to the incident beam, the photon energy ratio between the signal and idler beams can be varied. In this way, the output wavelength can be tuned.

The OPO was tuned to produce a signal beam at around 1.7 µm, and an idler beam in the mid-IR regime at around 2.7 µm (around 35 mJ). The 2.7 µm idler beam was used for CO$_2$ detection by targeting the (0000) → (1001) vibrational transition of CO$_2$. Due to its broad linewidth, which is estimated to be around 4 nm, the beam covers several rotational lines with a center at 2760 nm. Prior to the reactor, the beam was shaped into a laser sheet using a convex cylindrical lens ($f = 100$ mm). In the reactor, the CO$_2$ molecules interact with the beam, resulting in fluorescence at 4.3 µm [29]. This fluorescence was imaged using a 256×256 pixel LN$_2$-cooled InSb camera (santa barbara focalplane SBF-134). The large, varying thermal background was compensated for by setting up the camera to trigger at 20 Hz, i.e. also between laser pulses, to record the current background, which was subtracted in post-processing on a per-shot basis. The background is further reduced with a band-pass filter centered at 4.26 µm. In all, we achieved a spatial resolution per pixel of 80 µm in the image plane, and a resolution of around 100 µm in the normal plane, which was limited by the thickness of the laser sheet. Since the laser has a 10 Hz repetition rate, one snapshot image was recorded every 100 ms with the camera exposure time set to 30 µs, and with a delay of 10 µs from the laser pulse to avoid any direct laser reflections. For more in depth information about the PLIF setup and post-processing, refer to [16]. To map the signal to absolute temperatures, post processing was done in accordance with the methods presented in section 2.2. Using the HITRAN database [24, 25], the CO$_2$ spectrum between 2650 nm and 2850 nm was simulated for temperatures between 200 K and 1000 K. The simulated change in signal intensity at higher temperatures due to spectral changes was then combined with a calculated decrease in signal intensity due to the change in number density originating from the ideal gas law, creating a calibration which mapped an intensity decrease to a temperature. Two images, one a reference taken with the reactor at room temperature and another taken at a higher temperature were then selected, and the temperature data extracted by comparing the intensity loss to the calibration curve. With this done on a per-pixel basis, temperature maps of the entire reactor region were created.

#### 3.4.1. Spectral measurement

For the spectral method, the BBO crystal angle is continuously ramped to scan the laser wavelength over the entirety of the 2.7 µm absorption band in CO$_2$, yielding an absorption spectrum. Using the HITRAN
database [24, 25], the absorption spectrum within the relevant wavelength range was then simulated for all temperatures between 200 K and 1000 K. Two regions of the spectrum with a particularly large difference between low and high temperatures were chosen as shown in figure 4. The fraction of the integrated intensities in these regions was then determined for all simulated spectra as well as for the measured spectrum, where it was done on a per-pixel basis. Subsequently, each pixel was assigned a temperature value based on its ratio, resulting in a temperature map of the gas within the laser sheet. Since there are also intensity variations in the laser profile that originate from the scanning itself, a measurement at room temperature was conducted which was be used to compensate this effect.

3.5. IR camera

The InSb camera used to detect the CO$_2$ fluorescence can also be used as simply an IR camera to detect heat radiation. A Planck radiation curve is calculated for temperatures between 250 K and 800 K, after which the range transmitted by the 4.26 µm bandpass filter on the IR Camera is determined and taken into account. Differences in emissivity are corrected for by assuming that the final temperature reported by the calibrated thermocouple is correct, and that the sample temperature is at room temperature before any heating current is applied.

4. Results and discussion

4.1. Comparing the methods

We have performed gas temperature measurements using the three aforementioned techniques for the default flow configuration, the results are shown in figure 5. Here (a) shows the results using the IGL method, (b) uses the calibration method and (c) uses the spectral method. Note that (a) and (b) use the same raw image data, but with a different post-processing to map intensity variations to temperature variations, whereas (c) uses an entirely different dataset. Panels (d) through (i) in figure 5 trend the temperature of the respective method along the lines indicated in panels (a) through (c). The methods have a number of advantages and disadvantages, and they rely on different assumptions. The IGL method relies on a stable laser and that the decrease in intensity due to spectral changes can be accurately accounted for. The calibration method relies on a stable laser and on reliable temperature data of the catalyst surface. Also, while the calibration method technique does not rely on any spectrum simulations—all spectral effects should be ‘taken care of’ by the calibration—the method does require measurements during a temperature ramp. In contrast, the IGL method only requires a cold image and an image at the temperature to be mapped. Both aforementioned methods require an otherwise homogeneous gas distribution, which renders them difficult to use during actual catalytic activity, which itself often causes an inhomogeneous gas distribution around the catalyst.

The spectral method, on the other hand, works regardless of gas distribution, given that there is enough of the probed gas (in this case CO$_2$) present to generate a signal. In fact, it is possible to use the technique during *operando* measurements while simultaneously mapping the product distribution. However, the method does have a number of downsides. First, the spectral method requires the laser to be scanned, which takes around 5 min. Second, the method relies on a spatially homogeneous laser sheet during scanning. As scanning by crystal rotation will alter the beam path, this is not guaranteed. While this can be partially compensated for by comparing the spatial intensities at the two spectral regions at room temperature, it is difficult to completely compensate for the effect. Also, since the method relies on a fraction between two signals, it produces more noisy results compared with the other methods.

Comparing the images produced by the three techniques shows that they do yield similar results, however, it is clear that the spectral method shows a higher temperature for the regions further away from the sample, compared with the other methods. We mainly attribute this to changes in the spatial profile of the laser sheet as the OPO is scanned over the spectrum.

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**Figure 4.** The simulated spectra for 300 K and 650 K as well as an excitation scan showing the PLIF signal close to the sample as the thermocouple reports around 650 K. The purple and blue areas are the division regions used for the spectral method. The red region indicates the estimated laser envelope during the measurements used for the IGL and calibration methods.
4.2. Comparing flow configurations

We have further performed measurements with the three flow configurations outlined in figure 6. These show that different flow configurations give rise to very different gas temperature distributions, where stagnation flow (figure 6) gives the most well defined temperature gradient perpendicular to the sample surface. While the results here are in no way surprising, we believe that they can provide valuable insights. Both for the confirmation or adjustment of simulations or for better estimation of XPS signal loss mentioned in the introduction, but also for more practical issues. Examples could be knowledge of how warm certain elements in the reactor become, which is important to know to avoid contamination. It could also be useful to judge the amount of reactions that could occur in the gas phase, products of which could influence results if not considered. Also, experimental studies of the gas temperature distribution are useful to improve theoretical models of reactors.

4.3. Transient study

In another measurement, the sample temperature was gradually increased by linearly increasing the current that is fed through the heating element. Figure 7 shows the results of this
measurement, where the plots indicate the temperature of the gas in a region very close to the sample surface. Note that the red-shaded area indicated the temperature region for which the thermocouple is not calibrated. Further, it is worth mentioning that while the current increases linearly, the heating power will increase in a cubic fashion according to Ohms law. As is shown, the temperature of the gas according to the IGL method matches that of the IR camera and thermocouple rather well, albeit with considerable noise.

4.4. Operando study

As a proof-of-concept, we have also attempted to use the spectral method to measure the temperature of the gas surrounding an active Pd(1 0 0) catalyst sample during CO oxidation, while at the same time probing the spatial distribution of the CO₂ reaction product. Here the reactor was in the default flow configuration with a flow of 4% CO, 4% O₂, and 92% Ar at a total flow of 100 ml min⁻¹ with a total pressure of 150 mbar. The result is shown in figure 8. Here, instead of scanning the laser, two measurements at different laser wavelengths were carried out with while the sample was active. This measurement was performed at cooler temperatures, with the calibrated thermocouple temperature being only 336 °C. Another difficulty encountered here is that there is naturally very little CO₂ signal available at room temperature, as the sample not yet active then. This makes it challenging to create an in situ method with the thermocouple is not calibrated. Further, it is worth mentioning that while the current increases linearly, the heating power will increase in a cubic fashion according to Ohms law. As is shown, the temperature of the gas according to the IGL method matches that of the IR camera and thermocouple rather well, albeit with considerable noise.

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profile to compensate for spatial changes in laser intensity as the wavelength is changed between the two spectral regions.

5. Conclusion

In this work, we have investigated various methods to create spatially resolved temperature maps of the gas distribution in a typical reactor for operando heterogeneous catalysis experiments. Of the techniques we have tested, the IGL technique discussed in section 2.2.1 gives the most accurate and consistent results, and it is very convenient to use as it only requires two fluorescence snapshots, one at room temperature and the other at the temperature to be measured. It is also not dependent on any knowledge of the sample temperature. The downside of the IGL technique is that it requires a homogeneous gas distribution in the reactor. This property renders the IGL method unsuitable for use during operando experiments where the catalytic activity introduces a gas concentration gradient. Thus, we also present the spectral technique in section 2.2.3, which exploits the temperature sensitivity of molecular spectra. While the images produced by this technique are more noisy, and may be more difficult to calibrate to absolute temperatures, the spectral technique can be used in conjunction with an active catalyst and does not require a homogeneous gas distribution in the reactor.

Further, we have presented a method to calibrate a thermocouple not directly attached to the sample by using thermographic phosphors, which can then be used to calibrate an IR-camera signal. In all, we believe that the presented techniques can be used to better understand catalytic reactions, and to improve theoretical models of catalytic reactors. It could also be an aid in the choice of materials for reactor design, as it makes it easier to estimate which parts of the reactor are exposed to high temperatures.

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