IMPROVING TEMPERATURE MEASUREMENT AND CONTROL USING THE EXACTUS® OPTICAL THERMOMETERS

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Abstract: Offering excellent accuracy, resolution, repeatability, and stability, EXACTUS® optical thermometry technology provides significant performance advantages in non-contact temperature measurement in a practical, rugged and user-friendly design. To assess the performance of the EXACTUS® optical pyrometer device for controlling the temperature of steam cracking furnaces, ethane steam cracking experiments have been carried out in the Pilot plant set-up of the Laboratory for Chemical Technology (LCT), Gent, Belgium. The control performance of EXACTUS® was compared with that of a weld-on type K thermocouple, the latter being representative of the present state of the art in furnace control via wall temperature measurement. EXACTUS® equipment is found to be suited as a sensor to measure tube metal temperatures of a steam cracking reactor coil, either inside or outside of the furnace. It outperforms a weld-on thermocouple in providing a process value to the controller and hence offers an advantage over the present state of the art. The main benefit of EXACTUS® over thermocouples is when the temperature measurement is used to prevent overshoots of tube metal temperature, which have an adverse effect on the tube longevity and the coke formation.
Introduction

Accurate temperature measurements are of the utmost importance for stable operation and optimal product quality in most, if not all, industrial processes. Several methods for temperature measurement have been developed based on different physical principles. A distinction is made between contact and non-contact temperature measurements, with contact measurement being the industry’s favored method. Contact measurements are either based on mechanical effects, e.g. the volume change of gases, liquids or solids, or on electrical effects, e.g. the voltage generated between two dissimilar metals or the change in resistance of a metal. Non-contact measurements are mostly based on the intensity of electromagnetic radiation emitted by a hot surface.

Thermocouples are the most frequently used contact temperature measurement method due to their low cost, wide measurement range and relatively high accuracy. Their major drawback is thermal drift: recurrent recalibration or replacement of thermocouples is needed to maintain their absolute accuracy. Non-contact measurements are almost exclusively based on infrared measurements. These techniques have only recently been applied in industry, after issues of reliability, cost and sensor size were resolved. Research continues improve the reliability and applicability of the method. Advantages of infrared temperature measurements are the higher information rate (higher measurement frequency), the high longevity at high temperatures and the fact that no energy is removed from the measured surface. However, as the measurement is based on electromagnetic radiation, the optical path between the object and the sensor must be clear. An accurate measurement is inhibited by dust or smoke, as well as by contaminations on the sensor or the measurement surface. Moreover, only surface temperature measurements are possible. Non-contact temperature measurements have been successfully implemented in heavy-duty sectors such as metal production, power generation and the glass industry. Other applications benefit from these measurements as well, e.g. the paper industry, food and beverage industry and the automotive industry.

In this work, the potential of using optical thermometers for control purposes in a steam cracking furnace is assessed by testing the equipment in a Pilot plant set-up for steam cracking. First, the working principle of non-contact infrared thermometers is explained, followed by a description of the EXACTUS® optical thermometer. In a third section, the Pilot plant set-up for steam cracking of hydrocarbons is presented, including a description on how the EXACTUS® equipment was implemented and the procedure followed during the experiments. Subsequently the results for temperature, product yields and coke formation are presented and discussed. At the end, the conclusions of the study are summarized.

Working principle of optical thermometers

An optical thermometer or pyrometer determines the temperature of a radiating surface based on the known emissivity of the surface (by calibration) together with the measured radiation intensity. This discussion on the working principle is based on the work of Brown et al. The Stefan-Boltzmann law, given in Equation (1), forms the basis for calculating the temperature. It relates the total radiation intensity \( J \), i.e. the power of the radiation from a
certain surface received by the detector, to the temperature $T$ via the Stefan-Boltzmann constant $\sigma$ and the surface emissivity $\varepsilon$.

$$J = \varepsilon \sigma T^4$$

(1)

The Stefan-Boltzmann law applies to the full electromagnetic spectrum so it accounts for all the radiation emitted by a certain surface. However, detection of the full radiative power of a certain surface requires very tedious measurements. Therefore, the temperature of a surface can also be calculated based on the radiation intensity at a certain wavelength $\lambda$. This facilitates the measurement and via careful selection of the wavelength, interference with the environment can be minimized. Planck’s Law (Equation (2)) can be used instead of the Stefan-Boltzmann law to calculate the surface temperature based on the emissivity at a certain wavelength.

$$I'(\lambda, T) = \frac{2 \hbar c^2}{\lambda^5} \frac{1}{e^{\frac{\hbar c}{\lambda k_B T}} - 1}$$

(2)

In this equation, $I'$ is the radiation intensity, i.e. the energy per unit time radiated per unit area of emitting surface in the normal direction per unit solid angle per unit frequency, $\hbar$ is the Planck constant, $c$ is the speed of light in the medium and $k_B$ is the Boltzmann constant. Planck’s Law is visualized in Figure 1 for wavelengths in the interval $0 \, 10^{-6} \text{ m} - 7 \, 10^{-6} \text{ m}$ at temperatures of 800 K, 1000 K, 1200 K, 1400 K, and 1600 K. As the temperature increases, the maximum radiation intensity increases and the location of the peak shifts to shorter wavelengths. Planck’s Law can be used to select an appropriate wavelength for the range of temperatures that is to be measured with the pyrometer. The higher the radiation intensity of the surface at the selected wavelength, the higher the precision of the measurement.

Figure 1. Radiation intensity as function of wavelength according to Planck’s Law at different surface temperatures. 800 K; 1000 K; 1200 K; 1400 K; 1600 K
Planck’s Law is only valid for black bodies with an emissivity of 1 for all wavelengths. The radiation intensity of a real surface is lower than the radiation intensity of a black body. The ratio of the emitted radiation of a real surface and the radiation intensity of a black body is defined as the emissivity of the real surface, see Equation (3). Emissivity is both temperature and wavelength dependent.

\[ \varepsilon(\lambda, T) = \frac{I'_\text{actual}(\lambda, T)}{I'_\text{black body}(\lambda, T)} \]  

Incident radiation on a surface can either be absorbed, reflected or transmitted. These parts are respectively calculated via the reflectance \( \rho \), absorptance \( \alpha \) and the transmittance \( \tau \). Equation (4) follows directly from the conservation of energy. For opaque bodies, the transmittance is very small so the equation simplifies to equation (5). For black bodies, the reflectance is zero so the absorptance is equal to one.

\[ \rho + \alpha + \tau = 1 \]  
\[ \rho + \alpha = 1 \]  

In most applications, the transmittance of the emitting surface can be considered as zero. However, the absorptance of the surface is not equal to one so part of the incident radiation is reflected. To obtain an accurate measurement of the surface temperature of the real surface, the emissivity should be precisely known. As emissivity is both wavelength and temperature dependent, this is not so straightforward. Deviations on the emissivity value can significantly affect the accuracy of the measurement. A 10% error on the emissivity value can result in an absolute error on the temperature measurement of a couple of Kelvin at low surface temperatures but the error could increase to over 100 K at high surface temperatures for measurements at longer wavelengths. An experimental device to measure the temperature and wavelength dependent emissivity of a surface is described in the work of Brown et al. \(^{10}\).

The issue of not knowing the emissivity can be mitigated by measuring the radiation intensity of the surface at two distinct wavelengths sufficiently close together in the electromagnetic spectrum. In that case, the emissivity can be considered as equal for the two wavelengths. Plank’s Law can then be applied to the measurements at the two wavelengths, resulting in a set of two equations with two unknowns: the emissivity \( \varepsilon \) and the temperature \( T \). So-called multi-wavelength pyrometers implement this strategy for measuring the temperature of a surface with an unknown or varying emissivity \(^{2}\).

**EXACTUS® optical thermometer**

The EXACTUS® is an optical thermometer developed by the Temperature Sensing Group of BASF. Figure 2 provides a schematic overview of the equipment. The pyrometer consists of three main parts: a detector, an amplifier circuit and an optical system \(^{10}\). Via the collection optics, electromagnetic radiation emitted from the measurement surface is gathered and sent via and optional lightpipe to the photodetector incorporated in the probe head. The filter isolates the required wavelength from the incoming light. The amplified electrical signal from the photodetector is digitized and sent to a computer via a LAN-connection or transformed in an
analog signal e.g. a 4-20 mA signal or a 0-10 VDC signal which can be interpreted by a Programmable Logic Controller (PLC).

The benefits of the EXACTUS® device are a high accuracy down to 1.5 K with a repeatability of 0.10 K, a fast signal gathering up to 1000 Hz and a low drift of less than 0.1 K per year. An optional system with fiber-optic cables allows installing the electronic equipment away from the point where the light is gathered. This is necessary in industrial configurations where strict zoning laws apply. The downside is a slight loss in accuracy as the fiber-optic cable can influence the result. Calibration in place of the hardware can further reduce the measurement error.

Depending on the desired temperature range, light of different wavelengths is analyzed to determine the temperature. A photodetector tuned to radiation with a wavelength of 900 nm allows to measure temperatures in the range of 280 °C to 3000 °C. Radiation at 1600 nm is suited to provide temperature readings in the range of 65 °C to 2800 °C. The wavelengths are selected in such a way to avoid interference with common gaseous components in the air and in combustion gases (H₂O, CO₂, CO, CH₄, etc.).

Initially the EXACTUS® device has been developed for applications in the semiconductor industry where fast temperature readings with a high accuracy are needed in order to have good wafer growth. Optical measurements in such an environment are straightforward as these manufacturing facilities are free of dust. However, when applying EXACTUS® in other industries such as production of bulk chemicals or in the steel industry, it should be guaranteed that there is a clear line of sight between the optics of EXACTUS® and the measuring surface. Additionally, no depositions should be present on the optics and the state of the analyzed surface should not change since these changes will affect the surface emissivity.
Pilot plant set-up for steam cracking of hydrocarbons

The experimental work is carried out in the Pilot plant set-up for steam cracking of hydrocarbons at the Laboratory for Chemical Technology (LCT) of Ghent University, see Figure 3. Since the main parts of this unit, the analytical equipment and the calibration procedure have been described elsewhere 11,12, only a brief description, based on Wang et al. 13, Dhuyvetter et al. 14 and Van Geem et al. 15 is given below.

Figure 3. Picture of the LCT Pilot plant set-up for steam cracking of hydrocarbons.

The process flow diagram of the Pilot plant set-up is given in Figure 4. The feed section controls the supply of different feedstocks to the reactor coil. The measurement of the mass flow rate of liquid hydrocarbons and water is carried out using a CORI-FLOW mass flow controller. The pumping frequency of the CORI-FLOW pump is automatically adjusted by the controller of the CORI-FLOW. Gaseous hydrocarbons are fed to the reactor from pressurized gas cylinders by means of a separate CORI-FLOW mass flow controller.

The furnace, built using silica/alumina bricks (Li23), is about 4.0 m long, 0.7 m wide and 2.6 m high. It is fired by means of ninety premixed gas burners, mounted with automatic fire checks and arranged on the side walls in such a way as to provide a uniform heat distribution. The furnace is divided into seven separate cells, which can be fired independently to set any type of temperature profile.

The reaction section of the reactor coil is about 12 m long, made of high-alloy steel, and has an internal diameter of 9 \(10^{-3}\) m. These dimensions are chosen to achieve turbulent flow
conditions in the coil with reasonable feed flow rates (Re > 7000). Twenty thermocouples and eight manometers are located along the reactor coil to measure the temperature and pressure of the process gas as indicated on Figure 4. The pressure in the reactor is controlled by a reduction valve. At the reactor outlet, nitrogen is injected as internal standard for the analysis. Before cooling the effluent, a sample is taken for the on-line \( \text{C}_5^+ \) analysis. After cooling and knock-out of the liquefied products and tar, a second sample is taken for on-line \( \text{C}_4^- \) analysis. The rest of the effluent is sent to the flare.

For the current campaign, some modifications were made to the set-up in order to accommodate the EXACTUS\textsuperscript{®} equipment. These modifications are discussed in the next paragraph.

A custom collar is fitted around the reactor outlet tube between the insulation box of the transfer line exchanger (TLE) and the flange connecting the reactor to the analysis section, that is in the adiabatic section of the furnace. The custom designed collar displayed in Figure 5 allows to position 3 devices to measure tube metal temperature within a distance of 0.08 m. Two EXACTUS\textsuperscript{®} devices and one spring-loaded thermocouple were positioned in the custom collar in the following order (in the flow direction): EXACTUS\textsuperscript{®} 1, EXACTUS\textsuperscript{®} 2 and the spring loaded thermocouple. In between the insulation box for the TLE and the custom collar with the EXACTUS\textsuperscript{®} equipment, a type K thermocouple was welded to the tube as a reference measurement for the tube metal temperature. This thermocouple is not shown on Figure 5.

**Installation of the EXACTUS\textsuperscript{®} device in the Pilot plant set-up**

![Process flow diagram of the LCT Pilot plant set-up for steam cracking of hydrocarbons.](image)

Figure 4: Process flow diagram of the LCT Pilot plant set-up for steam cracking of hydrocarbons. ▲: temperature measurements; ⬠: pressure measurements.
Via the viewing ports in the furnace wall, EXACTUS® 3 was installed to measure the tube metal temperature inside the furnace close to the reactor outlet. The lens for this device was positioned by attaching a laser pointer to the fiber-optic cable and manually pointing the lens at the desired point in the reactor. Before each experiment the alignment was checked. The mounted EXACTUS® device and the position of the laser pointer on the coil in the furnace are shown in Figure 6.

The newly installed hardware allows to provide a process value for the furnace temperature control in the following three ways:

1. **EXACTUS ADIABATIC**: EXACTUS® 1, mounted in the custom collar in the adiabatic section
2. **TK ADIABATIC**: the weld-on type K thermocouple in the adiabatic section
3. **EXACTUS FURNACE**: EXACTUS® 3, mounted outside of the furnace and viewing the reactor coil via a viewing port in the refractory.

The names EXACTUS ADIABATIC, TK ADIABATIC and EXACTUS FURNACE will be used to refer to these three different control systems.
Experimental procedure

The process value for temperature in the furnace is delivered by either the EXACTUS® optical thermometer in the adiabatic section (EXACTUS ADIABATIC), the weld-on thermocouple in the adiabatic section (TK ADIABATIC) or the EXACTUS® optical thermometer pointed towards the reactor in the furnace (EXACTUS FURNACE). The default control system of the Pilot plant set-up is used during initial stabilization and decoking but it is disabled during the actual experiment (phases 2, 3 and 4). The following experimental procedure is adopted for all experiments.

- Leak test of the hot section using N\textsubscript{2} at a pressure of 4 bar during 5 minutes.
- In case there has been no experiment the previous day: pre-oxidation of the coil with air for 30 minutes.
- Preheating of the reactor using the default control system, reactor: H\textsubscript{2}O
- **Phase 1:** Cracking with 3000 g/h ethane and 1155 g/h water (dilution: 0.385 kg/kg) using the default control for stabilization. Addition of 100 ppm sulfur/kg hydrocarbons. Duration: 1h08.
- **Phase 2:** Switch furnace temperature control to the relevant alternative control system. The process set point for this phase is determined based on its stable temperature during phase 1. Continue cracking. Duration: 1h50.
- **Phase 3:** Increase process set point of the relevant alternative control system by 10 °C. Continue cracking. Duration: 1h26.
- **Phase 4:** Increase process set point of the relevant alternative control system by 15 °C. Continue cracking. Duration: 1h26.
- Stop cracking, reactor: N\textsubscript{2}
- Decoking of the reactor
- Cooling down of the reactor

All experiments are carried out using ethane as feedstock. It is supplied by Praxair Belgium with a specification of 99.999 %. Sulfur is added to the feed in the form of dimethyl disulfide. A solution of 1.13 wt% DMDS in hexane is made and fed to the reactor at a flow rate of 59.3 ml/h, resulting in a sulfur mass based content of 100 ppm per kg hydrocarbons.

Effluent composition analyses are done back-to-back. The C\textsubscript{4} analysis takes 29 minutes, and a new sample injection is started once the full C\textsubscript{4} analysis cycle is finished. The focus in the current campaign is on the C\textsubscript{4} analysis as only a small fraction of the reactor effluent in ethane cracking has a carbon number higher than 4.

Results and discussion

In total two experiments were carried out with each of the three available control systems listed in the section on the hardware modifications, resulting in a grand total of 6 experiments. The results of all experiments are systematically displayed. Three parameters are investigated in the remainder of this paper for their stability, accuracy and reproducibility: temperature, product yields and coke formation.
**Temperature**

During the experiments, the temperatures measured by EXACTUS ADIABATIC, TK ADIABATIC and EXACTUS FURNACE were recorded. Figure 7 displays a typical temperature profile in an experiment controlled by EXACTUS FURNACE. The process value and the set point value for the control system during phases 2, 3 and 4 of the experiment are displayed. The temperature measurement of the default control system was also recorded and plotted in Figure 7. This reference temperature measurement is referred to as DEFAULT.

![Figure 7. Typical temperature profiles during ethane cracking while controlling the furnace temperature based on EXACTUS FURNACE.](image)

In order to quantitatively compare the different control systems, a statistical analysis of the data is performed. The main goal is to analyze the fluctuations around the process set point (which depend on the control system that is applied) and the fluctuations of the DEFAULT measurement around its per-phase average. The measurement points in a time period of 20 minutes after a set point change are not taken into consideration to avoid the influence of transient effects. For both fluctuations, the root mean square (RMS) error is given, calculated by equation (6). The $\varepsilon_{RMS}$ value gives an indication of the magnitude of the error. For both fluctuations, also the maximum of the absolute value of the deviations is determined.

$$\varepsilon_{RMS} = \left( \frac{x_1^2 + x_2^2 + \cdots + x_i^2 + \cdots + x_n^2}{n} \right)^{\frac{1}{2}}$$  \hspace{1cm} (6)

The results of the statistical analysis are given in Table 1. The error on the process set point value provides an indication of the intrinsic process control quality of the measurement.
device. The RMS error on the process set point is of the same order of magnitude for the EXACTUS ADIABATIC control compared to the TK ADIABATIC control. The EXACTUS FURNACE control has a high $\varepsilon_{RMS}$ due to bad set point tracking in one of the experiments. Similar trends are observed in the maximum oscillation amplitude ($\varepsilon_{MAX}$ (process set point)): the cases EXACTUS ADIABATIC and TK ADIABATIC are of the same order of magnitude with slightly higher amplitudes for TK ADIABATIC. The maximum amplitude for EXACTUS FURNACE is also in the same range. The size of the maximum oscillation amplitude on the process set point is about a factor 8 larger than the size of the dead band on the control system.

Table 1. Root mean square (RMS) error and maximum error amplitude on the process set point and on the default temperature measurement.

<table>
<thead>
<tr>
<th></th>
<th>$\varepsilon_{RMS}$ (process set point) [K]</th>
<th>$\varepsilon_{MAX}$ (process set point) [K]</th>
<th>$\varepsilon_{RMS}$ (DEFAULT measurement) [K]</th>
<th>$\varepsilon_{MAX}$ (DEFAULT measurement) [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXACTUS ADIABATIC</td>
<td>2.62</td>
<td>8.59</td>
<td>4.15</td>
<td>12.15</td>
</tr>
<tr>
<td>TK ADIABATIC</td>
<td>2.72</td>
<td>7.60</td>
<td>4.25</td>
<td>12.58</td>
</tr>
<tr>
<td>EXACTUS FURNACE</td>
<td>3.76</td>
<td>8.34</td>
<td>1.10</td>
<td>2.72</td>
</tr>
</tbody>
</table>

Based on temperature, no clear distinction can be made between the EXACTUS® measurement device and the thermocouple measurement device in terms of control performance. Rather it becomes obvious that the location of the measurement has a much larger effect on the final result than the actual measurement device as seen in the results of the DEFAULT measurement. The measurements EXACTUS ADIABATIC and TK ADIABATIC are taken in the adiabatic section while EXACTUS FURNACE is measured in the furnace. The delay between control action and the change in the process value for EXACTUS ADIABATIC and TK ADIABATIC are not accounted for in the controller, resulting in adverse effects on the control performance. Also, there is a discrepancy between the time scales involved in the process control. The time scale of the furnace is of the order of magnitude of minutes. Changing the measurement device from the thermocouple (with time scale seconds) to the EXACTUS® device (with time scale $10^{-3}$ seconds) has little influence on a system with a much larger time scale such as the furnace.

**Product yields**

The influence of the control system on the process yields is investigated based on the results for ethane conversion and ethene yield. The data for the ethane conversion is given in Table 2. The goal of the conversion and yields analysis is to investigate the stability of the control system. Ideally, the difference in the values for each experiment between Phase 1 and Phase 2 is small as the same process set point is maintained, but with a different control system. Deviations in the values between Phase 1 and Phase 2 point to instabilities when changing the control system. The measurements at Phase 2, Phase 3 and Phase 4 should form a ‘logical series’. The set point temperature increases relative to the previous set point in this series so the ethane conversion should increase as well.
Table 2. Ethane conversion [%] with different alternative control systems (rows) for different set points (columns); Phase 1. default control during stabilization; Phase 2. set point 1 with alternative control; Phase 3. set point 2 with alternative control; Phase 4. set point 3 with alternative control.

<table>
<thead>
<tr>
<th>Control System</th>
<th>Phase 1</th>
<th>Phase 2</th>
<th>Phase 3</th>
<th>Phase 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXACTUS ADIABATIC</td>
<td>51.60 ± 0.32</td>
<td>49.16 ± 0.84</td>
<td>53.0 ± 0.55</td>
<td>58.62 ± 1.45</td>
</tr>
<tr>
<td>TK ADIABATIC</td>
<td>51.54 ± 0.40</td>
<td>49.91 ± 0.71</td>
<td>54.5 ± 1.24</td>
<td>60.31 ± 2.15</td>
</tr>
<tr>
<td>EXACTUS FURNACE</td>
<td>51.67 ± 0.20</td>
<td>51.09 ± 0.65</td>
<td>53.7 ± 1.19</td>
<td>56.89 ± 0.45</td>
</tr>
</tbody>
</table>

The data of Phase 1 is very consistent so the stabilization procedure at the start of each experiment reaches its goal, which is providing a reproducible initial state of the furnace for all experiments. When switching to the new process control system (Phase 2), the process yields change as a consequence of the temperature fluctuations. The difference in product conversion is directly related to the amplitude of the temperature fluctuations. For EXACTUS ADIABATIC, the conversion drops significantly by -2.43 % absolute between Phase 2 and Phase 1. The repeatability of the analysis also decreases resulting in a larger estimated standard deviation. The drop in conversion is also present in the TK ADIABATIC case but it is less pronounced, with decreases of -1.63 % absolute. This falls within the error margin on the analysis. The repeatability is also slightly better for TK ADIABATIC in Phase 2 compared to EXACTUS ADIABATIC in Phase 2. The conversion difference for EXACTUS FURNACE between Phase 2 and Phase 1 is -0.57 % absolute. This falls within the uncertainty on the conversion analysis.

The 'logical series' in the conversion at Phase 2, Phase 3 and Phase 4 is observed for all three control systems. However, the changes in conversion between phases for the EXACTUS ADIABATIC and TK ADIABATIC experiments are larger than the changes in conversion between phases for EXACTUS FURNACE. Set point changes in the adiabatic section hence have a larger influence on the furnace temperature than set point changes in the furnace temperature itself. The repeatability of TK ADIABATIC is lower in phases 3 and 4 than the repeatability of EXACTUS ADIABATIC. The lower thermal inertia of the EXACTUS® device over a type K thermocouple provides an advantage when the set point changes: the EXACTUS® device follows the temperature change more quickly and hence decreases the standard deviation on the ethane conversion in phases 3 and 4.

**Stability analysis**

The overall estimated standard deviations on the ethane conversion and the ethene yield are given in Table 3. When comparing EXACTUS ADIABATIC and TK ADIABATIC, it is seen that the standard deviations on the yields are smaller for measurements with EXACTUS® compared to measurements with a weld-on thermocouple. This indicates a better process stability in the case of EXACTUS® control compared to control via a weld-on thermocouple in the same location. The standard deviations for EXACTUS FURNACE are generally lower compared to EXACTUS ADIABATIC and TK ADIABATIC. This is a consequence of the position of the temperature measurement.
Table 3: Standard deviations on the analysis of ethane conversion and ethene yield for the different control systems.

<table>
<thead>
<tr>
<th></th>
<th>STDEV Ethane conversion [%]</th>
<th>STDEV Ethene yield [wt%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXACTUS ADIABATIC</td>
<td>0.79</td>
<td>0.59</td>
</tr>
<tr>
<td>TK ADIABATIC</td>
<td>1.13</td>
<td>0.84</td>
</tr>
<tr>
<td>EXACTUS FURNACE</td>
<td>0.62</td>
<td>0.47</td>
</tr>
</tbody>
</table>

Reproducibility of the ethane conversion and ethene yield

The main goal of the current analysis is to assess the reproducibility of certain process conditions based on the different control systems, that is answering the question “if the same temperature set point is applied in the different control situations, how does this affect the conversion and the ethene yield?”. The following strategy is applied to analyze this: plots are made of the measured conversion as function of four temperature measurements (EXACTUS ADIABATIC, TK ADIABATIC, EXACTUS FURNACE and DEFAULT) with different symbols depending on which control system was applied (EXACTUS ADIABATIC, TK ADIABATIC or EXACTUS FURNACE).

The plots are given in Figure 8. For EXACTUS ADIABATIC (a), TK ADIABATIC (b) and EXACTUS FURNACE (c), only the data points are shown which were obtained using the control method based on that measurement. For the DEFAULT measurement, all the data points are shown, i.e. for all the control systems. The spread of the points around the linear trendline is an indication of the correlation between the ethane conversion and the considered temperature measurement. The smaller the spread, the tighter the link between the temperature measurement and the conversion so the better this measurement method is suited for control. The spread of EXACTUS ADIABATIC and EXACTUS FURNACE around the trendline is fairly small as seen in Figure 8 (a) and (c). For TK ADIABATIC, two distinct trendlines can be observed in Figure 8 (b), belonging to the two experiments that were carried out using TK ADIABATIC control. The change in the mean temperature for the TK ADIABATIC measurement is a consequence of a change in the environmental conditions: a small readjustment of the EXACTUS® collar around the outlet affected the position of the thermocouple to such an extent that the heat losses to the environment were larger than before, resulting in a lower measured temperature. However, the spread around both trendlines is small, indicating a strong correlation between conversion and the measured temperature. For the DEFAULT measurement, all data points are plotted in Figure 8 (d). There is a strong correlation with conversion, independent of the control mechanism. However it is clear that some outliers are present for control based on EXACTUS ADIABATIC and TK ADIABATIC.
The following conclusions can be drawn from this analysis. First, it is not realistic to use the same absolute temperature set points for various control methods, i.e. there is no guarantee that the same absolute temperature set point for different control methods provides the same conversions and product yields. The control set points should be considered as an indication of conversion and should be tuned to each control method separately. Once this tuning is complete, any temperature measurement can be used to control the conversion as long as the correlation between the absolute temperature and the resulting conversion is known. Second, TK ADIABATIC is very sensitive to changes in the ambient condition. With this control method, matching absolute temperatures with a certain conversion is tricky as this relation can change significantly over time. EXACTUS ADIABATIC provides a more stable control system which is much less affected by external factors.
Coke formation

Instantaneous information about coke formation cannot be obtained from experiments in the Pilot plant set-up. However, analysis of the amount of gasified carbon during decoking gives a good indication of the amount of coke deposited during the experiment in the whole reactor. The information obtained during decoking is provided in Table 4.

Table 4: Coke yield for the different control methods.

<table>
<thead>
<tr>
<th>Method</th>
<th>Coke yield [g]</th>
<th>Maximum rate of coke gasification [g s⁻¹]</th>
<th>Total decoking time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXACTUS ADIABATIC</td>
<td>18.30 ± 0.92</td>
<td>0.26</td>
<td>6635</td>
</tr>
<tr>
<td>TK ADIABATIC</td>
<td>18.00 ± 0.90</td>
<td>0.26</td>
<td>7740</td>
</tr>
<tr>
<td>EXACTUS FURNACE</td>
<td>16.03 ± 0.80</td>
<td>0.27</td>
<td>6430</td>
</tr>
</tbody>
</table>

The difference in coke yield between EXACTUS ADIABATIC and TK ADIABATIC is only 0.3 g which falls within the 5 % uncertainty interval around the experimental value. However, the coke yield for EXACTUS FURNACE is significantly lower compared to EXACTUS ADIABATIC and TK ADIABATIC. The difference in maximum rate of coke gasification is small and should not be considered significant. However, there is a considerable difference in the total decoking time for TK ADIABATIC compared to the other experiments. This indicates that the coke formed during the TK ADIABATIC experiments has a higher density, pointing to more process instability with local overheating. Indeed, temperature peaks during the experiment cause a sudden increase in the rate of coke formation and also make the already formed coke denser.

In Figure 9, the end-of-run-coke yields are plotted as function of the tube metal temperature for the performed experiments. The experiments show a clear agreement with the trend calculated by the model proposed by Plehiers ¹⁶, indicated by the dotted line.

![Figure 9](image_url)

Figure 9. End-of-run coke yield [$10^{-3}$ kg] as function of tube metal temperature [K] in the furnace, measured via EXACTUS FURNACE. ⬤ experimental data, · · · · · · trendline based on the model of Plehiers et al. ¹⁶.
The data points at high average tube metal temperature belong to an EXACTUS ADIABATIC and TK ADIABATIC experiment. The explanation for the high coking yield in these experiments is related to the position of the process value measurement for temperature control. For EXACTUS ADIABATIC and TK ADIABATIC, the process measurement is taken outside of the furnace. While the control system prevents high temperatures in the adiabatic section, it does not prevent high temperatures in the furnace and hence causes additional coke formation. For EXACTUS FURNACE, the tube metal temperature is generally lower and hence the amount of coke formed is lower.

Conclusions

EXACTUS® pyrometers can be used as an alternative for type K thermocouples to supply the process value to the temperature controller of a steam cracking furnace. To test the performance of this technology, experiments in a Pilot plant set-up have been performed and the comparison has been made with the present state of the art for surface temperature measurements, that is a weld-on thermocouple.

Analysis of the temperature profiles indicated that the overall error on the process value of the controlled set point is slightly smaller for control with EXACTUS® compared with weld-on thermocouple control in the same location, however the maximum error is larger for EXACTUS®. The effect on the process itself is largely dependent on the distance between the area of influence of the control action and the set point process value measurement: it is of the utmost importance to measure directly after the coil and not after the adiabatic section. Overall, EXACTUS® provides a better control performance for the temperature compared to a weld-on thermocouple.

The conversion and products yields are taken as an indicator of the process stability given a certain control system. The ethane conversion shows similar trends for the different control systems when analyzing the standard deviation on the effluent analysis. The standard deviation on the product composition analysis is smaller for EXACTUS® compared to a weld-on thermocouple.

The results of the analysis of the formed coke during the experiment indicate that there is no significant difference in the amount of coke formed between EXACTUS® control and control via a weld-on thermocouple. The weld-on thermocouple control provides denser coke, resulting in longer decoking times. EXACTUS® control inside the furnace limits the tube metal temperature due to the lower thermal inertia of the measurement device, which results in lower amounts of deposited coke.

EXACTUS® equipment is suited as a sensor to measure tube metal temperature of a steam cracking reactor coil, either inside or outside of the furnace. It outperforms a weld-on thermocouple in providing a process value to the controller and hence offers an advantage over the present state of the art. The main advantage of EXACTUS® over thermocouples is when the temperature measurement is used to prevent overshoots of the tube metal temperature which have an adverse effect on the tube longevity and the coke formation.
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References