

Verifying optical simulations for infrared curing of powder coatings

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Abstract In line with the energy transition, it is desirable to replace fossil fuels in the curing process of industrial powder coatings. Infrared heating is the considered method here. NIR-emitter arrangement in the reflective heating chamber, their geometry and the dwell time of the components are crucial for a successful and efficient process. Process optimization has to consider the optical parameter variation of the powder coating during the procedure. Measurements in the NAPUBEST („Nachhaltige Pulverbeschichtungs-Technologie“: sustainable powder coating technology) prototype are compared with optical simulations of the setup to get the simulation parameters in agreement with reality and to provide a foundation for the layout of industrial processes.

Keywords: IR-curing, optical simulation, powder coating, sustainable energy transition, infrared heating

1. Introduction

The recent energy crisis revealed the dependence of many manufacturing companies on fossil fuels. Industrial processes need to be transformed into sustainable alternatives. For powder coatings, which traditionally rely on gas or oil heating systems, short wave infrared radiation e.g. from infrared heating emitters can deliver the required process heat. It is an approved method for flat steel strip surfaces in the steel industry [1]. The strong dependence of the IR absorption on the geometry of the irradiated parts as well as on the colour and sort of the coating powder [2][3] has to be considered before the deployment of this innovative heating. The aim of the NAPUBEST project (German abbreviation for “Nachhaltige Pulverbeschichtungs-Technologie” which means “Sustainable Powder Coating Technology”) is to get a better understanding of these correlations. In our laboratory, we created a prototype of an octagonal IR oven for test measurements. The high reflectivity of silver-coated reflector sheets facilitates the concentration of infrared radiation inside the oven. On the other hand, the absorption of powder-coated samples in different paint colours has an impact on the heating efficiency. The arrangement of the NIR-emitters in the reflective heating chamber, the geometry and the dwell time of the components are therefore crucial for a successful and efficient process. Process optimisation has to consider various optical and mechanical parameters for different coatings and components. Some of the parameters are also subject to change during the curing procedure.

The objective of this investigation is the verification of a simple simulation model with simplified optical parameters that can be easily adapted and used during production.

2. Simulation model and heating tests

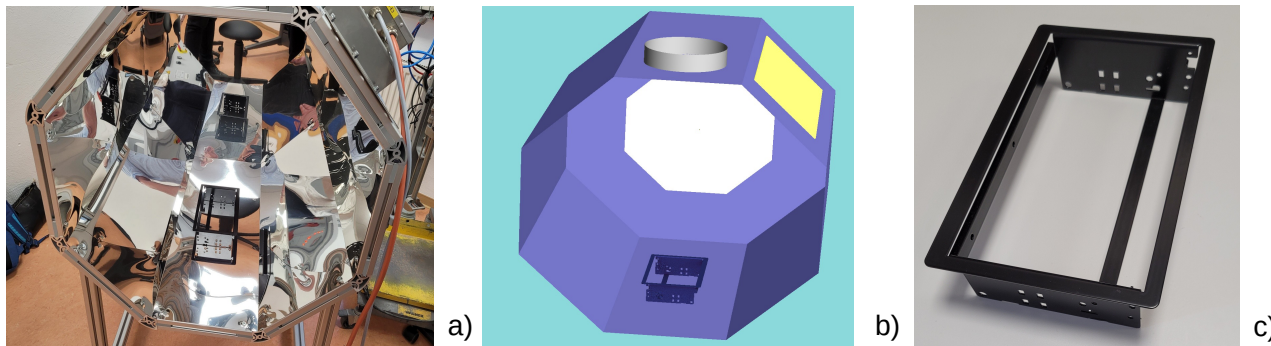
The NAPUBEST heating chamber is made of Alanod Miro Silver sidewalls and a Heraeus Noblelight M220x511 NIR/SWIR heating module with 4 fast short wave emitters (1.5 kW, 1.4 μm peak wavelength each) [4]. The high reflectivity of the Alanod sheets guarantees a homogeneous radiance inside the chamber (except in front of the infrared emitters). For the optical simulations, the program FRED from Photon Engineering was used. The geometry of the heating chamber was exactly reproduced in the simulation model. The heating module was represented by the aluminum backside of the emitter-mount, the fused silica glass cover and the 4 emitter tubes. The filaments of the emitters were simulated as an emitting tube.

Since the heating chamber has no facility (yet) to hang the samples into the middle of the chamber they were placed onto the bottom sheet. The same position was used in the simulation (see Fig1). Free hanging as in conventional gas ovens will be beneficial since the light will reach all sides of the sample and is planned to be implemented as a next step.

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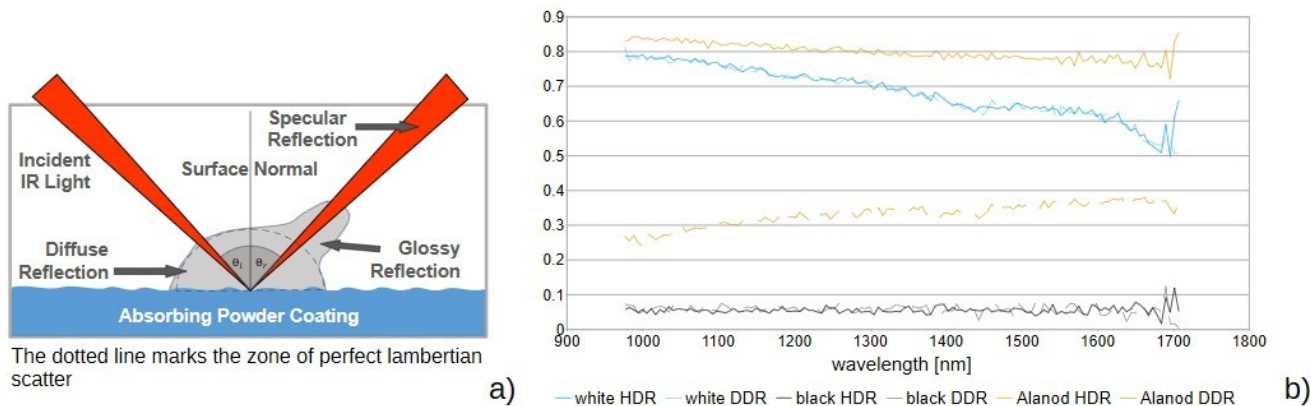
** These authors contributed equally to this work

44 For the verification, the CAD model of the specimen used in industrial fabrication and in the NAPUBEST oven was
 45 imported into FRED. The full surface of the specimen was used as the detector surface. The absorbed irradiance at the surface
 46 was simulated and the resulting irradiance map was exported as a CSV-file for post processing.



47 **Fig1.** a) NAPUBEST IR-oven with sample placed at the bottom of the chamber, b) same arrangement in the simulation model of
 48 NAPUBEST IR-oven including the sample placed at the bottom of the chamber c) black coated sample

49 The optical properties of all materials in the heating chamber were either taken from vendor data (fused silica transmittance
 50 and refractive index, reflectivity of emitter mount and gold coating of emitter backside) or measured using an Ulbricht Sphere
 51 for all other materials (see Fig2). The black and white coating were found to be perfectly lambertian: the HDR and DDR
 52 measurements had the same result, thus there is no specular fraction. For Alanod the two quantities have quite different values,
 53 resulting in a high specular fraction of the reflectivity, which is expected.



54 **Fig2.** a) description of different parts of reflection on a surface, b) Comparison of HDR (Hemispherical Directional Reflectivity) and
 55 DDR (Diffuse Hemispherical Directional Reflectivity) measurement in an Ulbricht Sphere of cured white and black powder
 56 coating and Alanod sheet. HDR and DDR are identical for the two coatings indicating a lambertian scatter whereas the two are
 57 quite different for the high specular Alanod.

58 Measurements and vendor data were used to create material, coating and scatter data [5] in FRED for the peak wavelength
 59 of the emitters only. This simplification largely reduced the simulation time.

60 As a first test of the equipment and the correspondence between experiment and simulation, a black and a white coated
 61 sample were heated for two minutes each in the NAPUBEST heating chamber. The sample was placed into the oven chamber
 62 as shown in Fig1 and the chamber was closed by the Alanod-covered front lid. All four emitters were running with full power
 63 for two minutes before the lid was re-opened and the temperature distribution was captured by an infrared camera 0, 1 and 2
 64 min later (Testo 883, 640x480 pixel). The corresponding simulation takes into account four emitters at full power and the
 65 respective BSDF of the coatings.

66 **3. Results**

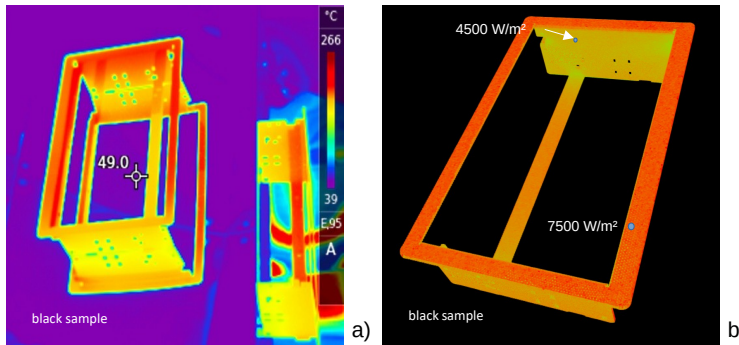
67 The temperatures of the specimen after two minutes of infrared irradiation were measured with the Testo infrared camera.
 68 Especial care had to be taken to not measure heat reflections of the lamps or of hot spots which get reflected on colder parts of

69 the sample. The reflecting sheets of the heating chamber create a mirror image of the sample with the advantage of making the
70 down facing surfaces of the sample visible.

71 The simulation results were displayed in an in-house developed software allowing the readout of surface irradiance point or
72 linewise. The results for maximum and minimum temperature as well as the corresponding irradiance are shown in Table1.
73 Regarding ratio and over all distribution, the measurement and simulation are in good accordance (see Fig3). As expected, the
74 temperature of the black sample was much higher than that of the white sample after the same dwell time in the oven due to the
75 higher infrared absorption.

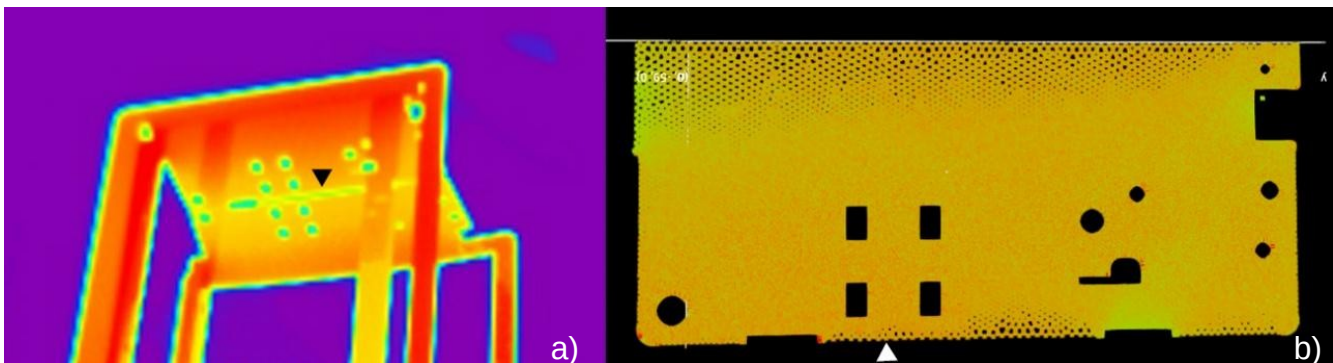
76 **Table1.** Results for maximum/minimum values of simulated irradiance and measured temperature of the white and black
77 sample (Values in the holes are excluded)

| | Max Irradiance | Min Irradiance | Ratio max/min | Max Temperature | Min Temperature | Ratio max/min |
|---------------------|-----------------------|-----------------------|---------------|-----------------|-----------------|---------------|
| | Simulated values | | | Measured values | | |
| White sample | 3200 W/m ² | 2300 W/m ² | 1.39 | 152 °C | 115 °C | 1.32 |
| Black sample | 7500 W/m ² | 4500 W/m ² | 1.67 | 266 °C | 190 °C | 1.40 |



78 **Fig3.** Simulation b) and heating results a) for the black sample. The ratio of temperatures matches the ratio of irradiances at the
79 main surfaces of the sample. The red color corresponds here to higher temperatures while yellow/green resembles lower
80 temperatures.

81 The temperature distribution though showed differences compared to the irradiance distribution (see Fig4) that we attribute
82 to heat flow and heat transfer in the system, e.g. at the point of support, the temperature is lower than the mean surface
83 temperature while the irradiance is more or less homogenously distributed over the side surface of the sample.



84 **Fig4.** Detailed results of simulation and infrared camera show differences due to heat flow inside the sample. The side wall in the IR-
85 picture a) shows a heat sink at the bottom: heat flow to Alanod sheets. The pure ray trace simulation b) doesn't show a lower
86 irradiance at the bottom of the side surface.

87 **4. Discussion**

88 Earlier simulations with a simple T-shaped sample [6] showed that inhomogeneities in irradiance at the sample surface can
89 be prevented by illuminating the sample from different positions. It allowed to reduce the max/min ratio of the irradiance from
90 4.2 to 1.9 for the T-shaped sample. In the real world this means to turn the sample in the oven and/or install multiple heating
91 modules in the oven.

92 The optical parameters of cured powder coating can be measured easily with an Ulbricht sphere and converted into
93 simplified scatter models. The results of this investigation show that this is sufficient to map the simulations to the
94 measurements. Heating results strongly depend on the coating colour and sample geometry as expected. The thermal effects
95 like thermal conduction exceed the expected magnitude and need to be taken into account.

96 **5. Conclusion**

97 These first results show that it is possible to predict the heating of complicated geometries by IR irradiation with sufficient
98 precision. The simulation model with simplified scatter models for the powder coating delivers accurate results to predict the
99 required heating power. Differences between the temperature distribution in the thermal images and the irradiance distributions
100 are evidence for the need to include thermal effects into the model for more accurate predictions.

101 The next challenge will be to create a process and as a long term objective a tool which helps to define irradiation power
102 sequences that lead to a more homogenous temperature distribution for easy and fast use at the production line.

103 **6. Outlook**

104 Next steps will be the investigation of different heating profiles with periods of reduced power to keep the temperature
105 level after initial heating and to verify sufficient temperature homogeneity at the sample surface. This is vital for the
106 application in powder coating with respect to the narrow curing process window of industrial powders. An additional thermal
107 simulation using the results of the optical simulation as input will be carried out to include heat flow inside the sample and
108 convection. When feasibility of the process in principle has proven, a larger research project will be initialised to investigate
109 processes during the curing of the powder and possible impacts of the coating colour on the process.

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115 **Conflicts of interest**

116 The authors have nothing to disclose.

117 **Author contribution statement**

118 Conceptualization, T.D., E.S. and M.K.; Methodology, T.D., E.S. and M.K.; Validation, T.D., E.S. and M.K.; Formal
119 Analysis, M.K.; Writing – Original Draft Preparation, M.K.; Writing – Review & Editing, T.D., E.S.; Visualization, M.K.;
120 Project Administration, M.K.; T.D.; Funding Acquisition, T.D.

121 **Glossary**

| | | |
|-----|----------|--|
| 122 | NIR | Near Infra Red |
| 123 | SWIR | Short Wave Infra Red |
| 124 | NAPUBEST | Nachhaltige Pulverbeschichtungs-Technologie: sustainable powder coating technology |

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125 NETZ Technology Transfer Center for Sustainable Energies
126 BSDF Bidirectional Scatter Distribution Function
127 FRED optical simulation software for non sequential ray tracing by Photon Engineering
128 HDR/THR Hemispherical Directional Reflectivity (includes specular reflection) / Total Hemispherical Reflection
129 DDR/DHR Diffuse Hemispherical Directional Reflectivity (excludes specular reflection) / Diffuse Hemispherical
130 Reflection)

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