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# EDDY – Enhanced Drying

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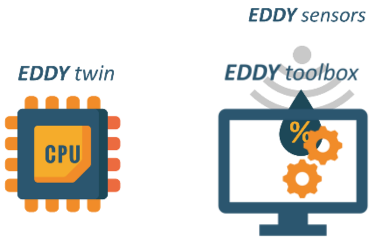
# 2 Introduction

A share of 12-25 % of the national industrial energy consumption is attributable to industrial drying in developed countries. Drying and dehydration are among the most energy intensive and wide-spread processes in the industry and are currently predominantly based on fossil fuels. ***EDDY*** focuses on the optimization of industrial drying in agricultural raw material industry and food industry.

The centerpiece of ***EDDY*** is an innovative compact and cost-effective optical infrared sensor (IR). Conventional humidity sensors (e.g. hygrometer, psychrometer) can only measure air humidity and not the product to be dried. Thus, a new sensor based on IR spectroscopy is developed to detect the moisture of the product itself. Even though IR spectroscopy is already well established in process analytics, IR spectrometers are currently too expensive and not sufficiently robust for drying processes. Within ***EDDY***, a low-cost IR moisture sensor is developed that is robust, reliable and long-term stable. It is implemented in drying processes at AGRANA Stärke GmbH and Fischer Brot GmbH to achieve the following goals:

- **Inline-monitoring** of product moisture in drying processes using novel **compact and cost-effective optical IR sensor technology** enabling real-time control
- **Optimized operating strategies** based on numerical models and monitoring data (increasing productivity, reducing $CO_2$ emissions and operating costs, ensuring high product quality independent from external influences), design of measures to further increase energy efficiency and use of renewable energy sources (e.g. heat pumps)




***EDDY*** paves the way to **substantially reduce fossil carbon emissions** in drying processes by **approximately 50 %.** The ***EDDY*** concept combines newly developed cost-effective sensors for online process analysis with advanced numerical models to enable energy efficient drying processes. The energy demand for drying and dehydration will thereby be **reduced by approx. 60 %** ending up in a **reduction of energy costs by 40 %**. Moreover, this innovation is **easily** transferable to other industrial drying processes and sectors.

# 3 Content presentation

## 3.1 State of the art in industrial moisture measurement

Knowledge about the exact moisture content of materials is of great importance in numerous industrial branches including wood, paper, construction, raw materials, chemical, pharmaceutical and food industry. Basically, any industry buying or selling raw materials and/or product by weight is interested in moisture measurements, since strict limits have to be adhered to when it comes to the water content for the raw material or product to be considered pure and high quality. Especially in food related industries, specific moisture levels must not be exceeded to avoid mould-induced spoilage of the product and to increase its shelf life. In order to reach the required dryness in any case, often large amounts of energy are invested in excess in drying processes, which often boils down to a huge waste of energy that could easily be avoided by accurate knowledge of moisture in the drying process.

A commonly used method to get information about material moisture in the industry is to monitor the humidity in the exhaust air of the dryer. This effectively gives a value for the drying rate of the material, however not a direct value for its moisture. Thus only rough estimations about the moisture content of the material itself are possible. Moreover, due to inhomogeneous conditions inside the dryer, measured values are usually strongly dependent on the dryer settings, as well as air humidity and temperature at the production site.

The most widely used technique to directly determine material moisture is (offline) gravimetric measurements, which rely on thermal drying of a sample and measuring the weight difference caused by water evaporation. Due to the nature of this method it cannot be used inline since the weighing has to be done on a vibration free surface to give reliable results. Further, the sample usually is destroyed during the measurement procedure. Another major downside of this approach is the long measurement time that is usually on the order of minutes. Therefore, only sporadic information about the moisture content of raw materials and/or product is available and real time monitoring or controlling of drying processes is impossible.

In order to determine moisture inline and in real time multiple different measurement techniques have already been proposed and tested. The most popular ones are dielectric, radiometric and microwave-based measurements as well as techniques utilizing near-infrared (NIR) radiation. Each of these solutions has its advantages and disadvantages when it comes to price, precision and operating distance.

Since in many applications, the moisture needs to be measured without direct contact to the material, dielectric measurements often do not qualify for the task since direct contact or at least very close proximity to the sample is necessary for precise measurements. In general, the method is very prone to electrical interferences.

Very precise moisture values can be achieved with radiometric measurements, where fast neutrons are emitted onto the sample, wherein they are slowed down by hydrogen nuclei. Subsequently the slowed-down neutrons are detected by a specific detector. Since the number of slow neutrons is directly related to the hydrogen content, this measurement gives very reliable values for the product moisture. The big downside of this technology is the high hardware price, particularly neutron source and detector and the required security precautions.

The two most applied techniques due to moderate prices and possibility for contact-less measurements are relying on the microwave and NIR part of the electromagnetic spectrum, respectively. Microwave based measurements exploit the very high dielectric constant of water compared to most other materials. This leads to a phase shift and attenuation due to energy transfer to water (as it also happens in a microwave oven). Both effects are measured and used to calculate the water content of the material of interest. The big downside of this measurement technique is that the amount of substance that is being measured must be exactly known since it directly influences attenuation and phase shift, which requires an additional, usually not straight forward, measurement[1]. Again, security measures have to be implemented due to harmful radiation.

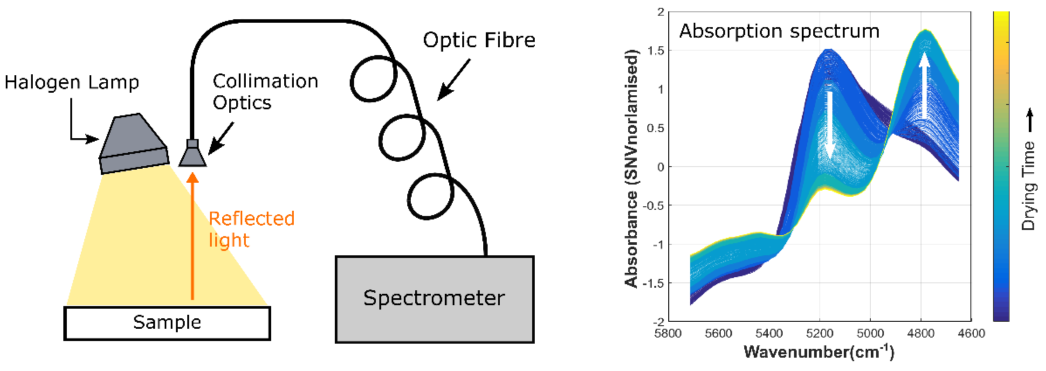



*Figure 1: Left – Schematic drawing of a NIR-based moisture measurement setup. Right – Sample spectra recorded during a drying process. Color goes from blue – high moisture to yellow – low moisture.*

The probably most easily applicable method for measuring the moisture of different materials without direct contact uses NIR light to probe the sample surface. For this purpose, a NIR light source, usually a halogen lamp, is used to illuminate the sample and the reflected NIR radiation is collected by a detector. In contrast to microwaves, NIR radiation can be manipulated using traditional and widely available optics, making it much easier to apply in different industrial settings. Moreover, NIR radiation is not harmful, thus no security precautions have to be implemented. Mostly NIR based moisture measurements rely on measuring the reflected light at two separate wavelengths by using filters[2]. One wavelength is absorbed by water and the other one is used as a reference (two-point measurement). A downside of this approach is reduced accuracy and influence of background radiation and sample composition. Alternatively, a continuous spectrum of the reflected NIR light can be collected using a spectrometer[3]. This gives higher precision and additional reliability due to the possibility of multivariate data analysis and machine learning techniques that can make use of the additional data. The reason why mostly two-point measurements are utilized is that conventional NIR spectrometers usually cost 40,000 EUR or more, an extra cost that is usually not considered reasonable. Furthermore, they are bulky and thus they cannot be used close to the measurement position making optical fibre networks and multiplexing a necessity. A schematic drawing of a spectra moisture measurement and exemplary spectra are shown in Figure 1.

## 3.2 Industrial drying

To this day drying is still one of the dominating industrial preservation processes for innumerable products. Industrialization helped to optimize drying processes, which are conducted under varying, but

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1 https://www.thermofisher.com/blog/mining/microwave-technology-can-be-used-to-measure-moisture-content-of-ores-coal-and-other-minerals/
2 https://www.processsensors.com/products/near-infrared-moisture-oil-coat-weight-sensors/on-line-fixed-sensors
3 https://www.apos.biz/products/process-application/apos-modularnir/

controlled conditions. The Handbook of Industrial Drying[4] gives at least 15 different dryer types and identifies more than 20 different industrial drying sectors, which makes it rather difficult to generalize drying technologies.

For every product a certain drying process or plant is characterized by the type of dryer, the quality of the final product, the extended product shelf-life, additionally needed processing, the ease of handling, sanitation, cost/energy effectiveness, and investment. Depending on the type of heat input, a distinction is made between convective drying by a hot gas stream, contact drying by hot surfaces and radiation drying, in which the energy is supplied by electromagnetic waves. However, the basic principle of drying is the same as it used to be thousands of years ago, and the most common dryer type is based on convective drying. Nevertheless, the developed ***EDDY*** sensor concept may be implemented independently from the type of heat input. Industrial convective drying plants are mainly operated by burning fossil energy sources and product waste. Convective drying processes are often used for continuous drying at high throughputs. An example is the spray drying of milk to dry milk powder. A comprehensive dryer comparison can be found here[5].

**Concepts for the integration of the heat pump technology**

Modern industrial drying processes are either an open loop system using heated ambient air or closed loop system with recirculation of the drying air. Heat pumps are characterized by the possibility to utilize a heat source at low temperatures (at the evaporator) and supply a heat sink at a higher temperature (condenser). For the case of closed loop drying this combined heat and cool load is used for the recovery of drying energy (basically the latent heat of water evaporation) and deliver this energy back into the drying process in the form of de-humidified and re-heated drying air (as illustrated in Figure 2).

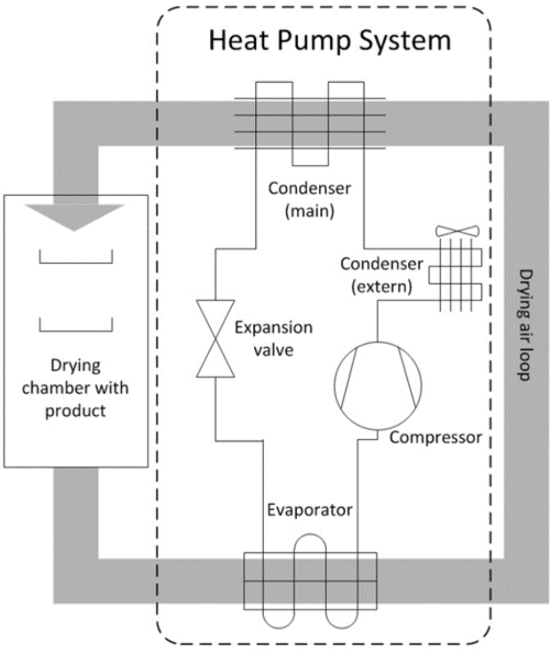



*Figure 2: Principal layout for heat pump assisted drying for convective (air) drying in closed loop.*

[4] Mujumdar, A. S. et al, Handbook of Industrial Drying, 3rd ed., Taylor & Francis, 2006
[5] [online]: Portal für industrielle Trocknungsanlagen (http://www.drying.de/)

From the literature[6], various concepts for drying with heat pumps are already known and are compared with other drying methods. The main advantages of the compression heat pump technology for drying are summarized as follows:

- **Higher efficiency**: Recovery and utilization of the energy of the water vapour by condensation, when leaving the air from the drying plant and thus increased efficiency. The resulting lower water load in the air also increases the drying rate.
- **Better controllability**: The air volume flow, temperature and moisture can be precisely controlled with compression heat pumps in drying plants.
- **Product quality**: Lower drying temperatures lead to higher product quality. In addition, the preservation of flavourings can be improved by using an inert atmosphere in recirculation mode.

Drying with heat pumps can achieve a specific electrical energy input in the range of 0.12 to 0.3 kWh/kg condensate, the exact figure depending strongly on the operating point and the inclusion of auxiliary electrical drives such as fans and circulators. In the case of convective exhaust air drying, which is now very widespread and is based on fossil fuels such as natural gas, the specific energy input is in the range of 1 to 2 kWh/kg condensate[7].

### 3.2.1.1 Technological problem

Drying processes involved in the production processes of a huge number of different industrial branches, are mostly carried out without knowledge of the moisture content of the drying material. Differences in air humidity, temperature and moisture of the raw material, caused for example by seasonal fluctuations, are not considered when it comes to the drying parameters of end or intermediate products. This usually leads to over-drying since the necessary dryness needs to be reached because no risk can be taken due to huge financial losses in case of production failure caused by excessive moisture content. For the sake of increasing efficiency and thus saving energy, a cost-effective reliable sensor solution for contactless inline measurements applicable to a wide range of different materials and industrial environments is desperately needed. Since companies struggle to bear the financial burden of the development of new sensor technology, funded research is necessary to aid the sensor development and subsequently exploit the huge savings potential associated with higher drying efficiency. The recent advent of cost-efficient miniature-spectrometer technology based on micro-

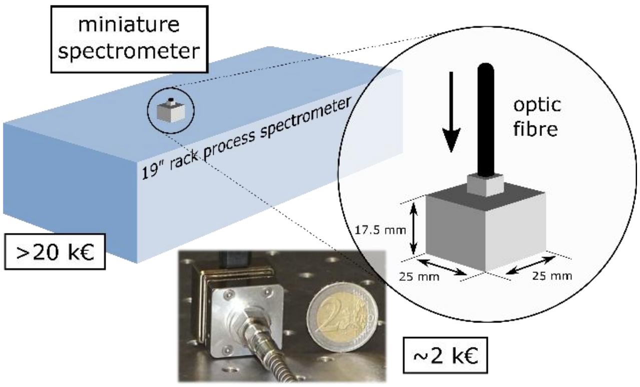



*Figure 3: Size comparison of a conventional 19" rack process spectrometer and a MEMS-based miniature spectrometer. The inset photograph shows the comparison of the miniature spectrometer to a 2€-coin.*

[6] Evangelos Tsotsas, Arun S. Mujumdar, Modern Drying Technology, Wiley-VCH Verlag GmbH & Co. KGaA, Germany, 2012
[7] Colak N. and Hepbasli, A., A review of heat pump drying: Part 1 – Systems, models and studies, Energy Conversion and Management 50, 2180-2186 (2009)

electro-mechanical systems (MEMS), significantly reduced the hardware costs for the measurement of continuous spectra in the NIR region. In addition to the strongly reduced price, these MEMS-based spectrometers obviously offer the advantage of much smaller size (Figure 3) in addition to significantly increased robustness due to the lack of moving parts. These properties allow placement of the sensors directly at the measurement position, eliminating the need for optical fibers and multiplexing. This further reduces implementation costs in an industrial process environment and increases flexibility. Despite all these advantages, this technology is not yet utilized for process monitoring and control in the industry. Compared to two point NIR moisture measurements, the collection of continuous spectra gives the opportunity to use multivariate data analysis and machine learning algorithms to more accurately extract information about material moisture from the sensor signal.

Using suitable optical components that can be combined with the spectral sensor, measurement distance and field of view can be accurately adjusted to fit the individual needs in the process environment. Additionally, by tuning the measurement parameters, an optimal balance between acquisition speed and accuracy can be found for the individual measurement conditions to get the most precise and reliable measurements possible.

#### 3.2.1.2 General situation of industrial drying

In about 85 % of all drying processes, fossil-fired, convective exhaust air dryers are used, with 99 % of these systems removing the water vapour via the exhaust air and not using it further. Studies show that drying processes in highly developed countries account for 12-25 %[8] of total industrial energy requirements worldwide. By far the most energy is used for paper drying. Other energy-intensive drying processes are found in the wood, sugar, paint, textile and brick industries.

Both industry partners in ***EDDY*** are companies in food and feed industry (NACE Code C10). The food industry is of great importance in Austria, as this sector has the highest gross value added and employs about 77,000 people[9]. Throughout Austria, more than 3,800 businesses are assigned to this sector. These holdings generate around 5.2 Billion EUR[10] annual revenue. The total energy consumption of the sector amounted to 6.6 TWh (2.1 % of total energy consumption in Austria) with an annual emission of around 0.3 Million tonnes $CO_2$ eq.[11]. There are specific processes that require high energy consumption and thus also show great savings potential. Fossil fuels are mainly used to provide process heat, for example for warm and hot water, for scalding, hygienizing and of course, drying. In Austria, about 50 % of the energy needs of the food industry are covered by

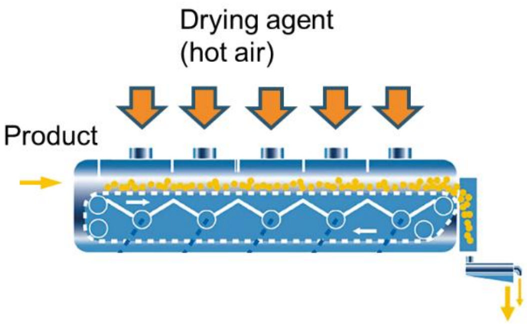



*Figure 4: Conveyor belt dryer at the selected bakery, Fischer Brot GmbH.*

[8] Mujumdar, A. (2007). "An overview of innovation in industrial drying: current status and R&D needs." Transport in porous media 66(1): 3-18.
[9] Smart Energy for Smart Industry, Final Report, 2016: AIT Austrian Institute of Technology GmbH & Institute for Energy at the JKU.
[10] The sector is called "food, beverages and tobacco" but since 2012 there has been no more tobacco processing in Austria.
[11] Verified emissions were taken from the Austrian Emissions Trading Registry (https://www.emissionshandelsregister.at/)

natural gas, the largest consumers are steam generators and gas-fired Industrial furnaces[12] which are often directly connected to the dryers.

#### 3.2.1.3 Fischer Brot GmbH

The selected plant is a site that produces around 14,000 tonnes of bakery products annually. The product range comprises more than 100 items and extends from traditional breads to special breads, pastries and household products such as dumplings and breadcrumbs. Figure 4 illustrates the dryer type used in the bakery.[13] The most important energy source is natural gas. Some furnaces are equipped with heat recovery heat exchangers. The exhaust gas from the burners is further cooled down and the heat into a heat recovery circuit that heats the dryers. The dryers are used for the production of dumpling bread and breadcrumbs. For this purpose, freshly baked breadcrumbs are dried in the dryers to a water content of 9 % and then diced.

#### 3.2.1.4 AGRANA Stärke GmbH

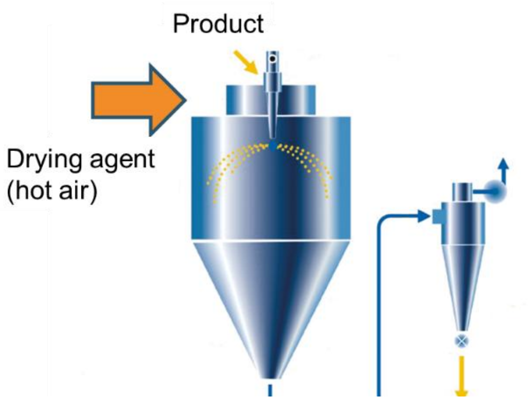


*Figure 5: Spray dryer at the selected plant, Agrana Stärke GmbH.*

AGRANA operates Austria's only potato starch factory at Gmünd (Lower Austria). Potato starch is produced in a so-called campaign from August to January and stored in silos. Potatoes are also used to produce potato flakes for the food industry and mashed potatoes for the food retail trade. In addition, starch is refined in a variety of ways at the site throughout the year. By chemical modification, starch is processed into adhesives or construction additives, for example, and so-called saccharification products (maltodextrins, glucose syrups) are produced by breaking down the starch. The spray drying plants at the Gmünd site were originally built to dry surplus milk, see Figure 5[14]. Spray drying plants are generally characterized by particularly gentle drying; worldwide, more than 25,000 such plants were already in operation in 2006.

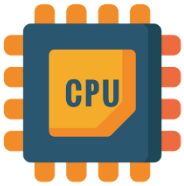
[12] Fleiter T., Schlomann B., Eichhammer W. (2013): Energy consumption and CO2 emissions of industrial process technologies - potential savings, obstacles and instruments. ISIS publication series "Innovation potentials". Fraunhofer Verlag
[13] www.gea.com.
[14] www.gea.com

### 3.2.2 Goals

In concrete terms, the ***EDDY*** project aims to achieve the following technical objectives:

1. ***EDDY sensors***:
   Development of cost-effective infrared moisture sensors for inline monitoring of selected industrial drying processes of the two end-users in the project, AGRANA (P2) and Fischer (P3)

2. ***EDDY twin:***
   a. With the ***EDDY sensors*** in place, establish a **feedback control** on the real dryers in order to account for fluctuations in product characteristics, weather conditions, etc.
   b. Development of **digital twins** of the drying processes.
   c. **Optimization** of the operating conditions of the drying processes with the integration of a compression heat pump in order to increase connections between different energy sources (gas + electricity)




3. ***EDDY toolbox***:
   Quick assessment tool for evaluation of the actual status of the drying process – mainly in the exploitation phase.

The drying processes used by AGRANA and Fischer are representative of other branches of industry, such as the particularly energy-intensive paper industry or the production of veneer panels. Thus, the results contribute significantly to offer the ***EDDY sensors***, the ***EDDY twin*** and the ***EDDY toolbox*** for a broad user group in the medium term.

In detail, the **following results** are aimed:

1. Sensor concept for contactless inline moisture monitoring ready for commercial production.
2. Validated digital twin of the drying process for the use of process optimization.
3. A comprehensive software toolbox for a quick assessment of different drying processes in terms of energy savings and productivity increase.

# 4 Results and conclusions

## 4.1 EDDY sensors

### 4.1.1 Sensor Concept AGRANA Stärke GmbH

The AGRANA Stärke GmbH is using a spray dryer, as depicted in Figure 6 on the left, to dry various starch products. The product feed is either a liquid or slurry and is dispersed using a spray nozzle which produces a spray with a controlled drop size. These drops are subsequently dried, using air as a drying medium. The dried product falls out of the dryer at the bottom where the moisture should be measured. An automated pneumatic plate sampler is used to extract a sample from the dryer. The sample is dropped into a chamber. The combination of sampler and sample chamber as installed at AGRANA

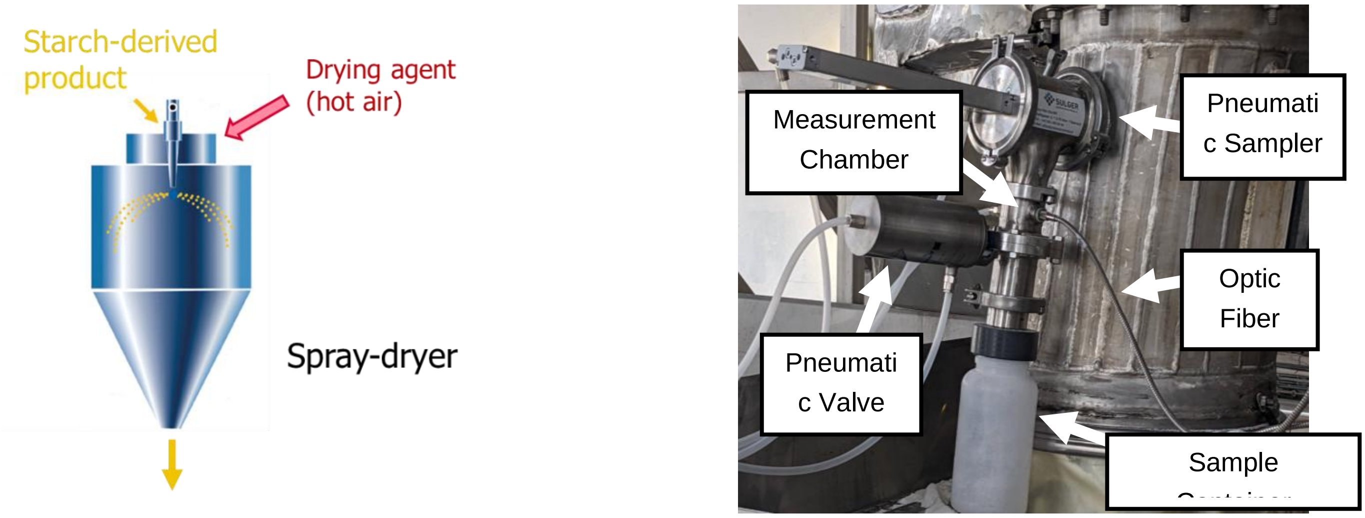



*Figure 6: Schematic drawing of a spray dryer as used at AGRANA Stärke GmbH (left). Photograph of the moisture measurement setup as installed at AGRANA Stärke GmbH with the most important parts indicated.*

Stärke GmbH is shown on the right side in Figure 6.

The measurement chamber can be closed with an automated lid and flushed with compressed air after the measurement. As sensor a Fabry-Pérot (FP) filter-based MOEMS NIR spectrometer has been selected, covering the spectral range characteristic for water absorption around 5200 $cm^{-1}$. The sampling point is in an explosion-risk area and therefore every part is pneumatically operated. Both the spectrometer and light source as well as all necessary electronics are placed in a sensor box outside of the explosion-risk area. A bifurcated optical fiber is used to illuminate the sample and collect the back-reflected light.

Example spectra gathered in the laboratory with this setup can be seen on the top in Figure 7. Therein raw spectra are shown on the top left and spectra after standard normal variate (SNV) normalization on the top right side. On the bottom, the results of a partial least squares (PLS) regression model are shown. In this Graph, the X-axis corresponds to the offline moisture values (measured gravimetrically) and the Y-axis gives the moisture values calculated from the gathered absorption spectra. Both values agree nicely with a low root mean squared error of cross validation (RMSECV) of under 0.16% moisture.

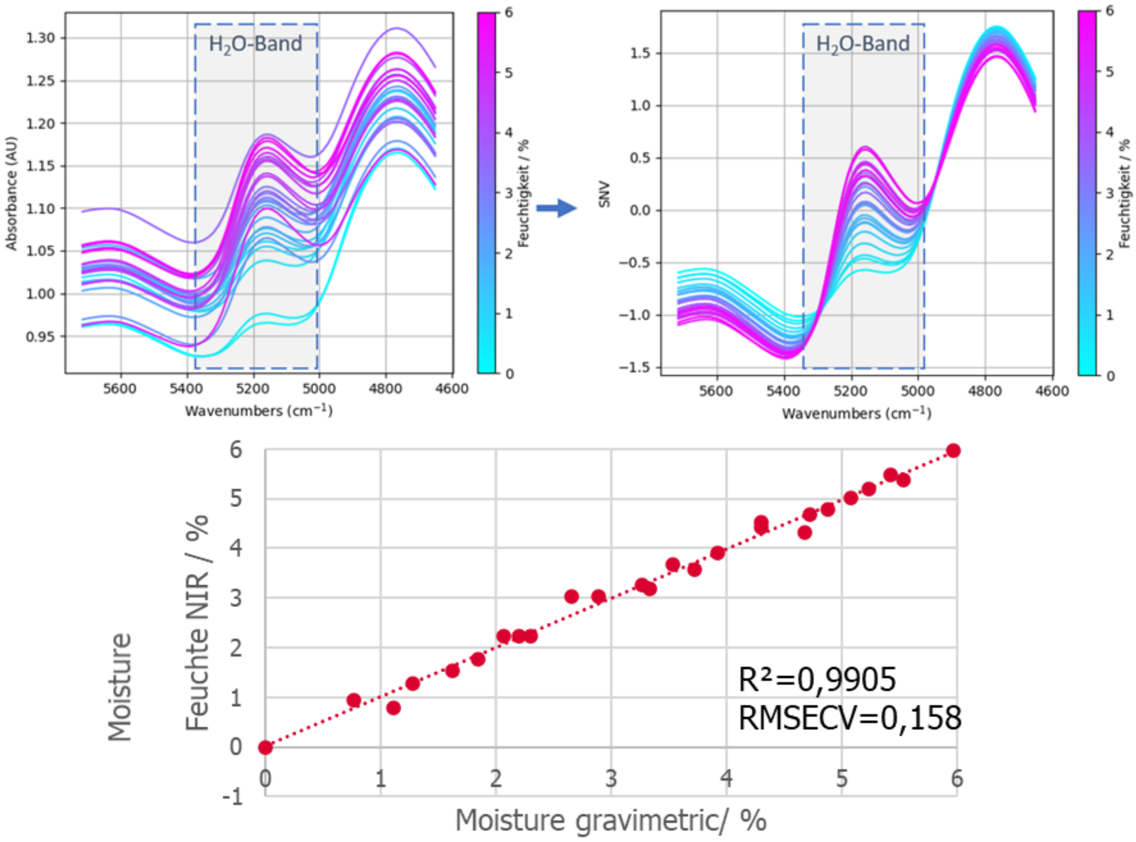



*Figure 7: Laboratory spectra collected with the setup for AGRANA Stärke GmbH (top) and data correlation with the offline reference measurement (bottom).*

### 4.1.2 Sensor Concept Fischer Brot GmbH

Fischer Brot GmbH is using a conveyor belt dryer for their product range which consists of mor than 100 different bread products. Figure 8 illustrates such a dryer. The temperatures in this dryer reach up to 90 °C and there is only about 20 cm of free space above the product. Therefore, the sensor must withstand these high temperatures and simultaneously fit within a narrow space. Furthermore, the use of glass is restricted by Fischer Brot GmbH unless it is enclosed.

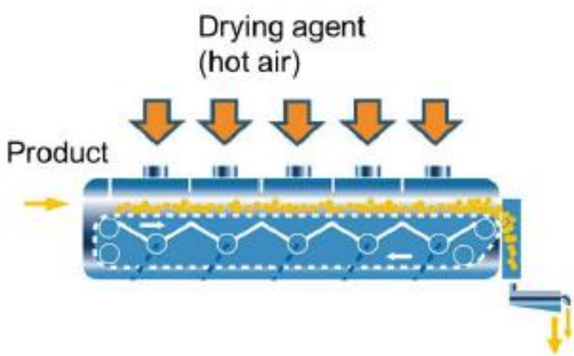



*Figure 8: Depiction of a conveyor belt dryer as used at Fischer Brot GmbH.*

Figure 9 shows the developed sensor concept. The sensor consists of two 50 W halogen light sources which are each pointed at an off-axis parabolic mirror as shown for one of the lamps in the schematic in Figure 9 on the left. The other lamp and mirror setup are arranged analogously, but tilted 90°, as can be seen in the photograph in Figure 9 on the right side. The parabolic mirror focuses the light onto the sample plane below the sensor. A plano-convex lens is used to focus the light from the sample into a SMA fiber which is coupled to a fully integrated FP-filter based MOEMS NIR spectrometer. This way the spectrometer can be placed outside of the dryer to avoid overheating.

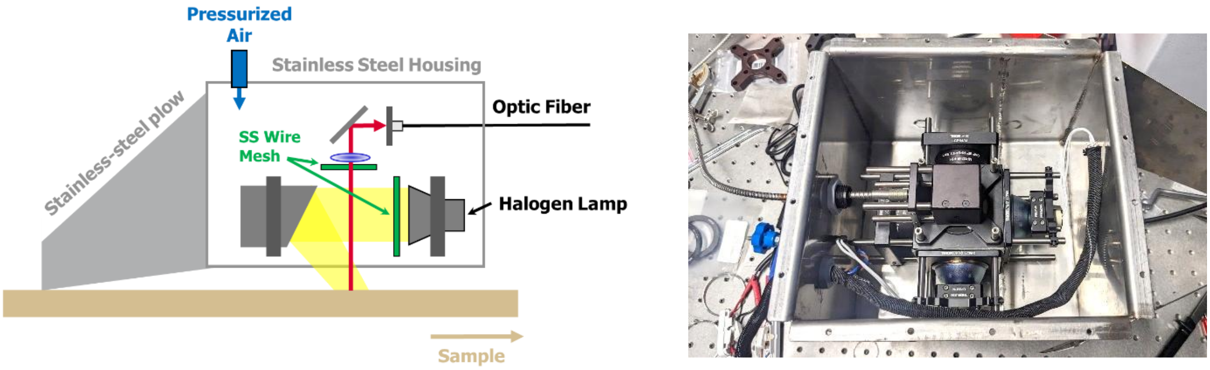



*Figure 9: Schematic drawing of the side-view sensor concept for Fischer Brot GmbH (left) and photograph of the sensor in the laboratory with its lid removed (right).*

All optical parts of the measurement head described above are enclosed inside stainless steel housing to comply with the food safety regulations at Fischer Brot GmbH. Additionally, stainless steel wire meshes are placed in front of the halogen lights as well as the plano-convex lens in front of the optic fiber, to make contamination of the sample with broken glass impossible, even in case of breakage inside the measurement head. The measurement distance is being kept as constant as possible via a stainless-steel plow at the front of the sensor, to maintain a constant sensor signal, even with varying amounts of breadcrumbs on the conveyor belt.

Figure 10 shows the absorption spectra of breadcrumbs on the left which were recorded with this sensor. SNV normalization was performed to improve the obtained data and show the regions with the most change. On the right side in Figure 10, the correlation of the moisture calculated from the measured NIR-spectra with the offline reference is shown, revealing an excellent root mean squared error (RMSE) of 0.78%.

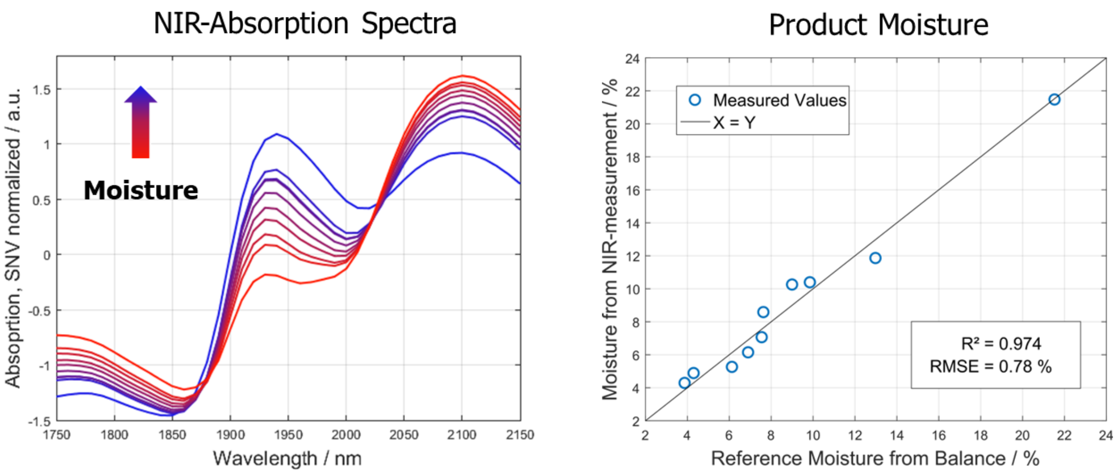



*Figure 10: Absorption spectra of breadcrumbs recorded in the laboratory with the developed sensor (left) and correlation with the offline reference measurement (right).*

Two sensor concepts to measure the moisture of various starch derived products at AGRANA Stärke GmbH and dumpling bread at Fischer Brot GmbH were developed. Both sensors use an FP-filter based MOEMS NIR spectrometer, which showed very good results during laboratory measurements.
At AGRANA Stärke GmbH a plate sampler extracts a sample from the spray dryer and subsequently drop it into a measurement chamber in which an optical fiber is incorporated. This fiber is connected to the NIR spectrometer. The chamber is closed with an automated lid and can be flushed with compressed air after the measurement to avoid contamination build-up. After the measurement, the sample is dumped into a sample container, from which the sample can either be taken for reference measurements or be disposed of, ensuring that no contamination can be introduced into the spray dryer. Due to the safety requirements at AGRANA Stärke GmbH, every motion is controlled pneumatically and the spectrometer and illumination source along with all electronic components can be placed in a safe distance.
The sensor concept at Fischer Brot GmbH is built as a cage system. Two 50 W halogen lamps in combination with parabolic mirrors are used to illuminate the sample. A plano-convex lens is used to collect the back-reflected light into an optic fiber, which is used to transport the signal to the spectrometer placed outside of the dryer to avoid overheating. To comply with company requirements, all the necessary optics as well as the halogen lamps are enclosed inside a stainless-steel housing that also provides a plow to keep the measurement distance as constant as possible. Additionally, all the parts made from glass (lens, halogen lamps) are shielded off by stainless steel meshes, to make contamination of the sample by broken glass impossible.
Both sensor concepts showed excellent measurement accuracy during laboratory measurements and are ready to be used for inline measurements at the respective industrial dryers.

## 4.2 EDDY Twin

Modeling and simulation are vital tools for the optimization of energy systems, including industrial drying processes. Through simulations, it becomes possible to analyze and understand complex heat and mass transfer phenomena involved in drying operations. This understanding enables the identification of energy-saving opportunities, energy-efficiency potential, optimization of drying parameters and the evaluation of alternative drying concepts. By simulating different scenarios, the most energy-efficient and environmentally friendly solutions can be identified and implemented.
In this regard, Modelica emerges as a critical programming language for the development of multi-domain physical models. Its importance stems from several factors. First, Modelica is an object-oriented modeling language that allows for the modular representation of various components and systems. This modularity facilitates the development of reusable and customizable models, enabling flexibility in modeling different drying processes and systems. Second, it provides a powerful and expressive framework for describing physical phenomena, making it well-suited for capturing the intricate HT and MT mechanisms involved in the investigated application (i.e. industrial drying). The language supports the formulation of differential and algebraic equations, enabling the representation of dynamic behavior and steady-state conditions within the models.

Furthermore, Modelica's compatibility with simulation environments like Dymola enhances the usability and integration of any simulation library. Dymola provides a user-friendly interface for model simulation, parameter estimation, and optimization, making it easier for users to develop a simulation library to their specific drying process simulations.

This deliverable provides insights into the development process of the simulation library, referred to as TheSpLib (Thermal Separation Library). It aims to offer a comprehensive understanding of the library's structure, as well as the underlying principles and fundamentals applied throughout its development. By delving into the details, this report explains the key steps undertaken to design and implement TheSpLib, ensuring a solid foundation for its practical utilization in the field of industrial drying simulations.

### 4.2.1 Fundamentals and principles of drying process

In order to comprehend the development of the simulation library for industrial drying, it is essential to establish a clear understanding of the fundamental principles governing the drying process. This section addresses key questions pertaining to the fundamentals and principles of drying.

### 4.2.2 Role of heat transfer in drying

Heat transfer plays a crucial role in the drying process. Heat is supplied to the wet material, leading to the evaporation of moisture. This heat transfer can occur through various mechanisms, such as conduction, convection, and radiation. Conduction involves the transfer of heat through direct contact between the heated medium and the material. Convection refers to the transfer of heat through the movement of fluid, either by natural convection or forced convection. Radiation involves the transfer of heat through electromagnetic waves emitted by a heat source.

In line with the objective of EDDY on optimizing industrial dryers within the facilities of industrial partners, *Fischer Brot GmbH* and *AGRANA Stärke GmbH*, the simulation library has a specific focus on convective drying.

Convective drying involves the use of hot air or gases to transfer heat to the material and facilitate the evaporation of moisture. This method is commonly employed in industrial drying processes due to its efficiency and versatility. Accordingly:

$$\dot{Q}_{\text{drying}} = \alpha \cdot A_{\text{p}} \cdot (T_{\text{gas}} - T_{\text{moist product}})_{\text{avg}} \tag{1}$$

Where $\dot{Q}_{\text{drying}}$ represents the heat rate supplied to the drying chamber via hot dry air during the drying process, $\alpha$ denotes the convective HT coefficient of the drying medium (i.e., air) and $A_{\text{p}}$ refers to the HT area, which can be considered as the contact area between the moist product and the hot air. The average temperature difference $(T_{\text{gas}} - T_{\text{moist product}})_{\text{avg}}$ can be calculated as follows [1]:

$$(T_{\text{gas}} - T_{\text{moist product}})_{\text{avg}} = \frac{T_{\text{gas,in}} - T_{\text{gas,out}}}{\ln\left(\frac{T_{\text{gas,in}} - T_{\text{moist product}}}{T_{\text{gas,out}} - T_{\text{moist product}}}\right)} \tag{2}$$

$$(T_{\text{gas}} - T_{\text{moist product}})_{\text{avg}} = T_{\text{gas,out}} - T_{\text{moist product}} \quad (3)$$

Here, $T_{\text{gas,in}}$ and $T_{\text{gas,out}}$ represent the temperatures of the hot air entering and leaving the drying chamber, respectively. $T_{\text{moist product}}$ corresponds to the temperature of the moist product being dried. It is noteworthy to consider the flow characteristics within the drying chamber when applying the appropriate equation for the calculation of the average temperature difference. Equation (2) is applicable when the assumption of plug flow holds valid. Plug flow implies that the drying medium (air) and the moist product move through the drying chamber without significant mixing or deviation from their respective flow paths. On the other hand, if ideal mixing is present within the drying chamber, where the drying medium and the moist product are thoroughly mixed, equation (3) can be utilized instead [1].

#### 4.2.3 Connection between mass transfer and heat transfer in a drying process

Mass transfer is intimately associated with HT in a drying process. As heat ($\dot{Q}_{\text{drying}}$) is transferred to the wet material, it causes the moisture within the material to undergo phase change from liquid to vapor. This transformation requires the transfer of mass (moisture) from the material to the surrounding drying air. The driving force for mass transfer is the difference in moisture concentration between the material and the air. As moisture evaporates from the material, it carries away latent heat, further influencing the HT process. Thus:

$$\dot{m}_{\text{drying}} = \frac{M_{\text{dry product}}}{A_{\text{p}}} \cdot \frac{dX}{dt} \quad (4)$$

Where $\dot{m}_{\text{drying}}$ represents the drying rate, $M_{\text{dry product}}$ is the mass of the dry product and $A_{\text{p}}$ refers to the contact area. ${}^{\text{d}X}/_{\text{d}t}$ denotes the change of moisture content with time. The drying rate ($\dot{m}_{\text{drying}}$) depends on the conditions of drying and on the moisture content ($X$). The drying conditions are specified by factors such as the air pressure, temperature, and humidity for convective dryers. The relationship of the drying rate m˙ and the moisture content ($X$) under constant drying conditions – this is $\dot{m}_{\text{drying}}(X)$ is called the *drying rate curve*.

Indeed, the drying rate ($\dot{m}_{\text{drying}}$) is influenced by the drying conditions and the moisture content ($X$) of the material being dried. The specific drying conditions are determined by factors such as air pressure, temperature, and humidity in the case of convective dryers. The relationship between the drying rate ($\dot{m}_{\text{drying}}$) and the moisture content ($X$) under constant drying conditions is commonly represented by the so-called *drying rate curve*.

#### 4.2.4 Drying rate curve

The drying rate curve depicts how the drying rate changes as the moisture content of the material decreases during the drying process. It illustrates the rate at which moisture is being removed from the material per unit time. The drying rate curve is determined experimentally or derived from empirical models, and it is specific to the drying conditions and the particular material being dried. Figure 11 illustrates a typical drying rate curve for paper stock drying with drying properties parameters of 40°C and 1 m/s as temperature and velocity of the drying air.

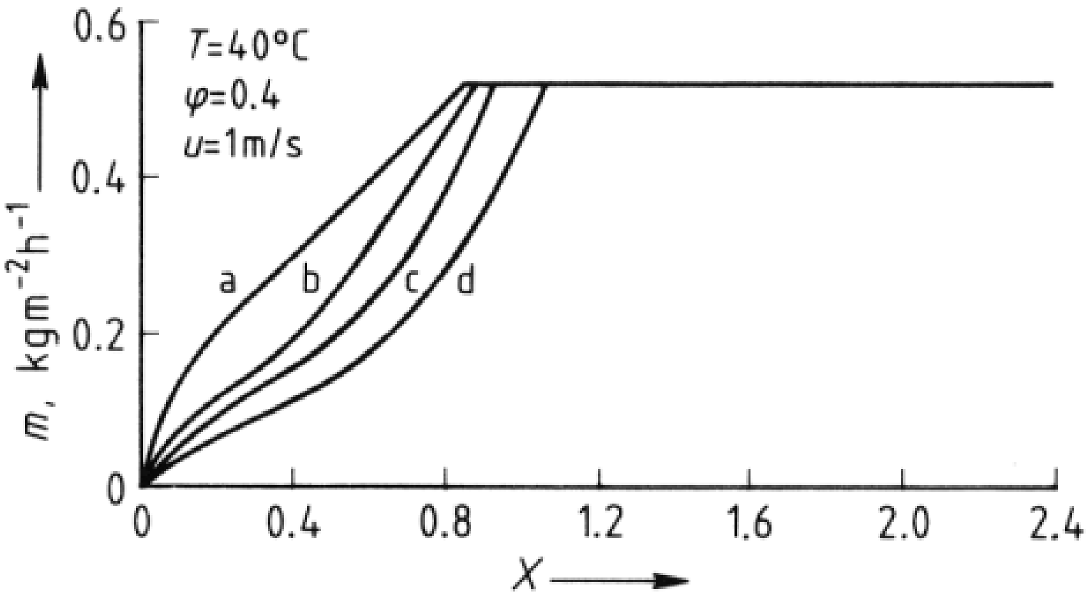



*Figure 11: Drying rate curves for paper stock of various thicknesses. Sample thickness s in mm a) 10; b) 15; c) 20; d) 30.*

The shape of the drying rate curve can vary depending on the characteristics of the material and the drying conditions. Typically, the drying rate is high at the beginning of the drying process when the moisture content is relatively high. As the moisture content decreases, the drying rate gradually decreases, often following a decreasing rate pattern. Eventually, the drying rate reaches a constant value when the material approaches the desired moisture content or equilibrium moisture content.
By incorporating the drying rate curve into the simulation library, it becomes possible to simulate the drying process more accurately. The drying rate curve allows for the determination of the drying rate at different moisture content levels, enabling a more realistic representation of the drying behavior and facilitating the optimization of drying conditions and parameters within the simulation framework.

### 4.2.5 Phases of the drying process

The drying process can be divided into several distinct phases. These phases are often referred to as the "*preheating phase*," "*constant drying rate phase*," and "*falling drying rate phase*." During the preheating phase, the material is initially heated to the desired temperature, preparing it for the subsequent drying process. In the constant drying rate phase, the moisture evaporates rapidly, and the rate of moisture removal remains relatively constant. Finally, in the falling drying rate phase, the moisture content decreases, and the drying rate gradually reduces due to limitations such as internal resistance and diffusion processes within the material. In this regard, Figure 12 shows a typical drying rate curve with the three different phases. Clearly, the moisture content decreases with increasing temperature in the preheating phase. Next, the drying rate is flat while the moisture content of the solid product decreases over time until it reaches the critical moisture content ($X_{crit}$). Beyond this, the drying rate begins to decline highlighting the falling rate phase. In this phase, the moisture content of the product proceeds to decrease until it gets in equilibrium with the moisture content of the drying medium (i.e. air). Thus, the drying process herein stops.

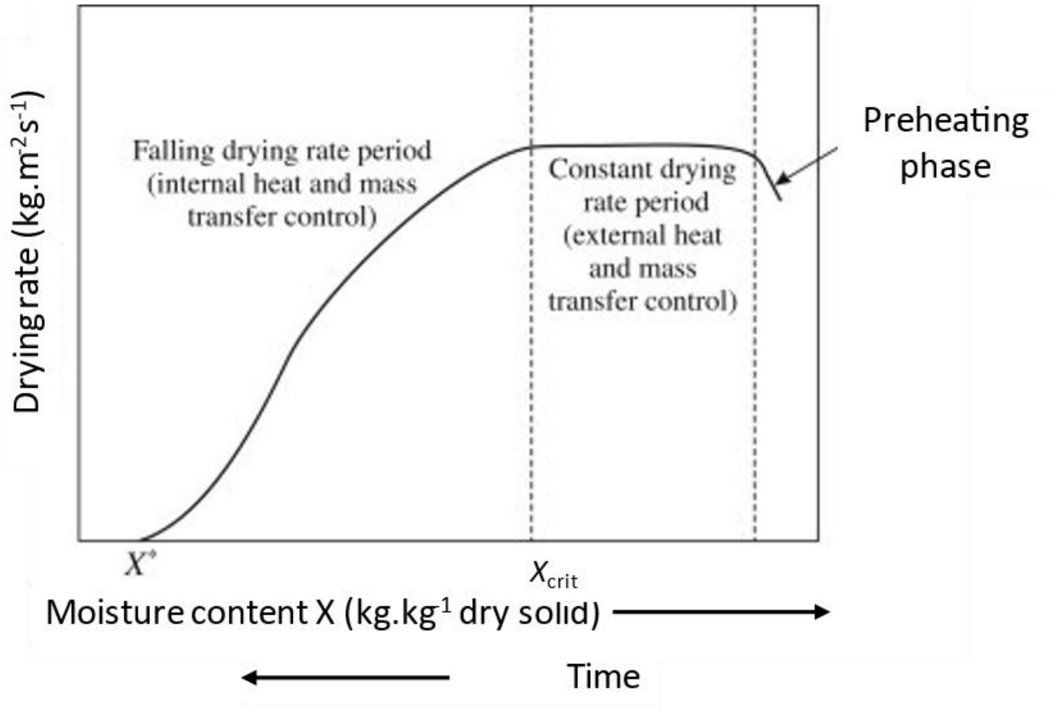



*Figure 12: A typical drying rate curve under constant drying conditions with three different phases of drying process.*

### 4.2.6 Numbers used in drying process

Various numbers are employed in the context of drying to characterize and analyze the process following the HT and MT fundamentals. These numbers include the Nusselt number, Prandtl number and Reynolds number for the HT. The Nusselt number relates the convective heat transfer to the conductive HT at the material's surface as expressed below:

$$\mathbf{Nu} = \frac{\boldsymbol{\alpha}_{\mathbf{g-p}} \cdot \boldsymbol{d}_{\mathbf{p}}}{\boldsymbol{\lambda}_{\mathbf{g}}} \quad (5)$$

$$\mathrm{Pr} = \frac{\mu_g \cdot c_{p,g}}{\lambda_g} \quad (6)$$

$$\mathrm{Re}_0 = \frac{u_0 \cdot d_0 \cdot \rho_g}{\eta_g} \quad (7)$$

Where $\lambda_g$, $\eta_g$, $c_{p,g}$ and $\rho_g$ represent the thermal conductivity, dynamic viscosity, specific heat capacity, and density of the drying medium, respectively. $\alpha_{g-p}$ denotes the convective HT coefficient between the drying medium and the product. The variable ($d_p$) refers to the average diameter of the product. It is important to highlight that the Nusselt number is a function of the gas-product properties, while the

Prandtl number is significantly influenced by the thermo-physical properties of the drying medium. Furthermore, it is noteworthy to mention that equation (7) represents the Reynolds number for an empty tube. Thus, the Nusselt number can be rearranged and expressed as following:

$$\mathbf{Nu} = \boldsymbol{C} \cdot \mathbf{Re^m} \cdot \mathbf{Pr^n} \qquad (8)$$

In the mass transfer part, the Sherwood number together with Schmidt number arise as crucial numbers. The Sherwood number quantifies the mass transfer rate at the surface of the material, whereas the Schmidt number considers the transport of moisture or volatile components in the drying medium. Thus:

$$\mathbf{Sh} = \frac{\boldsymbol{\beta} \cdot \boldsymbol{d}_\mathbf{p}}{\mathbf{D_{w-g}}} \qquad (9)$$

$$\mathrm{Sc} = \frac{\nu_\mathrm{g}}{\mathrm{D_{w-g}}} \qquad (10)$$

Where $\beta$ is the mass transfer coefficient, $\mathrm{D_{w-g}}$ is the diffusion coefficient of water vapor into gas (i.e. drying medium) and $\nu_\mathrm{g}$ is the kinematic viscosity of the drying medium. Following a similar approach of HT, the Sherwood number for mass transfer can be expressed as below:

$$\mathbf{Sh} = \boldsymbol{C} \cdot \mathbf{Re^m} \cdot \mathbf{Sc^n} \qquad (11)$$

The preceding arrangements highlight the analogy between HT and MT. Such an analogy can be captured by the Lewis number, which characterizes the relative importance of thermal diffusion and mass diffusion in a fluid. It signifies how HT and MT occur in a similar or different manner within the fluid. Accordingly:

$$\mathbf{Le} = \frac{\boldsymbol{\alpha}_\mathbf{g-p}}{\mathbf{D_{w-g}}} \qquad (12)$$

When the Lewis number is close to unity (Le ≈ 1), it indicates that HT and MT occur at similar rates, implying a balanced relationship between thermal and mass diffusion. In such cases, the temperature distribution and concentration distribution in the fluid tend to have similar profiles. For the water-air binary mixture, the assumption of (Le ≈ 1) holds valid and this is applicable for drying process.

#### 4.2.7 Library development

The development of the library is still an ongoing activity. The library is being developed with the aid of the commercial library "TIL 3.14.0" by TLK Thermo GmbH, which includes the "TILMedia" library for emulating thermophysical properties of working media such as refrigerants, water, and steam. This will facilitate the simulation of the entire energy system (gas burners, heat pumps, heat exchangers, etc.).

#### 4.2.8 Role of zone structure

The zone structure plays a crucial role in the development of the simulation library for industrial drying. A well-defined and structured zoning approach allows for the efficient representation and modeling of the drying process, enabling accurate simulations and optimization of drying systems. This section discusses the significance of the zone structure in the development of the library. Besides, this section will provide some insights into the difference between component models (detailed models based on heat and mass transfer computation with aid of computation fluid dynamics) and process models.

#### 4.2.9 Distinction between drying component models and drying process models

In the context of drying, there are two key models that are commonly used: the component model and the process model. These models serve different purposes and provide insights into different aspects of the drying system.

- **Component model**

The component model focuses on the characteristics and behavior of a specific component (e.g. the material being dried). It describes the multi-physical aspects and chemical properties of the component being investigated, such as moisture content, density, porosity, heat capacity and drying kinetics. The primary objective is to understand how the material responds to the drying process. It provides information on how the moisture content changes with time, temperature, and other drying conditions. The component model (in this case product model) helps in predicting the drying time, determining the critical moisture content, and assessing the quality attributes of the final dried product, such as uniformity, texture, and nutritional properties.

The component model is essential for optimizing the drying process to achieve the desired moisture content and quality of the product. It enables researchers and engineers to select appropriate drying parameters, design efficient drying systems, and evaluate the impact of different drying methods on the product characteristics.

- **Process simulation model**

The process model, on the other hand, focuses on the dynamics and behavior of the drying system itself. It describes the physical and thermal aspects of the drying process, including the heat and mass transfer mechanisms, airflow patterns, temperature profiles, and energy requirements. The process model considers factors such as drying chamber design, airflow rates, temperature control, and heat sources.

The primary objective of the process model is to understand and optimize the drying system's performance. It helps in assessing the energy efficiency, identifying potential bottlenecks, and evaluating the impact of process parameters on drying kinetics and overall productivity. The process model can provide insights into HT coefficients, drying rates, and energy consumption, allowing for the optimization of drying conditions, equipment design, and process control strategies.

The process model integrates various mathematical equations, empirical correlations, and computational algorithms to simulate the drying system's behavior. It takes into account the interactions between the drying medium (such as air) and the product, as well as the effects of heat and mass transfer mechanisms within the drying chamber.

Therefore, the primary focus of the simulation library will be on the development of process simulation models, specifically targeting the dynamics and performance of the drying system. Within the library, a dedicated drying zone will be developed, incorporating comprehensive considerations of heat and mass transfer as well as fluid flow phenomena.

In the development of the drying zone, a multi-physics approach will be employed to accurately capture the intricate interactions between different physical processes occurring during drying. This will involve integrating models for HT, MT, and fluid flow within the drying chamber. By incorporating these fundamental principles, the simulation library will enable detailed simulations of the drying process, allowing for a deeper understanding and optimization of the system.

To capture the drying kinetics, experimental data will serve as the basis for creating the characteristic drying curve. This curve represents the relationship between the moisture content of the product and the drying time under specific drying conditions. By utilizing experimental data, the simulation library will be able to accurately predict the drying behavior and provide valuable insights into the drying kinetics of different materials and under various operating conditions.

#### 4.2.10 Zone levels

The simulation library will distinguish between three levels of the drying zones. The top level differentiates the drying zone based on the contact between the drying medium and the moist product. This level primarily focuses on the structural orientation and encompasses the drying chamber along with its peripheral systems and utilities, such as valves, junctions, and air splitters.

The mid-level of the library focuses more on the spatial discretization of the drying zone, considering the arrangement and configuration of the drying medium and product. This level provides a more detailed representation of the physical layout and distribution within the drying chamber. Finally, the last level of the library focuses on the basic drying zone, which takes into account the multi-physical aspects of fluid flow, HT and MT. It emulates the drying kinetics by incorporating the characteristic drying curve based on experimental data. This level provides a comprehensive understanding of the dynamic behavior and interactions within the drying zone, enabling accurate simulations and optimization of the drying process.

In summary, the simulation library adopts a multi-level approach, encompassing structural orientation, spatial discretization, and multi-physical considerations, to accurately simulate and optimize the drying process. By utilizing experimental data and characteristic drying curves, the library provides valuable insights into the drying kinetics of different materials, allowing for efficient and effective design and operation of drying systems.

#### 4.2.11 Top level – structural zones

At the top level of the simulation library, the focus is on differentiating the drying zone based on the contact between the drying medium and the moist product. This level primarily deals with the structural aspects of the drying chamber and its peripheral systems and utilities. Within this level, various arrangements and configurations of the drying zone can be observed, such as cross-current and co-current drying. These arrangements determine the flow direction and the interaction between the drying medium (e.g., hot air) and the moist product.

Structural elements such as the drying chamber itself, along with its associated components, including valves, junctions, air splitters, and ducting systems, are considered at this level. The design and layout of these elements play a crucial role in facilitating the movement of the drying medium and ensuring effective heat and mass transfer between the drying medium and the product.

The top level of the simulation library provides a comprehensive understanding of the overall structure and configuration of the drying zone. It enables the modeling and simulation of the drying chamber and its peripheral systems, facilitating the analysis of the system's performance, energy efficiency, and optimization of drying conditions.

By considering the top level of the drying zone, the simulation library provides insights into the physical arrangement and interaction between the drying medium and the product, allowing for detailed simulations and evaluations of different drying configurations and their impact on the overall drying process.

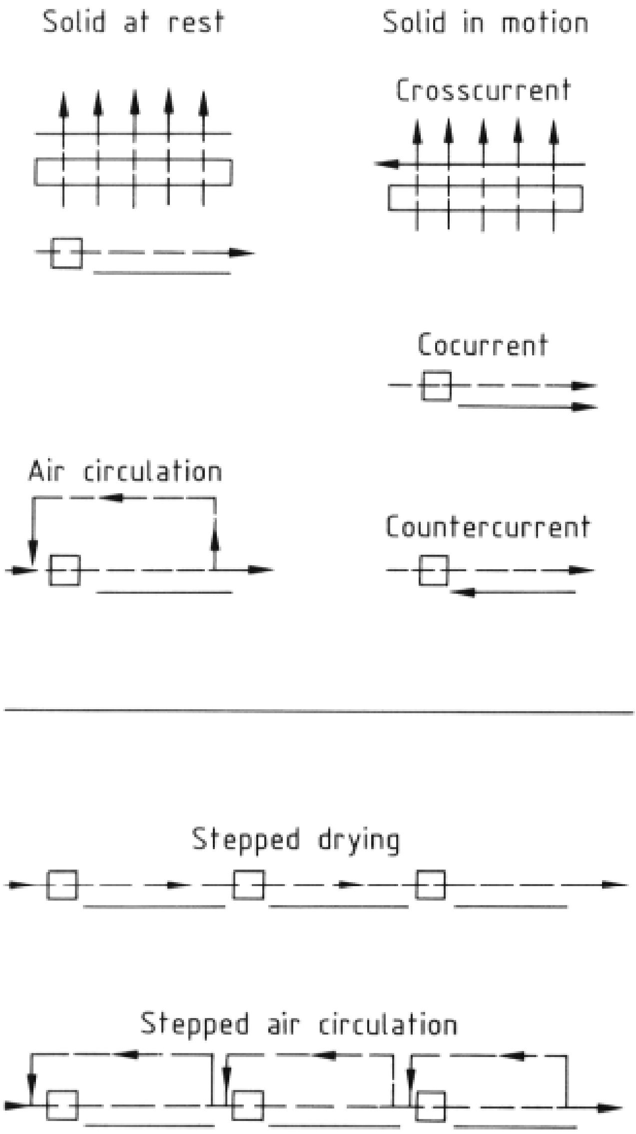



*Figure 13: Various arrangements between solid, heaters, and drying agent. (➔ Solid; – – → Drying agent; ☐ Heaters)*

### 4.2.12 Mid-level – spatially discretized zones

At the mid-level of the simulation library, the focus shifts to the spatial discretization of the drying zone. This level delves into the detailed representation of the drying chamber by dividing it into smaller spatially discretized zones.

The purpose of spatial discretization is to capture the spatial variations and distribution of temperature, moisture content, and other relevant variables within the drying chamber. By dividing the chamber into discrete zones, the simulation library enables a more granular analysis of the drying process and its spatial dynamics.

The spatial discretization can be achieved through various techniques, such as dividing the drying chamber into a grid or mesh structure. Each discretized zone within the chamber represents a specific region with its own set of properties and characteristics. These zones can be defined based on physical subdivisions within the chamber or based on computational requirements.

The spatially discretized zones enable the library to perform localized calculations and simulations, providing insights into temperature profiles, moisture gradients, and the behavior of the drying medium within different regions of the chamber. This level also supports the evaluation of heat and mass transfer coefficients, as well as the identification of potential areas of inefficiency or non-uniform drying.

#### 4.2.13 Detailed level – basic contact zone

At the basic drying zone, which represents the last level of the simulation library, the focus is on capturing the multi-physical aspects of the drying process. This level integrates fluid flow, HT, MT and drying kinetics to emulate the behavior of the drying system in detail. Within this level, the simulation library considers the complex interactions between the drying medium (e.g., air) and the product being dried. It takes into account the fluid flow patterns, temperature distributions, and moisture content variations within the drying chamber.

The library utilizes mathematical models and equations that describe the transport phenomena occurring during the drying process. These models incorporate fundamental principles of fluid mechanics, HT and MT to simulate the dynamics of the drying zone. The fluid flow aspect of the drying zone involves analyzing the velocity profiles and pressure drops within the drying zone. The library accounts for the heat exchange between the drying medium and the product, considering factors such as temperature gradients, convective HT coefficients, products porosity and thermal properties of the materials involved. Mass transfer, closely coupled with HT, is also taken into account. Figure 14 presents the basic drying zone with its components.

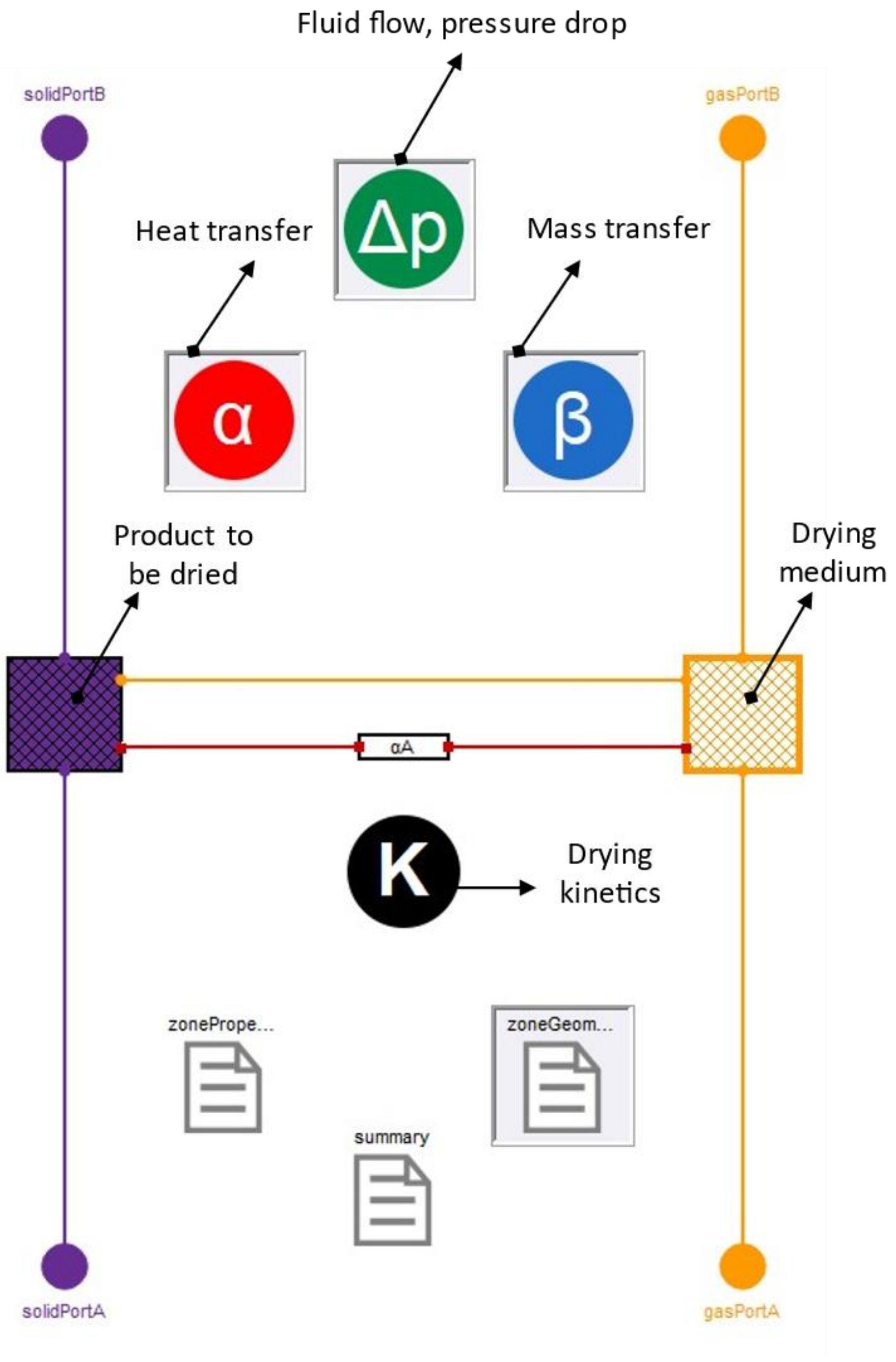



*Figure 14: An illustration of the built-in components and features of the basic drying zone.*

Accordingly, a dryer can be represented by multiple top-level zones if the flow direction differs from one zone to another. Each top-level zone can then be further divided into a number of mid-level zones (n_MidZone) to accurately capture the geometrical representation of the top-level zone. Finally, each mid-level zone can be discretized into several basic zones (x_BasicZone). This multi-level approach facilitates more precise and detailed simulations, resulting in improved optimization, efficiency, and control of the drying process.

It also provides a modular framework that can be customized and expanded to accommodate various drying configurations and materials. It allows for a comprehensive understanding and modeling of the drying process at different levels of detail. Each level addresses specific aspects of the drying system, from the overall structure and configuration to the spatial discretization and multi-physical phenomena. Figure 15 provides an exemplary illustration of a spray dryer being discretized using the multi-level approach, demonstrating its effectiveness in capturing the complexities of the drying process.

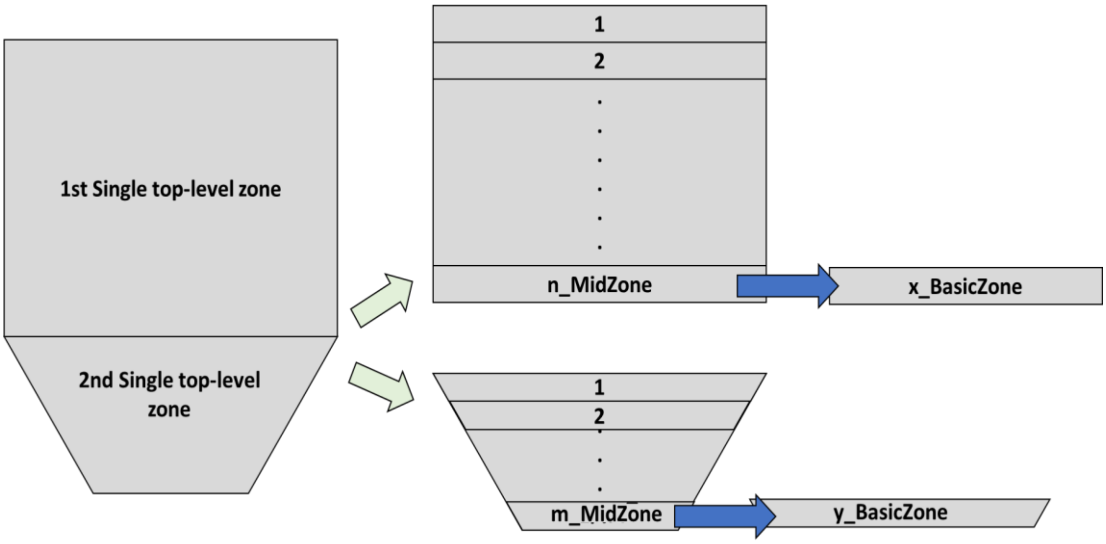



*Figure 15: An exemplary spray dryer with an illustration of the three levels adopted in the simulation library.*

### 4.2.14 Levels of multi-physical details

#### 4.2.14.1 Balance models

Balance models play a crucial role in the simulation library as they provide a framework for quantifying and tracking the key variables involved in the drying process. These models are based on the principles of conservation of mass, energy, and momentum, allowing for a comprehensive understanding of the system behavior.

The mass balance model is responsible for tracking the movement of moisture within the drying system. It accounts for the inflow and outflow of moisture, as well as the moisture content changes within different zones. By considering the mass transfer rates and moisture content gradients, the model enables accurate predictions of the drying kinetics and moisture distribution throughout the process.

The energy balance model focuses on the thermal aspects of the drying system. It considers the energy inputs and outputs, such as heat supplied to the drying chamber, heat losses, and energy absorbed by the product. The model accounts for the convective HT, and heat conduction within the system, ensuring an accurate representation of the temperature profiles and energy distribution during the drying process.

In addition to mass and energy, the momentum balance model is employed to analyze the fluid flow behavior within the drying chamber. This model considers factors such as pressure drop and velocity profiles.

The balance models within the simulation library are interconnected, allowing for the exchange of information and variables between them. For instance, the heat transfer rates calculated in the energy balance model influence the temperature profiles, which, in turn, impact the moisture content and drying rates predicted by the mass balance model. This integration ensures a comprehensive representation of the drying process, capturing the interdependencies between different variables and phenomena.

Throughout the development of the balance models, it became apparent that there must be a distinction between batch dryers and continuous dryers as they have different working principle. Accordingly:

$$\dot{M}_g \cdot (Y_f - Y_i) = M_s \cdot \frac{dX}{dt} \quad (13)$$

$$\dot{Q}_{heat} + \dot{W}_{vent} = \dot{M}_g \cdot (h_f - h_i) + M_s \cdot \frac{d(h_s + Xh_l)}{dt} + \dot{Q}_{loss} \quad (14)$$

Equations (13) and (14) represent the energy and mass balance for a batch dryer. Therein, $\dot{M}_g$ represents the mass flowrate of the drying medium, $(Y_f - Y_i)$ is the humidity difference of the drying medium, $M_s$ refers to the amount of the product being dried in the batch process and $dX/dt$ is the product moisture content change over time. In the energy balance, $\dot{Q}_{heat}$, $\dot{W}_{vent}$ and $\dot{Q}_{loss}$ represent the supplied heat to the batch drier, the ventilation power needed (if required) and the heat losses from the drying chamber, respectively. For the drying medium, $(h_f - h_i)$ denotes the enthalpy difference, whereas $(h_s + Xh_l)$ is the enthalpy of the product.

For a continuous dryer, the mass and energy balance can be expressed as follows:

$$\dot{M}_g \cdot (Y_f - Y_i) = \dot{M}_s \cdot (X_i - X_f) \quad (15)$$

$$\dot{Q}_{heat} + \dot{W}_{vent} = \dot{M}_g \cdot (h_f - h_i) + M_s \cdot [(h_{sf} - h_{si}) + (X_f h_{lf} - X_i h_{li})] + \dot{Q}_{loss} \quad (16)$$

The equations (13-16) are implemented in each zone whether it is a top-level or basic zone. Following the type of dryer (batch or continuous), the proper equations set will be activated to represent the mass and energy balance in the drying zone considered.

#### 4.2.14.2 Kinetic Models

Kinetic models play a crucial role in understanding and predicting the drying behavior of different materials. These models describe the relationship between the drying rate and the moisture content of the product under specific drying conditions. The determination of drying kinetics involves experimental measurements of the drying rate at different moisture contents and drying conditions. These data are then used to develop the characteristic drying curve, which represents the drying behavior of the material.

To determine the drying kinetics, experimental data is typically collected using specialized drying equipment. Samples of the material are subjected to controlled drying conditions, and the weight loss or moisture content change is measured over time. By analyzing these measurements, the characteristic drying curve is established, which provides valuable information about the drying behavior and allows for the development of kinetic models.

During the initial period of drying (denoted by $\dot{m}_{\mathrm{I}}$), the drying rate is dependent only on the conditions of drying and not on the characteristics of the solid: there is only evaporation from the surface of the solid. The temperature of the solid, denoted by $T_{\mathrm{I}}$, is established so that the heat flux from the drying agent to the solid, $\dot{q}$, is equal to the product of the drying rate and the vaporization enthalpy ($\Delta h_{\mathrm{v}}$) as follows:

$$\dot{q} = \dot{m}_{\mathrm{I}} \cdot \Delta h_{\mathrm{v}} \tag{16}$$

The drying agent, usually air, is completely saturated at the surface of the solid and accordingly:

$$Y_{@\text{surface of the product}} = Y^{*}(T_{\mathrm{I}}) \tag{17}$$

Assuming that the humidity in the bulk of the drying agent is represented by $Y$, where $Y$ is less than the equilibrium humidity $Y^{*}(T_{\mathrm{I}})$, the drying rate ($\dot{m}_{\mathrm{I}}$) is directly proportional to the difference between the equilibrium humidity and the actual humidity in the bulk of the drying agent. The proportionality constant in this relationship is referred to as the effective mass-transfer coefficient β0g. Accordingly:

$$\dot{m}_{\mathrm{I}} = \rho_{\mathrm{g}} \cdot \beta_{\mathrm{g}} \cdot [Y^{*}(T_{\mathrm{I}}) - Y] \tag{18}$$

As the drying process progresses into the second phase, determining the drying rate becomes more challenging, particularly during the falling rate period. To simplify this process, engineers and researchers often utilize a characteristic drying curve (CDC). The CDC involves normalizing the moisture content and drying rate values within a range of 0 to 1. This normalization allows for easier comparison and analysis across different materials and drying conditions.

By utilizing the CDC, engineers can effectively characterize the drying behavior of a material and determine the drying rate at various moisture content levels. This curve provides valuable insights into the kinetics of the drying process and aids in optimizing drying operations.

$$\eta = \frac{X - X_{\mathrm{eq}}}{X_{\mathrm{crit}} - X_{\mathrm{eq}}}; 0 \le \eta \le 1 \tag{19}$$

$$\dot{v}(\eta) = \frac{\dot{m}_{\mathrm{II}}}{\dot{m}_{\mathrm{I}}}; 0 \le \dot{v}(\eta) \le 1 \tag{20}$$

The critical moisture content ($X_{\mathrm{crit}}$) plays a crucial role in the transition from the first drying phase to the second drying phase. It represents the moisture content at which the product undergoes a significant change in the drying rate behavior. Determining the critical moisture content is essential for understanding the overall drying process.

To identify the critical moisture content, the normalized drying rate is used as a key parameter. The normalized drying rate provides a relative measure of the drying rate, taking into account the initial drying rate and the falling rate phase. By plotting the normalized drying rate against the moisture content, a distinct point can be observed where the rate of decline in the drying rate becomes significant.

At this critical moisture content, the drying process enters the second phase, characterized by a declining drying rate. The product reaches a state where further moisture removal becomes more challenging, and the drying rate starts to decrease. This critical moisture content marks the boundary between the initial drying phase and the falling rate phase.

### 4.2.15 Heat and mass transfer correlations

Heat and mass transfer correlations play a vital role in accurately modeling and simulating industrial drying processes. These correlations provide mathematical relationships that describe the transfer of heat and mass between the drying medium and the product being dried.

For heat transfer, correlations such as the Nusselt number correlation are used to determine the convective HT coefficient. These correlations consider factors such as the properties of the drying medium, the geometry of the drying chamber, and the flow conditions to estimate the heat transfer rate. Besides, these correlations consider the porosity (products distribution) in the drying chamber allowing to determine the effective heat transfer area, which later plays a role in the determination of the mass diffusion coefficient.

*Table 1: An example of the heat transfer correlations implemented in the library for industrial drying*

| Name | Correlation | Condition | Source |
|---|---|---|---|
| **Whitaker I** | $\mathrm{Nu} = [(0.5 \cdot \mathrm{Re_m}^{\frac{1}{2}}) + (0.2 \cdot \mathrm{Re_m}^{\frac{2}{3}})] \cdot \mathrm{Pr}^{\frac{1}{3}}$ <br> $\mathrm{Re_m} = \frac{\rho \cdot u_g d_p}{(1-\epsilon) \cdot \mu}$ | $22.8 < \mathrm{Re_m} < 1000$ <br> $\varepsilon \geq 0.65$ | [2] |
| **Gupta** | $\mathrm{Nu} = \frac{[2.876 + (0.3023 \cdot \mathrm{Re}^{0.65})] \cdot \mathrm{Pr}^{\frac{1}{3}}}{\epsilon}$ | $10 < \mathrm{Re} < 10000$ | [3] |
| **Dunkle** | $\mathrm{Nu} = 2.4 \cdot \mathrm{Pr} \cdot \mathrm{Re}^{0.7}$ | $10 < \mathrm{Re} < 10000$ | - |
| **Gunn** | $\mathrm{Nu} = [(7 - 10\epsilon + 5\epsilon^2) \cdot (1 + 0.7\mathrm{Re}^{0.2}) + (1.33 - 2.4\epsilon + 1.2\epsilon^2) \cdot (\mathrm{Re}^{0.7})] \cdot \mathrm{Pr}^{\frac{1}{3}}$ | $10 < \mathrm{Re} < 10000$ <br> $\varepsilon \geq 0.35$ | [4] |
| **Nie** | $\mathrm{Nu} = 0.0491 \cdot \mathrm{Re_{dh}}^{0.8572} \cdot \mathrm{Pr}^{\frac{1}{3}}$ | $5 < \mathrm{Re} < 280$ | [5] |

### 4.2.16 Material Properties

The simulation library takes into account the crucial role of material properties in accurately modeling industrial drying processes. Material properties such as thermal conductivity, specific heat capacity, density, and moisture diffusivity significantly impact the heat and mass transfer rates within the drying system.

By including comprehensive databases and models for material properties, TheSpLib enables the user to incorporate specific properties of different materials being dried and drying agents. These properties are essential for accurately predicting drying kinetics, temperature distribution, moisture content, and overall system behavior.

The development of TheSpLib, a simulation library for industrial drying processes, has been successfully outlined in this deliverable. The library offers a comprehensive solution for modeling, simulating, and optimizing drying operations in various industrial settings. The importance of industrial drying in decarbonization efforts and climate change mitigation has been emphasized. The ability to accurately model and simulate drying processes is crucial for optimizing energy systems and achieving energy efficiency.

The utilization of Modelica as the framework for developing the simulation library has proven to be highly advantageous. Modelica provides a versatile platform for multi-physics modeling, allowing for the integration of heat transfer, mass transfer, and fluid flow models within the drying chamber. This enables detailed and realistic simulations of the complex interactions occurring during the drying process.

The multi-level approach adopted in TheSpLib facilitates a hierarchical representation of the drying system, capturing the structural, spatial, and multi-physical aspects of the process. This approach enables users to analyze and optimize drying operations at different levels of detail, leading to improved efficiency, control, and overall performance.

The incorporation of balance models, kinetic models, and the characteristic drying curve enhances the library's capability to accurately predict drying kinetics and system behavior. By utilizing experimental data and material properties, TheSpLib provides valuable insights into the drying process and enables users to make informed decisions regarding process optimization and design.

The inclusion of HT and MT correlations and material properties further enhances the accuracy and reliability of the simulations. By considering the specific properties of different materials, the library ensures realistic predictions and enables users to customize and adapt the simulations to their specific drying applications.

In conclusion, TheSpLib is a valuable tool for engineers and researchers in the field of industrial drying. It provides a comprehensive platform for modeling, simulation, and optimization, contributing to improved energy efficiency, reduced environmental impact, and enhanced control of drying processes

## 4.3 EDDY Toolbox

The EDDY toolbox examines the most important heat recovery options and quantify their potential for improving the energy efficiency of a drying process. This toolbox model focuses on the analysis of the equipment before and after the dryer (e.g. heat exchangers, heat pumps). The dryer itself is only a simple sub-model based on material and energy balance equations without kinetics. This means that the toolbox model is mainly suitable for users who can define the dryer balance and want to quickly assess the potential for energy savings by integrating heat recovery systems.

The base model was created in the Dymola environment using the Modelica programming language. Dymola provides a graphical user interface in which the inputs and outputs for each submodel can be managed separately, as shown in Figure 16. All relevant submodels, such as the dryer, the product cooling zone, the heat recovery system and the air recirculation system, as well as some results, can already be seen at this level.

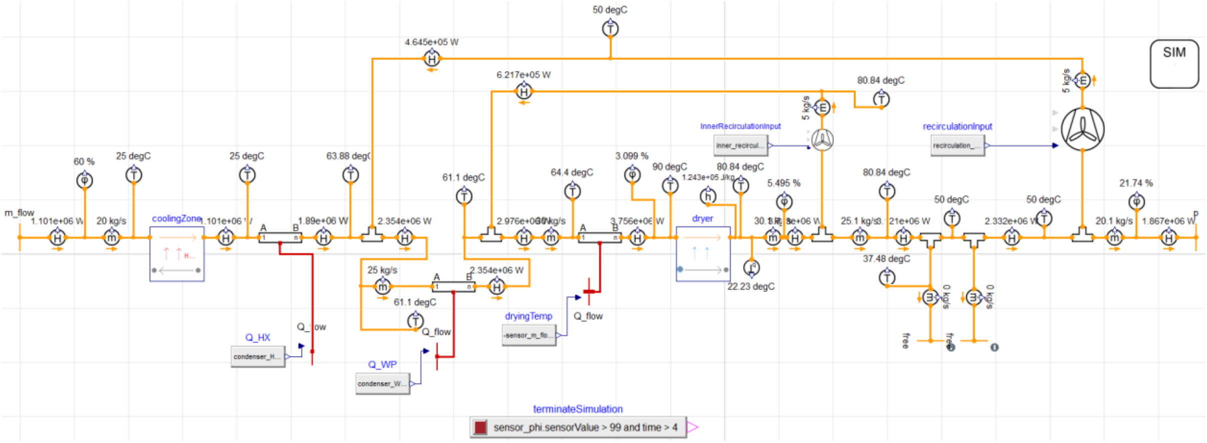



*Figure 16: Basic model in the Dymola environment*

An FMU (functional mock-up unit) was exported from Dymola and used as a black box model in JavaScript, since JavaScript is suitable for web applications. JavaScript is used to create the web application that displays the interactive input field where the user can select the parameters of the drying process. The user then clicks the “Calculate” button to transfer the input to the FMU model, which calculates the results and returns them to the web application interface. The results are presented in the general scheme of the drying process, as shown in Figure 17.

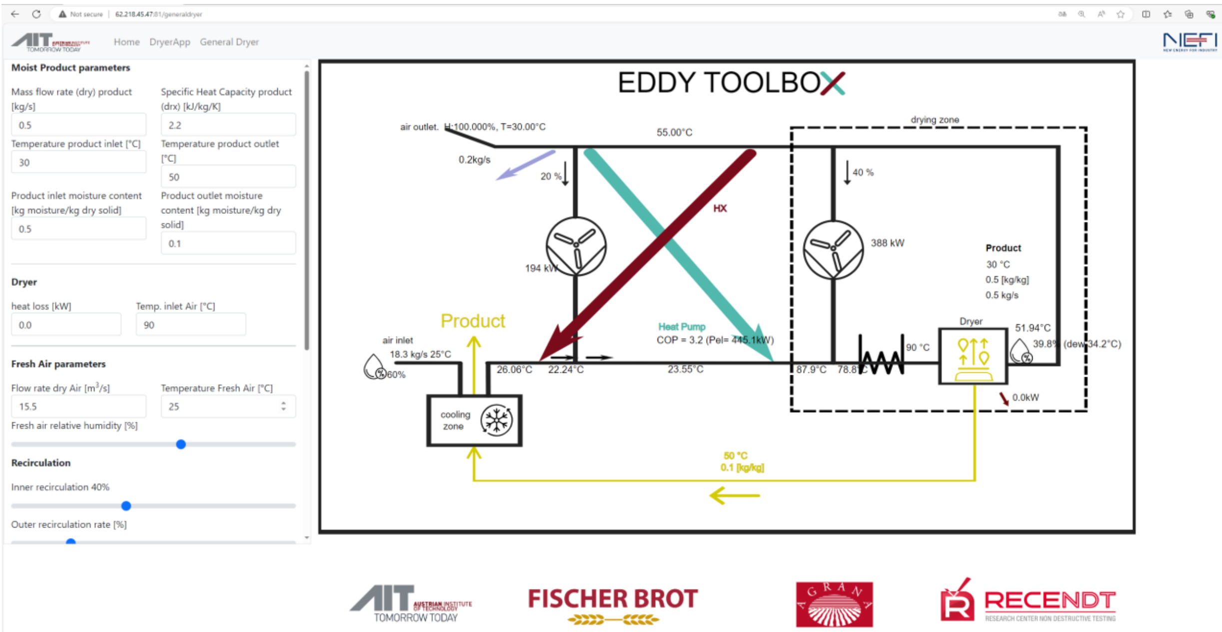



*Figure 17: EDDY Toolbox schema and input panel in Toolbox web application*

The panel with user-defined entries is shown on the left in Figure 2 and is divided into the following categories:

1. Moist product parameters
   1.1. Mass flow
   1.2. Heat capacity
   1.3. Initial temperature and moisture content
   1.4. Final temperature and moisture content
2. Dryer
   2.1. Heat losses
   2.2. Initial temperature of the drying air
3. Fresh air
   3.1. Flow rate
   3.2. Temperature
   3.3. Humidity
4. Recirculation
   4.1. Percentage of inner recirculation
   4.2. Percentage of the outer recirculation
   4.3. Efficiency of the fans and pressure difference (used only to calculate electric power of the fans)
5. Heat recovery
   5.1. Activation of heat recovery by heat exchanger
   5.2. Activation of heat recovery by heat exchanger boosted with heat pump
   5.3. End temperature of the air that serves as a heat source in heat exchanger
   5.4. End temperature of the air that serves as a heat source in heat exchanger boosted with the heat pump
6. Cooling Zone
   6.1. End temperature of the product after the cooling zone
   6.2. Heat losses of the cooling zone

If the Boolean parameters for activating the heat exchanger, the heat pump and the cooling zone are deactivated, these are automatically excluded from the diagram. If the recirculation fans are set to zero, their rotation is stopped and they are displayed in gray to indicate to the user that these devices are not being used. This is shown in Figure 18.

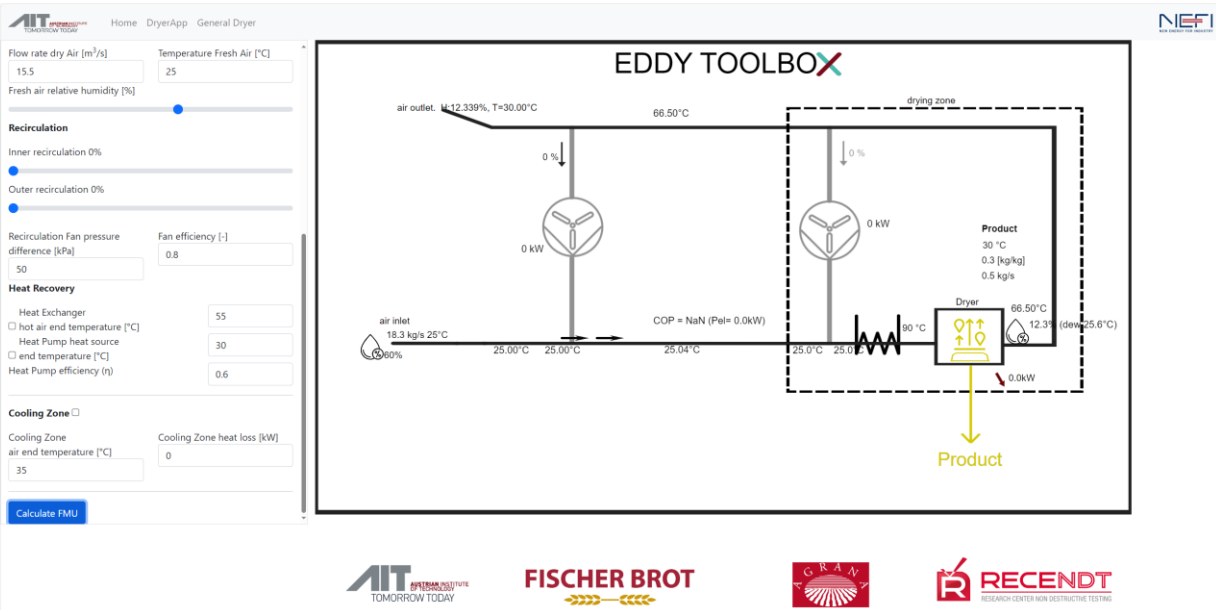



*Figure 18: EDDY Toolbox scheme without heat recovery systems*

After the calculation, which usually takes less than a second, the most important results are displayed directly on the schematic. These are shown in Figure 2 and include temperatures, humidity, COP of the heat pump, electrical power of the heat pump, etc. The user can, for example, see the dew point temperature of the air leaving the dryer and know to what temperature the air must be cooled to start condensation and thus latent heat recovery. If this is not possible with a classic heat exchanger (Toolbox will, for example, give an error message for reverse heat flow), the user is advised to use a heat pump heat exchanger instead. To make it clear that latent heat recovery is taking place, a light blue arrow with a value for the condensate mass flow is displayed in the diagram when this is the case. (This can be seen in Figure 2 with a value of 0.2 kg/s and is not visible in Figure 3 because no condensation takes place in this case).

A Sankey diagram of the energy flows is always calculated and displayed to visually support the analysis. It is shown in Figure 4. The drying air moves from left to right and is represented by the blue nodes. On its way, it increases its energy content through heat recovery, but also through material recirculation. The energy content is also increased by a heater, represented as “Dryer Heating”, and by the electrical power of the heat pump “Pel_HP”. The simplest use of the diagram is to visually compare the energy content of the supply and exhaust air and to check the amount of heat recovered. This is possible because the size of the nodes is proportional to their value. To obtain exact values, the user can move the mouse over the energy flow, as shown in Figure 19 for the case of “Air+OuterRec”.

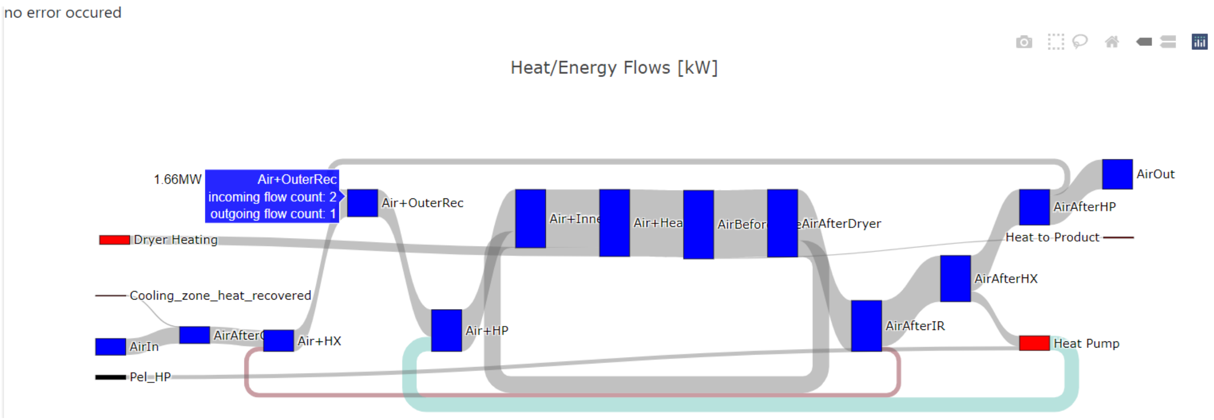
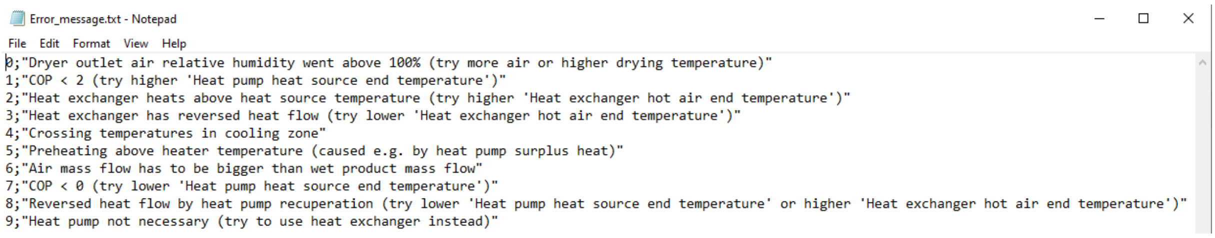



*Figure 19: Sankey diagram of the energy flows*

Toolbox allows the user to enter any input values that result in outcomes that cannot be calculated, are physically impossible, or are unusual for a normal process. In this case, Toolbox displays an error message that indicates the reason for the error. It also tells the user what to change to avoid the error. For example, if the drying rate causes the relative humidity to exceed 100%, the user will receive the following error message: "Dryer outlet air relative humidity exceeded 100% (try more air or higher drying temperature)." This is essential to using the toolbox, as testing/activating various heat recovery processes can change some parameters that the user may not necessarily be aware of. This way, the toolbox model guides the user to make sensible decisions and is therefore a good tool for iteratively adjusting the process to find the potential for energy savings. All error messages are shown in Figure 20.


Error_message.txt - Notepad
File Edit Format View Help

```
0;"Dryer outlet air relative humidity went above 100% (try more air or higher drying temperature)"
1;"COP < 2 (try higher 'Heat pump heat source end temperature')"
2;"Heat exchanger heats above heat source temperature (try higher 'Heat exchanger hot air end temperature')"
3;"Heat exchanger has reversed heat flow (try lower 'Heat exchanger hot air end temperature')"
4;"Crossing temperatures in cooling zone"
5;"Preheating above heater temperature (caused e.g. by heat pump surplus heat)"
6;"Air mass flow has to be bigger than wet product mass flow"
7;"COP < 0 (try lower 'Heat pump heat source end temperature')"
8;"Reversed heat flow by heat pump recuperation (try lower 'Heat pump heat source end temperature' or higher 'Heat exchanger hot air end temperature')"
9;"Heat pump not necessary (try to use heat exchanger instead)"
```

*Figure 20: TXT file with error messages*

# 5 Outlook and recommendations

The EDDY project addresses the energy-intensive processes of drying and dehydration, which are predominantly reliant on fossil fuels in industrial applications. The primary focus of the EDDY initiative is on optimizing drying processes in the agricultural raw material and food industries, aiming to reduce fossil carbon emissions and enhance energy efficiency. At the core of the project is the development of an innovative, compact, and cost-effective infrared (IR) moisture sensor that enables inline moisture monitoring in real-time. Unlike conventional humidity sensors, the IR sensor can directly measure the moisture content of the product being dried, providing more accurate and actionable data for optimizing drying processes.

The EDDY project successfully develops low-cost IR moisture sensors that are robust, reliable, and long-term stable, making them suitable for industrial drying processes at AGRANA Stärke GmbH and Fischer Brot GmbH. The sensor technology facilitates:

- Real-time inline monitoring of product moisture levels during drying.
- Optimization of drying operations using numerical models and monitoring data, ultimately leading to reduced CO2 emissions, lower operating costs, increased productivity, and higher product quality.

Additionally, the project explores the integration of heat pump technology to further increase energy efficiency and make use of renewable energy sources in drying operations. Through the implementation of advanced control strategies, the EDDY project demonstrates that fossil fuel usage can be reduced by up to 50% in drying processes, with energy costs cut by approximately 40%. The outcomes of the project are easily transferable to other industries, paving the way for significant energy savings and environmental benefits.

Looking ahead, the EDDY project aims to further refine and optimize the sensor technology and control strategies developed during the course of the research. Key areas for future work include:

- Scaling and Commercialization: The continued development of the IR moisture sensor will focus on making it ready for mass production, ensuring its affordability and reliability for widespread adoption across various industrial sectors.
- Broader Industry Adoption: With the positive results from AGRANA and Fischer Brot, the technology developed in the EDDY project has the potential to be applied to other energy-intensive drying processes across industries such as paper, textiles, and wood.
- Energy Efficiency Advancements: Future work will focus on integrating more renewable energy sources into the drying process and refining the optimization algorithms to further reduce energy consumption.
- Modeling and Simulation: The development of the simulation library (TheSpLib) will continue, enabling more accurate and detailed simulations of drying processes. The library will be used to

optimize drying conditions, predict energy usage, and assess the impact of process adjustments on product quality and energy consumption.

- Collaboration with Industry: The ongoing collaboration with industry partners will facilitate the transition from research to real-world applications, ensuring that the results are effectively integrated into industrial drying systems.

In conclusion, the EDDY project is poised to make significant contributions toward improving energy efficiency, reducing carbon emissions, and enhancing the overall sustainability of industrial drying processes. With its innovative approach combining advanced sensor technology, process optimization, and energy recovery, the EDDY concept offers a transformative solution for the drying industry worldwide.

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