Bottlenecks in continuous hops drying with conveyor-belt dryer

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ABSTRACT

Hops are an essential raw material in beer brewing, providing typical flavor and aroma characteristics to beer. Freshly harvested hop cones must be dried immediately. While conveyor-belt dryers are widely used, their operation is largely based on operator experience, which leads to energy-intensive operation whilst adversely affecting the quality. This work identifies the bottlenecks in hops drying by summarizing the results of previous studies, and experimentally analyzing an industrial dryer. Heterogeneous air-distribution, uneven drying and suboptimal control-strategies were identified as key issues which can be battled with accurate model-based process analysis and smart control systems, both of which need further research.

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Introduction

Of all the herbs that have been used to flavor and preserve beer over the ages, only hops are regarded as an essential raw material in brewing all across the world.\cite{1} Due to this obvious importance, in 2019, a total of 129,102 tonnes of hops was produced on 61,243 ha agricultural land around the world, with an upward trend.\cite{2} The largest producers of hops were the USA (51,275 t) and Germany (48,472 t), followed by the Czech Republic (7,145 t), China (7,044 t), Poland (2,900 t) and Slovenia (2,572 t). The German cultivated area (20,417 ha) covered 37.5% of the world’s demand at an average yield of 2,374 kg dry hops per hectare (worldwide average 2,108 kg/ha).

The hop plant (\textit{Humulus lupulus} L.) is a climbing plant belonging to the hemp family. Only female plants are cultivated, the vines of which grow every year on trellis wires in the hop gardens up to 7 m. The cones that can grow up to 4 cm in length develop from the unfertilized flowers of the female hops and may account for about 40% of the total plant mass. Hop cones are composed of four components: the stalk, the strig, the bracts sitting on the strig, and the lupulin glands. The lupulin glands are usually spherical zones of about 200 \textmu m which contain lupulin in widely varying concentrations across the cone.\cite{3} Lupulin is the chemical component valuable for brewing purposes and, to a very limited extent, for medicine, as well.\cite{4}

In order for the lupulin to be utilized in brewing or in any other industry, hops must go through a series of post-harvest steps. At harvest, the vines are cut and placed individually in picking machines, where the cones are separated from leaf and stem parts of the plants. The separated cones are regarded as green hops, which must be dried for preservation immediately after harvesting. This is because the cones respond to the removal from the plants with an increased respiration rate which is further intensified by injuries due to mechanical strains of picking.\cite{5} The volume of undamaged cones depends essentially on a number of factors such as the technical standard of the harvesting and picking equipment, the hop-variety, the degree of maturity of the cones, the particular year and locality as well as the level of husbandry.\cite{5} In order to ensure seamless drying of the green hops, the capacities of the picking machines and the dryers must be synchronized to each other.

The moisture content of freshly harvested hop cones is around 78–84% w.b. (wet basis). To achieve a reasonable shelf life, immediate drying of the green hops is required to drive the moisture content down to an average of 9–10%. The recommended range of drying temperature lies between 62–65°C,\cite{6} which ensures quality preservation during drying. The
challenge in drying is associated with the inevitable variation in moisture content within the dried hops. This stems from the fact that the bracts of the cones dry much faster than the strigs. Consequently, at the end of drying, the moisture content of the bracts usually remains below the target, while that of the strigs is above the target. Moreover, there are often large differences between individual cones. Therefore, after drying, hops are kept in a conditioning unit to achieve uniform moisture content. Equalization of moisture content occurs within a few hours and is facilitated by conditioned air either in closed chambers or, after continuous drying, on conveyor-belts. The ventilation of conditioning chambers should be carried out with air that has a relative humidity ranging between 58–65% and a temperature ranging between 20–24°C.[7] Dried hop cones are not only hygroscopic and photosensitive, but also prone to absorbing the scents of their environment. Hence, they should be packed and stored in pressed bales immediately after conditioning.[8]

For hops drying, convection dryers of different designs are used. For instance, the batch-type kiln dryers are often designed with several floors placed above each other and can be employed for hops drying.[9] In Europe, mainly three-floor kilns and belt dryers are used for hops, whereas in the USA one-floor kilns are most common. Typical time periods for kilning hops range from 5 to 8 hours, depending on the hop-variety and system in use. As for the energy source, fuel oil or gas burners are mostly used to heat fresh air to the usual drying temperatures of 63–68°C. The warm exhaust air is typically released to the atmosphere.[10] This is inefficient in terms of energy utilization, since the waste heat could be partially recovered from exhaust air at temperatures higher than 30°C.

Due to the short harvest time of around four to five weeks, continuous dryers specifically designed for and entirely dedicated to hops drying are rare. Usually, the drying of hops is treated as a special case and thus achieved in versatile continuous dryers. Among continuously operated dryers, conveyor-belt dryers are known to be the most versatile dryers and can handle a wide range of different products.[11] In most of the cases, three-belt dryers without belt cleaning devices and with only one indirectly oil-fired air heater are used.[12] Similar to the setups involving kiln dryers, systems for heat recovery are rarely found for those with continuous dryers as well.

In Germany, both belt and kiln dryers are used for hops drying on the hop farms.[13] Kiln dryers are found mainly in the southern growing areas. In the Eastern region of Elbe-Saale, continuously operated conveyor-belt dryers are used almost exclusively. These three-belt dryers of Czech design date from the 1970s. Heat is provided by burning light fuel oil via heat exchangers.

While the batch-type kiln dryers lead to relatively superior product quality, the continuous conveyor-belt dryers also have several advantages over the batch-type dryers, as reported by several plant operators in Germany during personal communications with the authors. For instance, higher throughput and lower drying time of the conveyor-belt dryers are likely to lead to more efficient drying with the possibility of variable temperature zones. Moreover, the dryers are more compact and thus require less space, as compared to kiln dryers. Furthermore, due to constant movements in belt dryer undesired wet-zones can be avoided.

Despite the abovementioned advantages, hops drying with conveyor-belt dryers is often associated with high operating costs and subpar product quality.[14] In addition to the challenges inherent to hops drying, the fact that the operation of the belt dryers essentially relies upon the experience of the operator often results in suboptimal drying and high energy consumption. A deeper understanding of the process would result in a more systematic approach, ultimately leading to an optimum dryer operation. Unfortunately, few detailed studies have delved into conveyor-belt drying of hops to alleviate this issue, with the exception of a series of studies conducted by a research group in the Czech Republic, e.g. [14–19]. A detailed review of those studies is presented in the next section. While these studies have provided valuable insights and experimental data at both lab and industrial scales, they also highlighted the need to conduct further research to better understand and optimize the process.

The aim of this study is to obtain a better understanding of the existing bottlenecks in hops drying so that the operation can be systematically improved. The optimization of the existing process first requires the determination of the status quo. Therefore, this paper first provides a comprehensive review of the literature available on hops drying. Then the operation of an industrial conveyor-belt dryer is analyzed in detail by means of data collected during real operation. This will provide further insight in the existing problems that need to be addressed for any potential improvement. The present study contributes to
minimizing the energy consumption and increasing the economic efficiency of hops drying.

**Literature review**

This section provides a comprehensive review of the available literature. This review attempts to summarize the results, identify gaps in knowledge, and derive future research needs. As indicated earlier, while the main focus is kept on conveyor-belt drying, some relevant studies conducted on batch-type kiln dryers are also included in the review.

**Influence of drying on the quality of hops**

Hops are the most complex and costly raw material used in brewing. Their chemical composition depends on genetically controlled factors that essentially distinguish hop varieties and is influenced by environmental factors and post-harvest processing. Chemical research provided the basis for improvements in hop breeding, conditioning, extraction, use, analysis etc.

In general, hop research focused on hops as a bittering agent, as an aroma contributor and as a preservative. Hop cones contain several components, such as resins, essential oils, proteins, polyphenols, lipids, waxes, cellulose and amino acids. The brewing value of hops is primarily attributed to the precursors of the flavor- and bitter-active compounds found in the resins secreted by the lupulin glands. The hop essential oils are also important as they provide typical flavor and aroma characteristics to the beer. The hop total resins can be further divided into soft and hard resins. The bulk of the brewing and bittering value of the hop is found in the soft resins which consist of α-acids and the β-fraction. It is well established that the alpha acids are by far the most important constituents of the hop resins. However, the content of alpha acids and essential oils and also the external appearance of the cones may be significantly influenced by the drying conditions. Only optimum drying can ensure that the unique and varietal aromas and flavors of the different hop-varieties will find their way into beer.

The importance of choosing the lowest possible drying temperature to ensure the quality and market value of hops was emphasized early on. The drying of hops at temperatures in the range of 43–65°C (110–150°F) showed that drying at higher temperatures always reduced the amount of essential oil, usually without noticeably affecting its composition. Temperatures above 65°C, even if they are applied only short term, lead to recognizable damage, which is reflected by the color change of the lupulin glands from normal lemon to golden yellow. Other important quality characteristics that are affected by drying include the aroma, the content of alpha acid, and the appearance of the cones in terms of their color, texture, and mechanical strains. Studies in Tasmanian hop kilns revealed fluctuations in the alpha acid content during drying as a function of temperature and time. During batch-type drying tests in California, Thompson et al. increased the temperature of the inlet air in the first three hours to 83°C and finished drying at lower temperatures. As long as 65°C were not exceeded, the experiments showed no significant effects on the product quality (alpha acid content). Quality studies on microwave-assisted drying of hops at 65°C did not show any changes in the optical evaluation or the alpha acid content compared to the sample merely dried with warm air.

Essential oils present in hops play an important role in brewing. Loss of essential oils reduces the intensity of hop aroma. The composition and amount of oil in dry hops are influenced by the drying conditions. The range of total hops oil lost during hops-drying have been reported to be between 10% and 60%. According to Sharpe & Laws, the highest drying temperature at which the loss of essential oil can be kept at a reasonable margin (around 3%) is 63°C. According to Hermánek et al., the chemical composition of hops on average includes 15% of total resins, 4% of polyphenol-type substances (also known as hop tannins) and 1% essential oil, all of which are deemed crucial as brewing constituents.

Desmethylxanthohumol is one of the important polyphenol-type substances that contribute to a pronounced and crispy beer taste alongside exhibiting a precipitating effect on proteins with high and intermediate molecular weight during hopping. Loss of desmethylxanthohumol was reported in the work to be significantly lower at drying temperatures of 40–45°C than that at 60°C. In further drying experiments, Rybka et al. analyzed the effect of the drying temperature on the content and composition of hops oils. They took the oil content in green hops as a reference and reported that the loss was significantly smaller at 40°C (10%) than at 55°C (36–43%). Similar investigations conducted on a different species of hops (of the Saaz variety), which were dried in an industrial chamber dryer, revealed oil losses below 15% at 40°C compared to up to 21% at 60°C. However, the drying time was increased by approx.
46%, which significantly reduced the throughput of the dryer. Investigations into color changes of hops during batch-type drying were conducted by Sturm et al. They found a positive correlation between the color degradation in the upper layers and the drying time, which is directly proportional to the bulk weight or the layer height. In practice, however, it is important to find the optimum compromise between the most favorable process settings including scheduling on the one hand and acceptable color changes on the other. Münsterer studied the quality degradation of green hops during the first stage of drying and reported that the longer the cones were exposed to virtually saturated air, the more adversely affected was their physical appearance at the end of drying. Sturm et al. employed noninvasive visual sensors in a pilot scale drying system in order to investigate the dynamic changes of several selected quality criteria. The study revealed that, in addition to bulk weight and temperature, harvesting conditions and specific mass flow rate of drying air have a significant influence on both the drying time and color changes of hops. They also developed mathematical models to predict moisture content and chromatic information during hops drying. While initial investigations showed promising results, the need to further hone the models was highlighted. It was concluded that smart drying systems which take dynamic changes in the product into consideration can be realized by developing a control system that incorporates the relevant information into the feedback loop.

In summary, although much is known on the influence of drying on the quality of hops, many knowledge gaps still need to be addressed. These include not only determining the optimum operating conditions such as drying temperature, but also developing smart control systems and adapting operation based on the specific aspects of different drying processes.

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**Equipment performance and energy consumption in hops drying**

Bernásek et al. used a lab-scale dryer with four boxes arranged above each other operated with an inlet air temperature of 60°C. It was found that the energy requirement could be reduced considerably by means of implementing a gradually declining rate of drying air flow. Hofmann et al. installed a cross-flow heat exchanger in an industrial scale hop kiln in order to recover energy from the outlet air and to recover hop oils. Having considered the electrical energy required to overcome the airflow resistance in the heat exchange system, a primary energy saving of approx. 20% was reported. However, a comparison with a system directly using the partially recirculated dryer exhaust air as dryer inlet air was not carried out in this study. Rybka et al. analyzed a Czech chamber dryer operating at a maximum temperature of about 55°C. To measure temperatures and relative humidities, they used both fixed sensors in the dryer and mobile data loggers. The data loggers were run together with hop cones through the dryer, continuously recording the temperatures during the entire course of the drying process. In order to reduce the loss of essential oils, investigations with lower drying temperatures up to 40°C were proposed. As already mentioned, however, lower temperatures generally reduce the throughput of dryers.

Studies of continuously operated conveyor-belt dryer for hops drying are relatively more common, as compared to batch-type drying. Zeisig developed a relatively small three-belt dryer which was operated in drying tests performed at about 65–117°C with a throughput of approx. 12-28 kg/h of dry hops. However, inadequacies in the rig-setup with regards to hops transport and air flow did not allow reasonable comparisons with the experimental results of batch-type drying to be drawn. Findings of measurements conducted in the 1990s of three-belt drying of different hop-varieties with subsequent conditioning of the moisture content were summarized by Heindl. The temperature of the inlet air during the trials ranged between 80–90°C for the upper belt (fresh hops) and was approx. 65°C for the lower belt (dry hops). The importance of an effective turning of the cones on the upper belt was highlighted in order to avoid quality-damaging product temperatures.

Based on studies of variation in hops quality performed on a three-belt dryer, Mejzr & Hanousek emphasized the need for optimization measures to minimize overdrying and energy requirements. The statement was confirmed by measurements of three-belt dryers of similar design. At drying temperatures of 55–60°C, hops were considerably overdried (moisture content 4–8%). The final moisture content (8–10%) was adjusted by subsequent conditioning. In practice, this mode of operation is intentional, working as prevention against the irregular occurrence of nests of moist hops. This conditioning, however, does not include targeted turning of the hop cones except for the turning that occurs during the transfer to the conditioning chamber. Overdrying was also observed in measurements performed on another
three-belt dryer by the same research group. During trials with a drying temperature of approx. 66 °C, hops were almost dry (10 ± 2.0% of moisture) already at the end of the second belt. Excessive drying leads to cone disintegration, which makes any further treatment of the hops difficult and results in greater losses of lupulin.\cite{14} The significantly higher drying rates of bracts compared to strigs, already known from batch-type drying, could be corroborated by measurements performed during continuous drying, as well.\cite{15}

The recent research efforts by the Czech research group led to installation of two double-arm rotors located above the first belt of the dryer to loosen up the drying hops. This improvement measure had a positive effect on the drying rate and also on the consumption of light fuel oil (LFO). Based on long-term monitoring, an average fuel saving of 13% was reported. Without rotors (2011-2014), annual fuel consumption was on an average 494 liters of LFO per ton of dry hops. By contrast, the average fuel consumption with rotors (2015-2017) was 431 l/t.\cite{17} The use of rotors should also reduce the risk of nests of moist hops and thus contribute to achieving improved product quality. It was concluded that reducing the drying duration and avoiding overdrying in combination with optimized conditioning of the hops can lead to significantly lower energy costs and higher product quality.\cite{43}

Regarding energy consumption, it is noteworthy that due to the high moisture content, the drying of freshly harvested hops is very energy-intensive and causes correspondingly high emissions of greenhouse gases (GHG). A GHG assessment of typical hop growing in Bavaria showed that the fossil fuels used for the electric power consumption as well as the drying are responsible for the highest portion of the total emissions (36% in the variety average). When the emissions resulting from the machinery manufacture, diesel production and diesel combustion are added to this 36%, the total goes up to 54% on an average. By contrast, the supply of nutrients to the hops through fertilization including the mineral fertilizer manufacture and utilization of shredded hop vines as organic fertilizer comprise 28–29% of the total emissions of the production process, while machinery manufacture excluding the working of the machinery contributes up to 4% of the overall emission.\cite{44}

Hauser & Shellhammer\cite{45} estimated the carbon dioxide emissions of hops production in the U.S. Pacific Northwest, where the vast majority of American hops were grown in 2017. The estimations focused on the states of Washington and Oregon, owing to data availability. It was reported that kilning (drying) and agricultural machinery tended to make up a larger proportion of the carbon footprint relative to pesticides and fertilizer. The contribution resulting from the agricultural machinery stemmed only from working the machinery and no manufacturing emissions were included in the calculation. As the most significant contributor, drying alone reportedly accounted for 31–48% of the total carbon emissions from hops production. These figures are similar to those estimated in Germany and establish the fact that drying proves to be the most energy-intensive stage of hops production.

**Modeling and simulation**

When it comes to modeling and simulation of hops drying, determination of the drying kinetics, equilibrium moisture content and the change in physical properties such as bulk density are considered as key components.

Drying curves obtained under controlled experimental conditions are an important basis for developing the drying model which is used to predict the specific drying kinetics of the material to be dried. In a very systematic work, Zeisig\cite{41} described numerous drying curves for hop layers with a thickness of 30 cm. For this purpose, he used a specially developed experimental dryer with variation of the temperature (60–120 °C) and the velocity (0.28–1.27 m/s) of the drying air. To the best of authors’ knowledge, more recent studies of comparable scope are not available in the literature.

The review of the available literature also revealed a similar scarcity of studies relating to the change of physicochemical properties of hops during drying. In-situ study of the behavior of hops bulk during drying revealed that the layer height of hops decreases in the course of drying by about a third.\cite{29} The mass and length of hop cones vary depending on the hops species, during the growing season and also from year to year.\cite{46} Very few studies have delved into the investigations regarding the density or bulk density of hop cones at different moisture contents, although it is an important parameter for harvesting, processing and storage.\cite{47} Roberts\cite{48} reported the bulk density of hops bales in the range of 100–150 kg/m³. One study investigated the relationships between the dielectric properties of bulk hops and bulk density. However the investigations were limited to freshly harvested and subsequently compressed cones, as opposed to investigating those during drying.\cite{49} With regards to
hops quality, for example, investigations of a pilot scale drying system revealed that color changes depended strongly on the bulk weight and resulting bulk thickness. The research demonstrated that the specific mass flow rate of drying air plays a critical role in determining the quality of the final product, as well as the processing time required. They also reported the bulk densities of the fresh samples which varied from 153.9 kg/m³ to 174 kg/m³. Münsterer investigated the bulk heights of hops at an identical bulk weight (26.56 kg/m²) and reported the data for different types of hops at different moisture contents of the freshly harvested samples. They found that the bulk heights are markedly dependent on the hops type. The determined bulk heights ranged roughly between 18 and 30 cm. The reported data translates to bulk densities varying between 88 kg/m³ and 147 kg/m³. Alongside the fresh hops, bulk densities of dry hops were also reported in a recent study by Ziegler & Teodorov which investigated the pressure loss through hops bulks. They reported the bulk densities of two different types of fresh and dried hops ranging from 80.9 kg/m³ (when fresh at 78.9% moisture) to 102.6 kg/m³ (when fresh at 78.6% moisture) and from 23.0 kg/m³ (when dry at 11.8% moisture) to 27.2 kg/m³ (when dry at 10.9% moisture) respectively. These studies have clearly established that the bulk density may vary quite a bit depending on the hops type and the initial moisture content affected by the weather at harvest (sunny, morning dew and rain) and obviously the final moisture content (when dried). However, none of the abovementioned studies have reported the continuous change of the bulk density in the complete course of drying. To fill the gap in the knowledge, more research is required to consider the optimum bulk and process parameters, to optimize the hop drying process and to improve process efficiency as well product quality.

As for the modeling of the drying equipment, one of the first mathematical models suitable for the design and process analysis of conveyor-belt dryers was developed by Kiranoudis et al. and applied to convective drying of raw or sliced potato. Results of measurements performed on laboratory or industrial scale are often integrated in belt dryer models for different products, for example residual or sewage sludge, yellow corn grains, pecrite, forage grass seeds, leaves and twigs of yerba mate, wood chips and other biomass, olive leaves, apple slices, fish feed pellets, small particles of potatoes, alfalfa, Chlorella microalgae, Eugenia uniflora L. leaves, or cellulosic fiber. Conveyor-belt dryers may also be an option for the drying of cannabis in the future. However, there is also a need to study the diffusivity and mass transfer characteristics in cannabis, which plays an important role in choosing the appropriate drying technology. Several publications investigating single-pass conveyor-belt dryers set the focus on achieving improved energy efficiency. To the best of authors knowledge, no modeling studies focused on hops drying was conducted.

A number of simulation studies can be found in the literature that addressed various issues regarding control of a conveyor-belt dryer. Due to their spatial dimensions, conveyor-belt dryers are difficult to control, as fluctuations occurring at the inlet of the dryer, for example variations in inlet moisture content of the solids, are only detected at the outlet after a considerable time lag. This information delay may significantly affect the dryer performance, since the response time is inevitably high. Kiranoudis et al. analyzed the dynamic behavior and control of an industrial conveyor-belt dryer for wet raisins based on a detailed model of the process. The single-pass dryer consisted of three drying chambers and a cooling section, while the same conveyor-belt passed through all sections. The study recommended the use of feedback controllers for each of the individual chambers. Further simulation results showed that both material moisture content and material temperature can be controlled by adjusting the heat supply and the fresh air flowrate at the drying chambers. Another feedback control strategy was investigated for the case of conveyor-belt drying of mate leaves. In this study, the belt velocity was adjusted in order to maintain the discharge moisture content in an acceptable range. Similar objectives were pursued for continuous drying of paddy grains by means of a simplified neuro-fuzzy controller. However, it must be emphasized that only single-pass conveyor-belt dryers were investigated in the publications mentioned above.

In multiple-pass dryers, the individual conveyer-belts are arranged one above the other and run in opposite directions on every adjacent level. This arrangement requires a much smaller space than the multi-stage dryer configuration with several single-pass dryers arranged in series. Although multiple-pass dryers are found in many industries, there are relatively few scientific publications focusing on this particular type of equipment. Sebastian et al. developed a numerical model of conveyor-belt drying based on heat and mass transfer correlations. However, the analysis was limited to multiple-belt
dryers working in counterflow and parallel-flow. Khankari & Patankar\cite{58} investigated convention drying and demonstrated the use of computational fluid dynamics (CFD) techniques for the simulation and analysis of a double-deck conveyor dryer for corn. They could perform detailed and systematic analysis such as variations in the product moisture content and temperature across the entire belt as well as the bed height to evaluate the performance of the dryer. They highlighted how such numerical experiments can be carried out resource-efficiently in contrast to field experiments to improve the product quality as well as dryer performance. In another similar work, using the finite volume method to solve the governing conservation equations, de Farias et al.\cite{58} developed a numerical model for continuous cross-flow drying of yellow corn grain which was expanded and adapted to multiple-pass drying of silkworm cocoons.\cite{96} They have reportedly achieved a good agreement between the simulation and experimental results and thus using their model they could conduct detailed sensitivity analysis to understand the effect of various process parameters on the drying performance as well as on the products. They concluded that such approaches can be useful to researchers to optimize similar dryers.

In terms of using the CFD technique to study the conveyor-belt dryers, it was found that the most common focus of the studies was on homogenizing the air flow distribution. Uneven air distribution in drying chambers often results in inefficient drying and non-uniform moisture content of the products. One of the first analyses of multiple-pass dryers using commercial CFD software (FLUENT) investigated the drying of garlic slices.\cite{97} After having established a good agreement between the prediction and experimental data they reported a poor efficiency of drying air utilization and inhomogeneous air distribution. They also showed the potential of CFD analysis to achieve optimum air flow arrangements. Measurements on an industrial five-belt dryer for spice plants first showed large differences in the moisture content across the belt width.\cite{98} In order to reduce the negative effects of lateral uneven air supply, the dryer was then analyzed using FLUENT, as well.\cite{99} Simulation results led to the addition of roof-shaped air guiding plates below the first (upper) belt. Since a larger proportion of the inlet air was now directed to the middle of the belt, the distribution of the product moisture was found to be more uniform over the belt width.\cite{100} Furthermore, CFD analyses of different belt dryer configurations for extruded feed showed that the arrangement of the individual belts and the thickness of the feed layer significantly affect the distribution of air flow in the drying chamber.\cite{101,102} The authors concluded that experimental verifications are required in order to further investigate these complicated structures of dryers. Recently, the research group analyzed the airflow distribution inside a newly designed two-belt dryer.\cite{103} Nine anemometers were placed above the feed layer of the dryer. The measurements showed good agreement between the experimental and simulation results of airflow velocities. The study demonstrated that the design of belt dryers can be significantly improved with the help of CFD techniques.

It can be seen that conveyor-belt dryers are widely used in Europe, but their operation is carried out largely based on the experience of their operators. Only a few research works have studied modeling, simulation and control of multiple-pass dryers. Therefore, there is a considerable demand for the collection of in-situ data of industrial drying operations, the development of accurate models including those for CFD environment as well as the identification and realization of optimization measures to reduce energy consumption and improve product quality.

**Material and methods**

In this section, we present the methodology and details of the trials conducted in an industrial drying plant to identify the bottlenecks in hops drying.

**Description of the drying plant**

A conveyor-belt dryer which is specially designed for drying hops was investigated in this study. The dryer consisting of three conveyor-belts is also known as type PCHB-750. A simplified 3D view of the dryer is shown in Figure 1. The base area is 72 m², while the external height, length and width of the dryer are 4.2 m, 22.5 m and 3.2 m respectively. With a belt width of 3.0 m, the total drying area amounts to approx. 155 m². The supply air ducts and the wall on the right side of the dryer are thermally insulated, unlike the outlet air ducts, the ceiling and the wall on the left side of the dryer that have no insulation.

The freshly harvested hops are introduced directly in the feed system of the belt dryer (not shown here). A feed belt conveys the material to be dried onto the top belt (belt 1), whilst a roller ensures a uniform layer thickness. When the material reaches the end of each belt, it falls onto the next belt running underneath, which conveys the material in the opposite
direction. The total residence time of the hops to be dried can be variably adjusted in the range between 2 to 12 hours. The choice of belt speeds and thus the layer thicknesses depend on several parameters such as moisture content as well as the type and composition of the fresh hops, temperature and relative humidity of the fresh air, desired final moisture content of the dry hops, and set inlet temperature of the drying air. Considering all the factors that are impacted, typical residence times of around 5 to 6.5 hours have been recommended.\textsuperscript{[104]} Three glass inspection windows located above each dryer belt facilitates monitoring and control.

In order to help the readers better appreciate the entire system and put the dryer in perspective of the entire setup, Figure 2 shows a simplified block flow diagram (BFD) of the production process. As can be seen from the BFD, immediately after drying, the hops are first transferred to two additional belts in a continuous conditioning system. Subsequently, in order to achieve a further homogenization of retained moisture, the hop cones are stored in stationary ventilation chambers for a few hours. Then these are pressed and packed in bales. The two conditioning belts as well as the ventilation chambers are operated with humidified outlet air from the dryer. The required heat for the dryer is generated by means of an automated oil-fired heating system located in an adjoining room. The inlet temperature of the drying air is measured continuously and controlled by manipulating the burner output. The entire drying air is sucked in by a radial air blower located in the adjoining room and heated to the required inlet temperature in the heat exchanger of the oil-fired boiler. An air splitter placed in the central supply air duct can divide the total air stream into two separate air streams. One of these air streams is introduced under the lower belt 3 at the front side of the dryer. The remaining air stream passes through air ducts on the right side of the dryer (seen from the inlet side) and is fed under belts 2 and 3. The outlet air from the dryer is extracted through six outlet air hoods and combined in a central outlet air duct. A second radial

\textbf{Figure 1.} A simplified 3D sketch of the investigated conveyor-belt dryer (PCHB-750) for hops.

\textbf{Figure 2.} Simplified block flow diagram of the production process.
air blower situated in the adjoining room sucks the total air stream out of the outlet air duct. There are manually adjustable air valves in each of the six outlet air hoods. These facilitate adjusting the air distribution over the length of the dryer. The entire outlet air from the dryer is currently discarded and thus a partial recycle of the outlet air is not available.

Previous works published by the authors\cite{105,106} with regards to drying of medicinal and spice plants have clearly shown that recycling of the exhaust moist air is a complex task and requires consideration of several points. In order to maintain a sufficiently high drying potential of the air and to achieve high drying efficiency, the moisture content of both the exhaust air as well as the continuously changing weather-dependent fresh air must be considered to determine the optimum mixing ratio of these two streams. Additionally, improper mixing may lead to even more pronounced inhomogeneous drying of the product. Hence, in order to implement a successful and optimum air recycling, proper instrumentations as well as an intelligent automatic control system is necessary. The investigated dryer in this work did not have any of these elements nor the engineering constructions enabling such recycle, which is why the recycle is currently unavailable.

Before the production begins, the belt speeds are set depending on the specific type of hops to be dried and then usually not changed during the course of drying. The belt speeds are set essentially based on the experience of the plant operator. While the speeds of belts 1 and 2 can be selected independent of each other within certain ranges, the belt 3 is coupled with belt 2 via a worm gear. As a result, the speed of belt 3 amounts to two thirds of the speed of belt 2.

The drying system is operated via a touch panel on which the key measured values and operating parameters of the programmable logic controller (PLC) are shown. The throughput is regulated by monitoring the relative humidity of the outlet air. The humidity sensor feeding back to the control loop is located in the outlet air hood 1. The operating approach governing the control of the dryer starts by specifying a certain setpoint for the outlet air humidity at the beginning of the drying process, whilst the speed of the feed belt is continuously manipulated based on the actual humidity reading. If the target value is not reached, the throughput is automatically increased and vice versa. It is noteworthy that the associated measured humidity value is strongly influenced by the entrained air infiltrating the dryer on the feed belt (see Figure 1). As a result, drying is carried out under strongly fluctuating operating conditions eventually leading to frequent interruptions. This leads to a high maintenance demand including the need to regularly monitor and frequently intervene by manual adjustment of the setpoint for regulating the throughput. The two radial air blowers are equipped with frequency inverters that enable the speed of the AC motors of the blowers to be controlled. However, the flow rates of the inlet and outlet air streams are not continuously controlled. Instead these are manually set and manipulated by the operator. Such a manual operation is naturally cumbersome. This can be eased and the performance of the dryer can be optimized by developing an automatic control system that incorporates the insights obtained from the experiences of the operator.

**Measurement and calculation methodology**

The measurements for obtaining the status quo of the investigated dryer were carried out on a three-belt convection dryer located in Schrebitz, Saxony, Germany during the time period from 2 to 13 September 2019. Capacitive temperature and humidity sensors (Ahlborn Mess- und Regelungstechnik GmbH, Germany) were employed to perform the measurements. The sensors (model FHAD46C43AL10) have a measurement range for temperatures between $-40^\circ C$ and $85^\circ C$ and relative humidities between 5% and 98%. The measured data were recorded on two data- loggers of the model Ahlborn 5690 and Ahlborn 2890-9, respectively (Ahlborn Mess- und Regelungstechnik GmbH, Germany). The air conditions at the following locations in the dryer system were continuously recorded each minute for the entire duration of the measurements: (a) the fresh air outside the hall, (b) the inlet air immediately prior to the inlet air blower, (c) the inlet air in the supply air duct immediately prior to the dryer inlet, (d) the air in the six outlet air hoods above belt 1, and (e) the outlet air after the outlet air blower. The conditions of (a) and (d) were measured with one sensor each, while two sensors were employed for each of the locations (b), (c) and (e). For the analyses, mean values were used for the air conditions measured by two sensors. The reason why two sensors were used was simply to be able to capture any potential local variations and thus be more confident about the measured data. Fresh air was an exception to this, as the measurement sensor was positioned outside the hall in a protected place, and thus it was fairly unlikely for the measurements to be affected by any undesired source of error. This
is why the single sensor measurements were deemed sufficient. The other exception was the points in the outlet air hoods, where negligible local variation was anticipated due to the relatively small dimensions of the individual duct.

The mass flow rate of air \( m_A \) could not be measured directly and was therefore determined based on a simplified energy balance around the boiler:

\[
\dot{m}_A (h_{in} - h_{amb}) = \eta_B \dot{m}_F \Delta h_F
\]

where \( h_{in} \) and \( h_{amb} \) represent the specific enthalpy of the dryer inlet and ambient air, respectively. The fuel mass flow rate \( \dot{m}_F \) (consumption of light heating oil) was read on the oil meter and the thermal efficiency \( \eta_B \) was estimated to be 92%, which includes the occurring heat loss to the environment. The estimation of the thermal efficiency was based on several experimental observations and corresponding energy balances around the heating system. Hence, the used value of 92% is specific to the heating system that was under investigation in this work. The lower heating value of the fuel \( D \) was assumed to be 42.6 MJ/kg (10 kWh/litre). The air flow rate was assumed to be constant over time. The moisture extraction rate \( MER \) and the specific thermal energy consumption \( STC \) were calculated as follows:

\[
MER = \frac{\dot{m}_A (Y_{out} - Y_{in})}{\eta_B \dot{m}_F \Delta h_F}
\]

\[
STC = \frac{1}{\eta_B} \frac{\dot{m}_F (h_{in} - h_{amb})}{(Y_{out} - Y_{in})}
\]

where \( Y_{out} \) and \( Y_{in} \) denote the humidity ratio of the dryer outlet and inlet air, respectively. The measured values and calculated quantities described so far allow a continuous air-side assessment of the investigated dryer. The material throughput \( \dot{m}_H \), which could not be measured directly, was calculated with the aid of the material moisture content and the \( MER \) determined on the air side as shown in Equation (4):

\[
\dot{m}_H (X_{in} - X_{out}) = MER
\]

with \( X_{in} \) and \( X_{out} \) representing the moisture content d.b. (dry basis) of the fresh and dried hops, respectively. In order to determine the required moisture content of hops, several hops samples were taken at the inlet and outlet of the dryer. At least three samples were collected and investigated to determine the representative moisture content at each position. Each of the samples had a mass of approx. 50 g dry substance. The moisture contents of the samples (fresh hops and dry hops) were then determined by drying in a drying oven (Memmert GmbH, Germany) for 24 h under 105°C. The moisture contents are given in Table 1.

In addition, mobile temperature data loggers were used to analyze the temporal and local temperature during the drying process. For this purpose, at the beginning of belt 1, several data loggers were placed on top of the hops and allowed to run through the dryer along with the product. The datalogger, model UP330A (UNI-TREND, Germany), has a precision of ±0.5 K in the operating range from −40°C to 80°C. The dimensions of the employed mobile temperature sensors are 120 × 32 x 23 mm (length x width x height). The data loggers were placed on both sides near the walls. The distances between the data loggers in the direction of the belt movement were approx. 80 cm, and the distances to the outer walls were approx. 50 cm. At the end of belt 1 there is a flap that extends across the entire width of the dryer. Through this flap, the data loggers could be manually removed from belt 1 and immediately placed back on belt 2 with little effort. This ensured that the data loggers were not buried under the hop pile. The same procedure was followed at the end of belt 2 for the placement of the data loggers on belt 3. Here, the inspection windows were used to remove and replace the data loggers. Additionally, numerous hops samples were taken through the inspection windows from both sides of the dryer during operation. The moisture content was then determined in a drying oven following the same procedure described above.

### Results and discussion

As already mentioned, the continuous operation was interrupted several times during the measurement period. Nevertheless, in order to be able to determine the status quo of the hops dryer, a representative period of operation had to be selected. Upon investigation of the recorded data, a typical period of 36 hours was selected. To improve the presentation of the strongly fluctuating air conditions, moving averages over 19 minutes were calculated.

### Table 1. Overview of the key parameters related to the investigated hops drying trials.

| Parameter                  | Value   | Remarks                  |
|----------------------------|---------|--------------------------|
| Hop-variety                | Saaz    |                          |
| Period of measurement      | 5–6 Sep | 6 a.m. – 6 a.m. (24 h)   |
| Drying temperature (°C)    | 69.6    | average of dryer inlet air |
| Moisture contents          |         |                          |
| Green hops (%)             | 79.2    |                          |
| Dry hops (%)               | 11.3    | before conditioning      |
| Drying ratio (–)           | 4.26    | fresh mass / dry mass    |
| Parameter value            | Remarks                  |
| Moisture content           |            |                          |
| Green hops (%)             | 79.2%    |                          |
| Dry hops (%)               | 11.3%    |                          |
| Drying ratio (–)           | 4.26%    |                          |
Analysis of the drying process by means of air side measurements

Figure 3 (left) shows the temperature history of the fresh air, the inlet air to the blower, the supply air in the collecting duct prior to the dryer inlet, and the outlet air after the outlet air blower. During the measurement period shown, the temperature of the fresh air was between approx. 10°C (at night) and approx. 20°C (during the day), the temperature of the inlet air was approx. 17–24°C. The temperature of the inlet air was elevated due to the heat lost from the oil-fired heater. The temperature of the inlet air fluctuated around 70°C, while that of the outlet air fluctuated roughly in a range of 35–40°C. The corresponding history of relative humidities is shown in Figure 3 (right). In this presentation, the fluctuations in the relative humidity of the outlet air must be particularly noted, since these led to the unsteady regulation of the throughput according to the implemented control scheme.

In order to better understand the dryer operation, the temperatures and relative humidities measured in the six outlet air hoods were analyzed next (Figure 4). The strong fluctuations in the measured values are evident in these graphs as well. The record of major interruptions can also be seen, for instance, at 6:00 p.m., the operation was stopped for about an hour, as the moisture content of the hop cones at the dryer outlet was found to be too high. The heating was not turned off during this interruption which was reflected by the persisting high temperatures of the inlet air (see Figure 3, left). The operation was continued after an hour. During the night and in the early morning hours, the relative humidity of the outlet air continued to rise. Hence, the drying had to be interrupted again at around 10:00 a.m. This time, the heating was switched off alongside the belts.

Figure 3. Temperatures (a) and relative humidities (b) during belt drying of hops.

Figure 4. Temperatures (a) and relative humidities (b) of outlet air, measured in the six outlet air hoods.
One of the main reasons for the unstable throughput control can be deduced from the humidity ratios in the six outlet air hoods shown in Figure 5 (left). As mentioned earlier, the throughput is controlled by monitoring the relative humidity of the outlet air under the hood 1. Owing to the pronounced fluctuations of the humidity value, the throughput control could not be stabilized. From the recorded humidities, it can also be seen that the humidity of the air under outlet air hoods 2–7 progressively decreased. This consistent decrease along the length of the dryer can be attributed to the fact that significantly less water can be evaporated from relatively drier hop cones in the rear area of the dryer, when compared to relatively moist and fresh cones shortly after the material is fed.

Hence, the humidity under outlet air hood 1 is expected to show the highest value. Interestingly, the measurements were contrary to this expectation. This anomaly was attributed to the entrained ambient air that was sucked into the dryer above the feed belt. It is noteworthy that the dryer is situated in a hall and the ambient air comes from the close surroundings of the dryer and must not be mistaken as the fresh outside ambient air. Thus, the entrained air with considerably lower humidity infiltrated the dryer and mixed with the actual moist outlet air, ultimately leading to a humidity that was the lowest of all outlet air readings.

The values measured under hood 1, therefore, do not correspond to the actual condition of the outlet air at this point of the dryer. The specific enthalpies presented in Figure 5 (right) provide additional evidence to the occurrence of undesired mixing. While the values under hoods 2–6 were comparatively close to one another, the specific enthalpy under hood 1 decreased significantly due to the mixing of the two air streams. The actual drying process at steady state generally runs at an approximately constant specific enthalpy, which is accordingly reflected by the humidity history recorded under outlet hoods 2 and 3. The slightly smaller values under hoods 4–6 are due to the heat loss from the dryer.

Figure 6 shows representative air conditions of different locations of the dryer in the Mollier h,Y-chart for moist air. The points shown represent mean values over a period of two hours (4:00 pm – 6:00 pm). The progression of drying (outlet air 2–6) is manifested by the continuous shifting of the outlet point toward the lower humidity region (to the left) along the line of nearly constant enthalpy. The point 1 highlighted in red in Figure 6 represents the air conditions measured for the outlet air under outlet air hood 1. The deviation of the air condition under outlet air hood 1 can be clearly seen, as the point 1 lies in the region between the ambient air and the expected outlet air. The slightly closer proximity of point 1 to the ambient air suggests that the proportion of the entrained air in the mixture at this point in time amounted to over 50%. Consequently, the regulation of the throughput was strongly influenced by the infiltrating air.
It is well known that for higher humidity of the inlet air, the drying process shifts to the right in the Mollier h,Y-chart. If more humid inlet air occurs due to any other reason, for example due to the naturally fluctuating humidity of the fresh air, the problem of an unsteady control of the throughput will persist. Even if the influence of the entrained air is reduced or another measurement location for the control sensor is selected, the issue will most likely remain, though to a lesser extent. In order to reduce the adverse effects of the air-side monitors on the throughput control, the humidity of the inlet air should be homogenized across the course of the operation. This could be achieved through the introduction of controlled and partial recirculation of the outlet air, since the recirculated portion of the outlet air would help buffer the undesired fluctuations of the inlet air humidity and thus the sensitivity of the throughput control.

The history of the moisture extraction rate (MER) and the specific thermal energy consumption (STC) are shown in Figure 7. The mass and heat balances as described in Equation (1–4) were based on a volume flow of the inlet air of 52,000 m³/h. Apart from the two interruptions, the average MER was approx. 600–700 kg/h, whilst the STC amounted to approx. 4.5–5.5 MJ/kg of evaporated water. Average values were calculated over 24 hours for the most important operation data of the dryer (6:00 a.m. – 6:00 a.m.). The key results are summarized in Table 2.

### Table 2. Results of mass and energy balances (averaged values over 24 h).

| Parameter                  | Value | Remarks               |
|----------------------------|-------|-----------------------|
| **Humidity ratios**        |       |                       |
| Inlet air (g/kg)           | 7.4   |                       |
| Outlet air (g/kg)          | 18.0  | outlet air – inlet air|
| Difference \( \Delta Y \) (g/kg) | 10.5  | outlet air – inlet air|
| **Mass flow rates**        |       |                       |
| Drying air (kg/s)          | 16.9  | blower inlet: 52,000 m³/h |
| MER (kg/h)                 | 644   |                       |
| Green hops (kg/h)          | 838   |                       |
| Dry hops (kg/h)            | 194   |                       |
| **Energy consumption**     |       |                       |
| Light heating oil (l/h)    | 92.1  | lower heating value: 10 kWh/litre |
| Fuel input (kW)            | 921   |                       |
| Heat output (kW)           | 847   | thermal efficiency: 92% |
| STC (MJ/kg)                | 5.15  |                       |

### Analysis of drying history

In addition to the air-side analysis, measurements of the drying history were carried out by determining a representative temperature and moisture profile of the material as it runs through the dryer. The history of the measured temperatures is shown in Figure 8. These are the mean values obtained from the measurements recorded by the three data loggers on each side of the dryer. The dead time in terms of measurement of approx. 23 minutes can be clearly seen in Figure 8 and was considered in the analysis of the data.

The temperatures measured with the data loggers placed on belt 2 and belt 3 showed a consistent bias. The temperature was significantly higher on the left side than that measured on the right side. On belt 3, the temperature difference amounted to approx. 12–13 K. This indicates that the hops dried significantly faster on the left side of the dryer than on the right side. The moisture contents of the collected hops samples confirmed the inhomogeneous drying. All moisture contents summarized in Table 3 represent mean values from three moisture content measurements for each case. It can be seen that the hop cones on belt 1 were already drier on the left side than those on the right side. On belt 2 and up to about the middle of belt 3, there were considerable differences in the moisture content. The differences in the moisture
content decreased somewhat by the end of belt 3. This can be attributed to the fact that the drying rate significantly decreases the hop cones approach to the equilibrium moisture content. Toward the end of belt 3, the already drier hop cones on the left side were subjected to a lower drying rate than the less dry hop cones on the right side. Hence, the difference in moisture content could be somewhat decreased.

In conclusion, the measurements show a considerably uneven drying process across the width of the belt dryer examined. This finding contradicts previously published measurements on a belt dryer of the same type PCHB-750. It is noteworthy that the data loggers in that study were placed more toward the middle of the belts, and thus were recording conditions of regions that were about 1 m away from the outer walls of the dryer. Due to this, the drying behavior across the belt width could not be discerned from their report and compared with the measurements conducted in this study. The findings obtained from the present study, however, indicate that the problem of inhomogeneous drying is very much existent. It is unclear at the moment whether or not this problem is widespread, although our personal communications with the operators of hops drying plants in Germany suggest that the occurrence is very likely common. Nevertheless, more experimental data are required to make that determination with certainty.

### Conclusion and future work

In this article, we have endeavored to establish the key areas of hops drying that need further research attention. To this end, a comprehensive review of the published literature was presented at first. It was found that the majority of the scientific publications on hops drying are experimental studies that focus on quality aspects and process analyses. In particular, the influence of the drying temperature on different quality parameters of hops was examined by several researchers. Temperatures well below 65°C have been proposed, in order to maximize the content of valuable ingredients in contrast to the widespread industrial practice. In general, the content of valuable ingredients decreases with an increase in drying temperature. On the other hand, the specific energy requirement of drying is inversely proportional to the applied drying temperature, as higher throughput can be achieved at higher temperatures. Considering the contrasting effect of temperature on the quality and energy-use efficiency, in order to achieve an optimum operation in terms of hops quality and throughput, drying temperatures between 62–65°C are generally recommended.

With regards to the current industrial practice, it was established that the widely used multiple-pass dryers are run largely based on the personal experience of the respective plant operators rather than on a systematic approach. After drying, there are often large differences between the moisture contents of individual cones. This can be largely attributed to an uneven distribution and poor utilization of the air flow inside of the dryer. Overdrying is another common problem that negatively affects product quality.

In order to achieve further insight into a current representative industrial practice, in the second part of the study, measurements on an industrial three-belt dryer were conducted and the data were further analyzed. This enabled the bottlenecks in existing industrial practice to be better understood. The most important findings obtained from the experiments can be summarized as follows:

- The measurements showed strong fluctuations in the exhaust air conditions as well as in the drying performance. The control system employed in the investigated dryer performed poorly. This often led to interruptions in the continuous operation for several hours.
- The main reason behind the fluctuations in the air temperature and humidity was identified to be the unoptimized process control. The process control currently employed was fairly sensitive and was strongly affected by the fluctuating humidity of the fresh air as well as the entrained ambient air.
- Temperature profiles measured with mobile data loggers as well as the measured moisture contents of hops samples revealed markedly uneven drying across the width of the belt dryer examined. The hop cones on the left were dried much faster than those lying on the right side of the belts.

| Table 3. Moisture contents of hop cones during conveyor-belt drying (average values from three samples each). |
| --- |
| Hop-variety: Saaz Green hops | Left | Middle | End | Diff. | Mean |
| Belt 1 |  |  |  |  |  |
| Middle | 70.8 | 71.8 | 71.3 |
| End | 67.7 | 68.5 | 68.1 |
| Belt 2 |  |  |  |  |  |
| Middle | 47.5 | 55.0 | 51.3 |
| End | 31.4 | 47.0 | 39.2 |
| Belt 3 |  |  |  |  |  |
| Middle | 7.3 | 18.7 | 13.0 |
| End | 8.7 | 13.8 | 11.3 |
A fairly high energy consumption reflected by the resulting STC amounting to approx. 4.5–5.5 MJ/kg of evaporated water was recorded.

Based on the findings obtained from the conducted trials, the following recommendations can be made to improve dryer performance for similar dryer setups:

- A controlled partial recirculation of the exhaust air should be implemented to better buffer the water content of the dryer inlet air. Drying with partial air recirculation would significantly contribute to stabilizing the drying process whilst reducing the energy demand for heating air.
- The entrained ambient air that gets sucked on to the feed belt should be reduced as much as possible. Alongside reducing the drying potential of the drying air, this leakage air directly influences the air humidity in outlet air hood 1, which serves as the feedback for controlling the throughput. In order to reduce the influence of the entrained air even further, the humidity in outlet air hood 2 should also be included in the control system.
- An uneven air distribution in the dryer contributes significantly to the inhomogeneous drying. In order to achieve a better air distribution across the width of the dryer, baffles could be installed to divert the supply air. Better air distribution over the length of the dryer could be achieved by optimizing the setting of the flaps in the six outlet air hoods. In achieving an overall improved air distribution throughout the dryer, CFD simulations of the air flow patterns would be immensely helpful.

While the recommendations above may help rectify a few specific issues, a holistic approach to filling the existing key knowledge gaps in the field of hops drying altogether is much required. Nowadays, mathematical modeling and numerical simulation are indispensable in application-oriented research, particularly when it comes to gaining a better understanding and thus developing new techniques or improving existing ones. However, to date, few scientific studies have been conducted on the simulation of conveyor-belt dryers for hops. Little is known about the change in important physicochemical properties of the various hop-varieties in the course of drying, for instance the bulk density of the cones at different moisture contents is a crucial parameter. Furthermore, only a few studies can be found to obtain drying curves under controlled conditions on a laboratory scale. Further work is needed to facilitate accurate modeling of the drying kinetics, particularly using computationally inexpensive approaches. While several studies focused on single-pass drying of other products, multiple-pass dryers have been rarely studied with simulation tools. This may be due to the complicated structure of the dryers, which leads to high computational demands, especially for CFD analyses.

With regards to hops drying in general, from an economic and also from an energy consumption perspective, maximum exploitation of the drying capacity during the harvesting season is a top priority. There are several possible approaches to increasing the energy efficiency of hops drying whilst improving the product quality. To this end, model-based process analysis and control offers the most promising options. This, however, requires a well-founded description of the drying kinetics, more detailed information on material properties of hops, development of more accurate mathematical models as well as smart control system, and further systematic measurements on industrial dryers.

**Nomenclature**

- $h$: specific enthalpy (J/kg dry air)
- $\Delta h_F$: lower heating value of fuel (J/kg)
- $\dot{m}$: mass flow rate (kg/s)
- MER: moisture extraction rate (kg/s)
- STC: specific thermal energy consumption (J/kg water)
- $X$: moisture content d.b. (kg/kg dry matter)
- $Y$: humidity ratio (kg/kg dry air)
- $\eta$: efficiency (–)

**Subscripts**

- $A$: air
- $amb$: ambient air
- $B$: boiler
- $F$: fuel
- $H$: hops
- $in$: dryer inlet
- $out$: dryer outlet

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