Master Thesis

Czech
Technical
University
in Prague

F2

Faculty of Mechanical Engineering
Department of Instrumentation and Control Engineering

Dynamic Modeling of Kilning Process in Matlab & Simulink Environment

Bc. Yan Shchankin

Supervisor: prof. Ing. Milan Hofreiter, CSc.
Field of study: Instrumentation and Control Engineering
August 2019

MASTER'S THESIS ASSIGNMENT

I. Personal and study details

Student's name: **Shchankin Yan** Personal ID number: **437103**

Faculty / Institute: **Faculty of Mechanical Engineering**

Department / Institute: **Department of Instrumentation and Control Engineering**

Study program: **Mechanical Engineering**

Branch of study: **Instrumentation and Control Engineering**

II. Master's thesis details

Master's thesis title in English:

Dynamic Modeling of Kilning Process in Matlab & Simulink Environment

Master's thesis title in Czech:

Dynamické modelování procesu hvozdění sladu v prostředí Matlab a Simulink

Guidelines:

1) Investigation of kilning process in an industrial malting plant
2) Setting up the existing simulation model
3) Verification of the model, comparison with measured values
4) Fan and heater dimensioning for a specific kiln
5) Optimization of the kilning process, relation between time and energy consumption

Bibliography / sources:

1) D.E. Briggs: Malts and Malting, Springer US, 1998
2) W. Kunze: Technology Brewing and Malting, VLB Berlin, 2014
3) The MathWorks, Inc.: Simulink® User's Guide, 2019

Name and workplace of master's thesis supervisor:

prof. Ing. Milan Hofreiter, CSc., U12110.3

Name and workplace of second master's thesis supervisor or consultant:

Date of master's thesis assignment: **26.04.2019** Deadline for master's thesis submission: **12.06.2019**

Assignment valid until: ______________

prof. Ing. Milan Hofreiter, CSc.
Supervisor's signature

Head of department's signature

prof. Ing. Michael Valášek, DrSc.
Dean's signature

III. Assignment receipt

The student acknowledges that the master's thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the master's thesis, the author must state the names of consultants and include a list of references.

18. 4. 2019
Date of assignment receipt

Student's signature

Acknowledgements

I would first like to thank my thesis supervisor prof. Ing. Milan Hofreiter, CSc. for his valuable advices and consultations.

I greatly appreciate the help and collaboration of my colleagues from Bühler:

I am grateful to Kilian Kessler for the opportunity to write my thesis in Bühler.

I would like to express my gratitude to Andrea Ortó for her efforts in leading me through the thesis preparation. I greatly appreciate her time, advices, assistance and helpful feedback.

Special thanks are to Soloviov Vitalii, who was always willing to help me with any questions.

I would also like to thank Sebastian Agly for providing me with necessary documentation.

Declaration

I hereby declare that I compiled this thesis independently, using only the listed resources and literature.

Yan Shchankin

In Prague, 14. August 2019

Abstract

The main aim of this work is to simulate and analyse the final phase of the malting process – kilning. For this purpose, the Simulink model of a single-deck circular kiln is used (owned by Bühler [21]). The theoretical part describes all the steps of the malt production including the equipment commonly used in a modern malt house. The kilning process is described in detail in a separate chapter. The practical part is dedicated to the simulation of the kilning process. Firstly, the thesis focuses on the model analysis, its modification and setting according to the selected real kiln. Then the model verification follows, using different kilning recipes and under different ambient conditions by comparing simulated values with measurements. The work continues with suggestions how the model can be used for the dimensioning of air heaters and fans. Finally, the practical part deals with various possibilities for reducing the thermal and electric energy consumption. Based on the simulation results, the relationship between the energy consumption and process time is described.

Keywords: kilning, malting, drying, kiln, malt, malt house, Simulink, Matlab, simulation, energy consumption

Supervisor: prof. Ing. Milan Hofreiter, CSc.
Department of Instrumentation and Control Engineering,
Technická 1902/4,
Prague 6

Abstrakt

Hlavním cílem této práce je simulace závěrečné fáze procesu sladování – hvozdění. K tomuto účelu je v práci analyzován a následně použit model jednolískového kruhového hvozdu v Simulinku (model vlastní společnost Bühler [21]). Teoretická část popisuje všechny úseky výroby sladu včetně zařízení používaného v moderní sladovně. Proces hvozdění je podrobně popsán v samostatné kapitole. Praktická část je věnována simulaci procesu hvozdění. Nejprve se práce zaměřuje na analýzu modelu, jeho modifikaci a nastavení podle vybraného skutečného hvozdu. Následuje verifikace modelu pro různé receptury hvozdění a za různých okolních podmínek porovnáním simulovaných hodnot s měřením. Práce pokračuje návrhy, jak lze model použít pro dimenzování ohřívačů vzduchu a ventilátorů. Nakonec se praktická část zabývá různými možnostmi snížení spotřeby tepelné a elektrické energie. Na základě výsledků simulace vzniká závislost mezi spotřebou energie a dobou procesu.

Klíčová slova: hvozdění, sladování, sušení, hvozd, slad, sladovna, Simulink, Matlab, simulace, spotřeba energie

Překlad názvu: Dynamické modelování procesu hvozdění sladu v prostředí Matlab a Simulink

Contents

Figures

Tables

Chapter 1

Introduction

Malt is cereal grain that has been germinated and then dried. It is one of the basic ingredients in brewing, the most common being barley malt. For various purposes and to a lesser extent, malt is also produced from wheat, sorghum, rye, oats, triticale, maize, millet, rice, etc. In addition to beer, malt is also used for the production of whiskey, vinegar, malted milkshakes, flavoured drinks, various confections or baked goods. [2], [15]

This work is focused on barley malt (Figure 1.1).

Figure 1.1: Barley malt [1]

The process of malt production is known as malting. It is a complex and lengthy technological process, so there is a separate branch in brewing concerned with malting process, its technology and special equipment.

The main aim of this work is to simulate the final phase of the malting process – malt kilning. The kilning process is highly energy and time intensive, therefore the equipment must be well dimensioned and the process efficiently controlled. Theoretically, an accurate simulation model could be used for dimensioning of a new kiln or for testing different kilning technologies. For better understanding of the specific context, the theoretical part gives an overview of the malting process in an industrial malt house with a detailed description of the kilning process and the technical equipment used.

Part I

Theoretical Part

Chapter 2

Overview of the malting process in an industrial malt house

2.1 Introduction

Recently, breweries produced malt by themselves and for own use. Nowadays, there are high-capacity malt houses (malting plants) built separately from breweries. They produce malt on a large scale all year round, store and supply it to breweries. There are many different types of equipment for malt production. In malting, a batch of malt is known as a "piece" and may be up to 400 tons in a modern malt house. [2], [4]

The aim of malting is to convert barley into malt in accordance with the technology for the particular malt type and at minimal cost. Figure 2.1 shows a general scheme of the malting process.

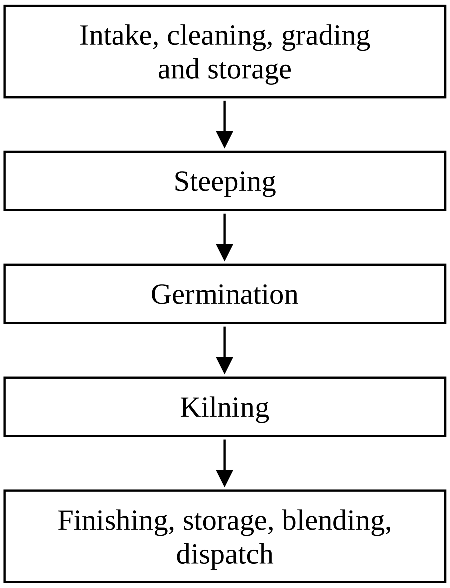


Figure 2.1: The malting process in outline

The malting process begins with steeping, during which it is necessary to ensure optimal conditions for the next step of barley germination. Important enzymes are activated and synthesized in the grain during germination. After that, the kilning process follows, when the warm air dries the malt and induces chemical reactions necessary for the taste, flavour, aroma, color and quality of the beer. Finally, the dried malt undergoes finishing, also can be blended for the higher homogeneity and then dispatched to the customer. [2], [4], [6]

2.2 Intake, cleaning, grading and storage

Barley is usually delivered from the farmer in trucks, railway wagons, tanks, barges or ships. Samples are taken from each delivery for laboratory testing. The grain is typically checked for [2], [4], [6]:

- Varietal purity
- Size distribution
- Moisture content
- Nitrogen content
- Germinative capacity
- Absence of insects, fungal growth and metabolites
- Percentage of impurities and broken grains

The received barley contains different impurities: broken grains, weed seeds, dust, clods of earth, stones, sand, loose husks, awns, straws, leaves, snail shells, wood or metal fragments. Therefore, grain must be cleaned and sorted: dust, dirt and impurities removed and grain sorted according to size and quality. The technical equipment of malt houses for this purpose includes: transport equipment (screw, chain, and belt conveyors, elevators, pneumatic systems), sampling devices, automatic weighers (scales), aspirators, cyclones, air filters, airlocks, fans, blowers, magnetic separators, de-awner, de-stoner, grain cleaners, graders, various separators, dryers and other machines and equipment. The working principle of some equipment is described below. [2], [4]

Iron or steel fragments (nails, bolts, nuts, etc.) may damage machines, tramp iron may strike sparks. This kind of impurities is removed by **magnetic separators** at various stages of malt production. Different types are used: permanent magnets, electromagnets, rotating magnetizable cylinders or belts. [2], [4]

Dust and light impurities are removed in **aspirators**, which are often built into cleaning and handling machines. In principle, a current of air flows through a falling stream of grain and takes away dust and light impurities into a cyclone separator or directly to a central dust-collection point. The dusty airstream is typically cleaned with the help of a **cyclone** with an **airlock** (a rotating valve) and an **air filter**. The air filter is periodically cleaned by a blast of reverse air. [2], [4], [6]

Occasionally, in case of high moisture of the received barley, it should be dried into special grain dryers. It is necessary for long-term storage of grain. Numerous types of machines are used for pre-cleaning, cleaning and grading of grain. [2]

Half-grains and weed seeds may be removed by a **Trieur cylinder**. It is a horizontally rotating drum with indentations or pockets on the inner side of the cylinder. The indentations (or pockets) are designed to lift only half-grains and weed seeds, then these small impurities fall into a catch trough and are carried away by a screw conveyor. Also, there are other types of cylinder and disc separators. [2], [4], [16]

The grain is typically graded and cleaned on a **sieving machine** into 3 classes, for example [4]:

- I. grade - barley grains greater than 2.5 mm
- II. grade - barley grains 2.2-2.5 mm
- Screenings - less than 2.2 mm, usually used for animal feed

Finally, the cleaned and graded barley is weighed with an **automatic scale** and stored according to its variety and size in silos, bins or flat-bed storages, which are equipped with ventilation. Traditionally, in small malt houses grain was stored in sacks or in heaps. Barley in a storage is a living organism that is influenced by the water content in the grain, temperature, damages, quality of cleaning and sorting, and the presence of insects, fungus, etc. [4], [2], [16], [17]

2.3 Steeping

Barley steeping is a very important stage in the malt production, it determines the final malt quality.

2.3.1 Process overview

The aim of steeping is to increase the moisture content of the grain from 10-15 % to 42-48 % to activate enzymes and ensure optimal conditions for germination. At the same time, the grain is washed and floating grains and light impurities are removed. The target moisture content depends on the type of malt produced: for pale malts it is 42-45 %, for dark malts it is 45-48 %. The influence of the moisture content in barley grain is described in Table 2.1. [2], [4], [6]

Moisture content	Description
8–10 %	water for the grain viability
30 %	increasing intensity of life processes
38 %	rapid germination
40–48 %	endosperm modification, activation of enzymes

Table 2.1: The influence of the moisture content in barley grain [13]

The most important factors affecting water uptake rates [4] :

- **Water temperature** – a critical factor; the warmer the water, the faster the water uptake
- **Grain size** – the larger the grain, the slower the water uptake
- **Grain structure** – given by grain varieties and climatic conditions of the year
- **Grain aeration** - the uptake of oxygen and the evolution of carbon dioxide during the process (grain respiration)

A typical steeping technology usually has 3 stages [4]:

- 1. steeping – up to 30 % of moisture content (2-6 hours under water), then a dry period follows (14-20 hours)
- 2. steeping – up to 38-40 % of moisture content (6-10 hours under water), then a dry period follows
- 3. steeping – up to 42-44 % of moisture content (4-6 hours under water), then a dry period follows (2-4 hours) or the grain with the water is discharged into a germination unit.

2.3.2 Equipment

There are numerous designs of the steeping equipment: various hopper-bottomed (conical-bottomed) vessels or flat-bottom steeps. Steeps are intended to provide enough water and air (oxygen for the grain respiration). They are mainly constructed of stainless steel, in the past they were also made of cast iron, stone or concrete. Also, modern malting plants usually have a barley washer before the steeps. [2], [4]

Barley washer

Barley washers are often installed in modern malting plants. Typically, the capacity of the device is 6 tons per hour [4]. The most common type of such equipment is the washer, where the grain is washed and lifted by an inclined screw. Dust and floating grains are removed with overflowing water. Stones and sand may be removed into a catch-trough by a small screw. The advantages of the barley washer include saving water and possibility of replacing the first stage of steeping in a steep. [2], [4]

Conical-bottomed steeps

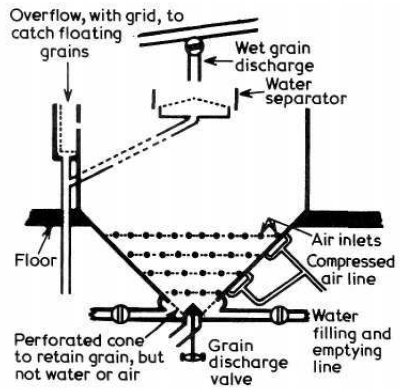


Figure 2.2: Self-empting conical steeping vessel with aeration rings [2]

A conical steep is a cylindrical steel vessel with a hopper (conical) bottom for quick self-emptying. These vessels are manufactured with a capacity of up to 50 tons of the steeping barley and a depth of up to 6 m [4]. Figure 2.2 shows a drawing of a conical steep. A modern steep may also have overhead water sprays for grain damping or vessel cleaning. Grain aeration is done by compressed air through aeration rings in the cone of the vessel. Another design is a centrally positioned air-lift tube ensuring intensive aeration and grain-water circulation. Carbon dioxide extraction (downward ventilation) is implemented by a suction fan from the base of the vessel. [2], [4], [6]

Figure 2.3: Steeping vessel - loading (MOPOS) [3]

Flat-bottomed steeps

Large flat-bottomed steeps with capacities of up to 320 tons are common in modern malt houses. They have a perforated deck and an universal device called a giracleur. The giracleur may be raised or lowered and is used for loading and discharging grain, also it typically has water sprays and cleaning sprays on it. The main disadvantages of flat-bottomed steeps are: high water consumption (under-deck space must be filled with water) and complicated cleaning of the steep. [2], [4], [6]

2.4 Germination

The aim of barley germination is to activate and synthesize enzymes in the grain and achieve the desired grain modification at minimal cost and loss.

2.4.1 Process overview

Activation and synthesis of enzymes

Activation and synthesis of new enzymes is the most important process in malting. The most significant enzymes are amylases (α-amylase, β-amylase), which later break down the starch (a source of extract for the brewers). Enzyme activation and synthesis require a sufficient amount of metabolic energy. Therefore, during steeping and at the beginning of germination, enough oxygen is needed for grain respiration. The quantity of amylases is given by the barley variety, climatic conditions of the year, the moisture content of the grain, and the technology of germination (more amylases are synthesized at lower temperatures, although higher temperatures have a beneficial effect on enzyme activity). [2], [4], [6]

During the germination process with the help of enzymes, the grain modification occurs (splitting of high-molecular substances into their by-products). Generally it lies in breaking down the cell walls, the matrix proteins and the starch granules. The by-products are consumed in a limited amount for the embryo nourishment and for the acrospire and rootlets growth (malting losses) [4], [2].

Growth of acrospire and rootlets

The growth of the chit (root sheath) at the end of the grain is the first visible sign of germination. Then the chit splits and the rootlets (culms) grow. The acrospire (coleoptile) grows under the grain husk along the dorsal side of the grain. The desired length of the acrospire depends on the malt type: for pale malts it must be from 2/3 to 3/4 of the grain length, for dark malts -

from 3/4 to the whole grain length [4]. Overgrown grains (known as a huzzar or a bolter [2]) are undesirable, because they are brittle and are consequently a source of broken grains and malt dust. [2], [4], [6]

Basic parameters that influence germination [4]:

- **Barley quality** - given by variety, climatic conditions of the year, storage, cleaning, grading and steeping conditions
- **Grain moisture content** - controlled by sprinkling the grain and by circulation of humidified and cooled air (the moisture content is typically raised to 43-45 % for Pilsner malt and to 48-50 % for dark Bavarian malt
- **Grain temperature** - controlled by turning the grain and by circulation of humidified and cooled air
- **Amount of oxygen and carbon dioxide** – controlled by turning the grain and by circulation of humidified and cooled air
- **Germination time** – usually 4-7 days

2.4.2 Equipment

Various germination units were developed, they can be divided according to different aspects [4]:

- By the type: traditional (germination floors), pneumatic (drums, boxes, towers, moving piece systems)
- By the grain movement: horizontal or vertical systems
- By the process continuity: periodic, semi-continuous or continuous systems

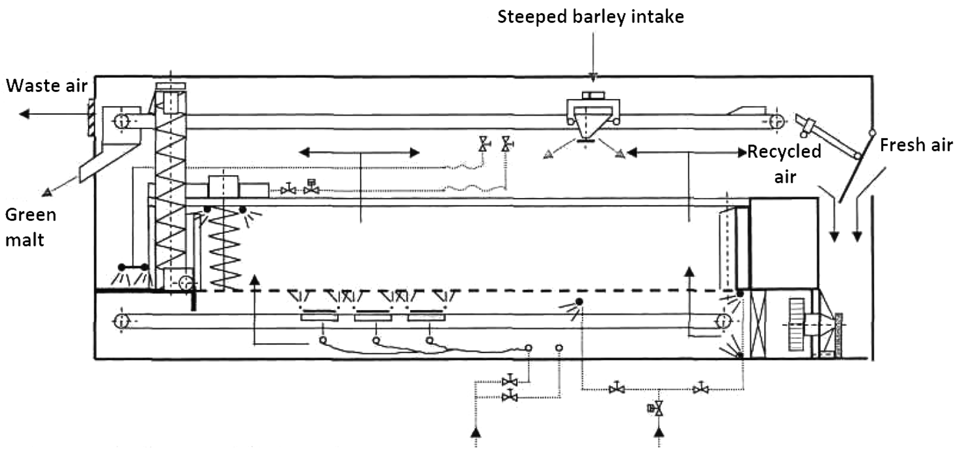
Germination floors

In traditional floor-maltings, germination is carried out on concrete or tiled floors. The humidified and cooled air is usually circulated with the help of ventilation ducts in the walls and ceilings. For barley sprinkling, there is a water supply with rose sprays under the ceiling. Some of floor-maltings have special machines, which can perform the grain moving, turning, sprinkling or even washing the floor. Despite partial process mechanization in floor-maltings, manual labor prevails and it is difficult to meet modern market demands for volume and homogeneity of malt produced. [2], [4], [6]

Germination drums

Germination drum is a horizontal or vertical steel cylinder in which germination occurs at slow and continuous rotation, thereby ensuring the mixing and turning the barley inside. The humidified and cooled air is blown into the drum by a perforated deck, cylinder or ducts and passes through the grain. Modern germination drums are high-capacity and fully automated, but energy intensive. [2], [4], [6]

Germination boxes



(own translation)

Figure 2.4: Saladin box (Seeger) [4]

Germination box is the most widely used type of the barley germination unit. To avoid grain damages during transporting and loading, the germination compartment is usually built under the steeps. Typically, it has a perforated deck with an air plenum chamber (an under-deck space for air distribution). The humidified and cooled air is blown by a fan (or fans) under the perforated deck and the air passes through the entire barley (malt) layer. Ducts and louvres allow the leaving air to be partly recirculated or to de directed to another unit. Grain loading, levelling, turning and discharging is carried out by a special rotating (moving) unit with helical screw turners and a cross screw on it. The cross screw may be raised and lowered over the deck and is used for loading, levelling and discharging. In another design, the moving helical screw is used for discharging. The unit is also equipped with sprays for sprinkling or washing. Also, the sprays can be installed under the ceiling. Germination compartments widely vary in design, they can have a rectangular or circular plan and be a part of a tower circular malt house; a typical example is Saladin box (Figure 2.4). Usually, germination box systems are automated and ensure homogeneity, high quality, and large capacity of malt produced. [2], [4], [6]

Figure 2.5: Germination circular box with un-/loader and screw turners (MOPOS) [5]

Moving piece system

A moving piece system belongs to semi-continuous malting plants. The steeped barley is loaded on one side of a long box (a street) and green malt is unloaded on the opposite side. The piece is moved along the street by a single- or double-throw turner away from the steeps towards the kiln. Ventilation of the piece is carried out similarly to the malt boxes (through a perforated base). The disadvantages are: difficult maintenance of the system, higher grain damage and worse malt homogeneity. [2], [4]

Other types

Germination may also occur in multifunction malting equipment, where two or three processes of malting (steeping, germination, kilning) are carried out in one unit. Continuous malting plants are not widely used, they are usually equipped with moving decks or belts, on which grain moves through sequential processing sections. [2], [4]

2.5 Kilning

Kilning is the final process of malt production. The aim of kilning is to convert green malt into stable and storable malt at minimal cost and loss. During kilning, the malt develops flavour, colour and aroma. Malt may be also roasted for the production of special or coloured malts. [2]

The kilning process in an industrial malting plant is described in detail in Chapter 3.

2.6 Finishing, storage, blending, dispatch

Finishing (dressing) of kilned or roasted malt includes: cooling, deculming, culms collecting, cleaning and polishing before dispatch.

Deculming

Malt culms (for barley malt, mainly rootlets) are usually removed in special deculming machines, at the same time the kilned malt is cooled. A malt deculming machine is typically a cylinder with rotating angled beaters or a modified screw conveyor. The dislodged malt rootlets, the damaged grains and husk fall through the perforated cylinder to the bottom of the machine, where they are collected by a screw conveyor. Another design of the machine is without culm separation. In that case, the culms are separated with the help of sieves. The deculming machine is also connected to an aspiration channel, so dust and other light particles are sucked into a cyclone separator. Also, the malt rootlets can be collected and removed by a screw conveyor from the plenum chamber under the kiln deck. Malt culms may be used in pharmacology (for the high content of vitamins B and E [16]) or for animal-feed production (4-6 kg of culms are obtained from 100 kg of malt [4]). [2], [4]

Malt storage

The deculmed malt is weighed with an automatic scale and stored in silos or bins (in the past, in heaps). For proper storage, malt must be well deculmed, dried and cooled. Pale malt is usually left to "mature" in a storage for 4-6 weeks before dispatch. Instead, special or coloured malts should be used soon after being produced not to lose their characteristics. For a constant quality of the malt produced and according to customer's requirements, different batches of malt may be mixed into another silo or bin using transport equipment (conveyors and elevators). [2], [4]

Dispatch

Firstly, it is necessary to remove broken grains, husk, dust and other impurities from the malt before dispatch. Cleaning is carried out by a magnetic separator, sieves and an aspirator with a cyclone. Rarely, malt is also polished with brushes. The cleaned malt is weighed and transported to loading bins, then it may be packed and shipped to the customer (or shipped in bulk). [2], [4]

Chapter 3

Kilning in an industrial malt house

3.1 Introduction

The kilning process follows after germination and, typically, it is the final stage of malt production. As mentioned earlier, the aim of kilning is to convert green malt into stable and storable malt at minimal cost and loss. During kilning, further germination is terminated and the correct malt characteristics (depending on malt type being produced) are achieved: "character", extract yield, enzyme complement, flavour, aroma and colour. [2], [4], [6]

In the past, green malt was dried on a small scale in a thin layer in the sun or in a loft (wind malts). In this work, the most attention is paid to the kilning process in modern deep-loaded kilns (especially, in a single-deck kiln). [2]

3.2 Theory of kilning

3.2.1 Moisture content

The moisture content of grain (malt) u [%] is expressed as follows:

$$u = \frac{m_{\text{wet}} - m_{\text{dry}}}{m_{\text{wet}}} \cdot 100 \tag{3.1}$$

where m_{wet} is the mass (weight) of the wet grain and m_{dry} is the mass (weight) of the dry grain. Also, a symbol χ can be used instead of u.

The moisture content of the green malt includes:

- **Bound moisture** - the moisture, which exerts an equilibrium vapour pressure lower than that of pure water at the same temperature. It is retained in the grain by capillaries and by physical or chemical adsorption.
- **Unbound moisture** - the moisture, which exerts an equilibrium vapour pressure equal to that of pure water at the same temperature. It is retained on the grain surface and in the voids between the grains.

Free moisture is the moisture content in excess of the equilibrium moisture, it consists of unbound and partly bound moisture. During drying, only free moisture is evaporated. Critical moisture content is the point, when the constant rate of drying ends and the decreasing rate begins. The amount of rootlets of the green malt is also important for the rates of drying: more rootlets allow evaporation from a large surface area. [18], [4], [2]

3.2.2 Changes during kilning

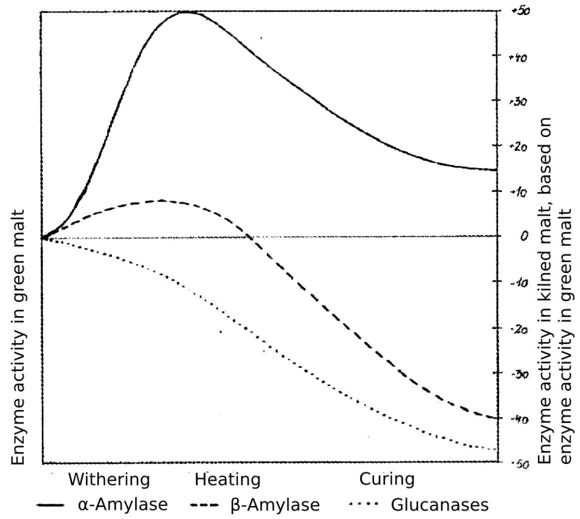
Moisture content removal. The moisture content (water content) of green malt is lowered with a current of warm air from over 40 % to less than 5 %. [4]

Termination of germination and modification. With the water removal and the rising temperatures, germination and further modification are terminated. The grain acrospires and rootlets stop their growing, breakdown processes in the grain are also stopped. [2], [4]

Enzyme inactivation and survival. Enzymes are inactivated during kilning, whether due to heat (temperatures above 60 °C [4]) or loss of moisture in the grain. Generally, enzymes are less resistant to heat at higher moisture content in the grain. Therefore, the drying process should ensure that the moisture content is removed at low temperatures of the grain (withering). For the pale malt production, enzymes survival is favoured. Dark and other special malts are dried with higher temperatures, so the final product has less sufficient enzyme content. [2], [4], [6]

Figure 3.1 shows the activity of the most significant enzymes during the kilning process of pale malt. The most stable enzyme is α-amylase. During the withering stage, the α-amylase activity increases up to 50 %. Then, it decreases during the curing stage, and the final level of the α-amylase activity is about 15 % higher than that in green malt. Also, it follows from Figure 3.1 that β-amylase is more temperature sensitive. At the end of kilning, the final β-amylase activity is about 40 % less then that in green malt. [2], [4], [6]

Formation of flavour and colour substances. During curing, melanoidins and other colour, flavour and aroma substances are formed in the grain. The formation of melanoidins is known as Maillard reactions, which occur at higher temperatures (above 90 °C) and longer exposure time. For dark malts, a high amount of Maillard products (colour and flavour compounds) is produced. In contrast, for pale malts, the formation of these compounds is avoided. Dimethyl sulphide (DMS) is a compound which can cause unwanted flavour and aroma in beer. The desirable quantity of DMS and DMS precursors can be also influenced by kilning. [2], [4], [6] [6]



(own translation)

Figure 3.1: Enzyme inactivation during the kilning process of pale malt [6]

3.2.3 Process description

Various kilning strategies are used to produce different types of malt. Generally, green malt is dried with a flow of warm or hot air passing through it. The target moisture content is less then 5 %. The process may last from 17 to 48 hours, depending on the malt type, the technology and the equipment used. [2], [4], [6]

The kilning process may be divided into 4 phases (Figure 3.2):

1. **Withering phase** - also known as initial drying, pre-drying or free drying. It is the phase with constant rate of malt drying. At this stage, the moisture content is typically reduced from 40-45 % to 10-12 % (for pale malts). It is the longest phase of the kilning process and takes about 10-12 hours in a single-deck kiln [4] (depending on the equipment used and the depth of green malt loaded). During the withering phase, a large amount (maximum possible volumetric flow rate) of incoming air (air-on) with low relative humidity goes upward through the grain and removes the unbound moisture. Firstly, the low layers of grain are dried, where the energy of dry and warm air is used for water evaporation. At this time, the upper layers are in stewing conditions and further germination of the grain occurs there. The leaving air (air-off) is saturated and is not recirculated during withering. When the unbound moisture is removed from the top layer of green malt, the withering phase ends. It is detected with decreasing relative humidity and increasing temperature of the air-off. This is a crucial moment in the kilning process, which is called the **break point**. [2], [4], [6]

   The air temperature, as well as the drying rate, affects the activity of the enzymes necessary for the particular type of malt. For pale malts,

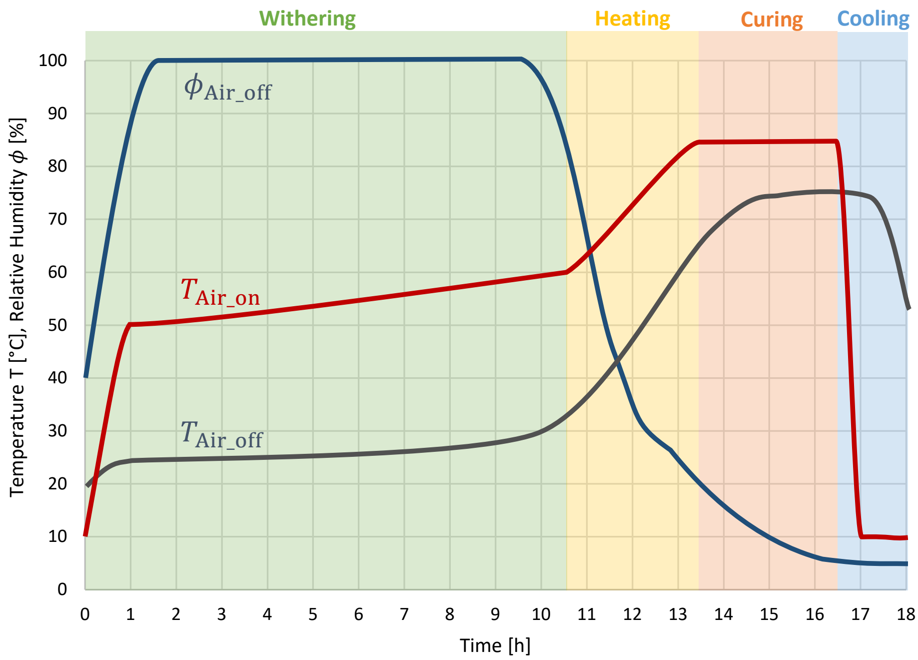


Figure 3.2: A typical kilning process in a single-deck kiln (average values for the pale malt production, based on Bühler data)

the air-on temperature at this stage is not the decisive factor (however, for the enzymes survival, it shouldn't be too high, typically 55-60 °C [4]). For dark malt, the withering stage is slower and occurs with lower temperatures, that ensures higher enzyme activity and allows the curing stage with higher temperatures to form desirable flavour and colour. [2], [4]

2. **Heating phase** - an intermediate phase between the withering and curing phases. The phase begins after the break point, which signifies, that the malt can be heated with higher temperatures for the flavour and colour formation. The heating phase typically takes 3-4 hours and the air-on temperature is increased up to the curing temperatures (given by the malt type). Since the air-off is no longer saturated, it may be partly recirculated or reused for withering in another kiln or deck. Also, the amount of air is no longer a decisive factor, therefore the fan speed (the air-on volumetric flow rate) may be reduced to 50-60 % for energy saving. [4], [19]

3. **Curing phase** - during this phase flavour, aroma and color substances are formed according to desirable malt character. The decisive factor here is the temperature of the air and the degree of grain modification. The bound moisture is removed from the grain during the curing phase and it takes about 3-5 hours. The drying rate is no longer constant and is decreasing. The target moisture content for pale malts is 3-4 %, for

dark malts 1.5-2 %. The curing temperatures for pale malts are 80-85 °C, for dark malts up to 105 °C [4]. Some of enzymes are destroyed due to high temperatures (Figure 3.1). At this stage, a large amount of the air-off may be recirculated thanks to its high temperature and low relative humidity. [2], [4], [6]

4. **Cooling phase** - after the curing phase, the malt must be cooled by a large amount of fresh air (typically, to 50-55 °C). This phase is necessary not to allow the additional malt colouring and the enzyme activity impairment, which may have an adverse effect on the taste of beer. [4]

3.2.4 Psychrometric chart for withering

Psychrometric processes of air can be graphically represented on the psychrometric chart. The idealized processes of drying air during the withering phase in a single-deck kiln with indirect heating system and glass tube heat exchanger are shown in Figure 3.3 (an example) [19]:

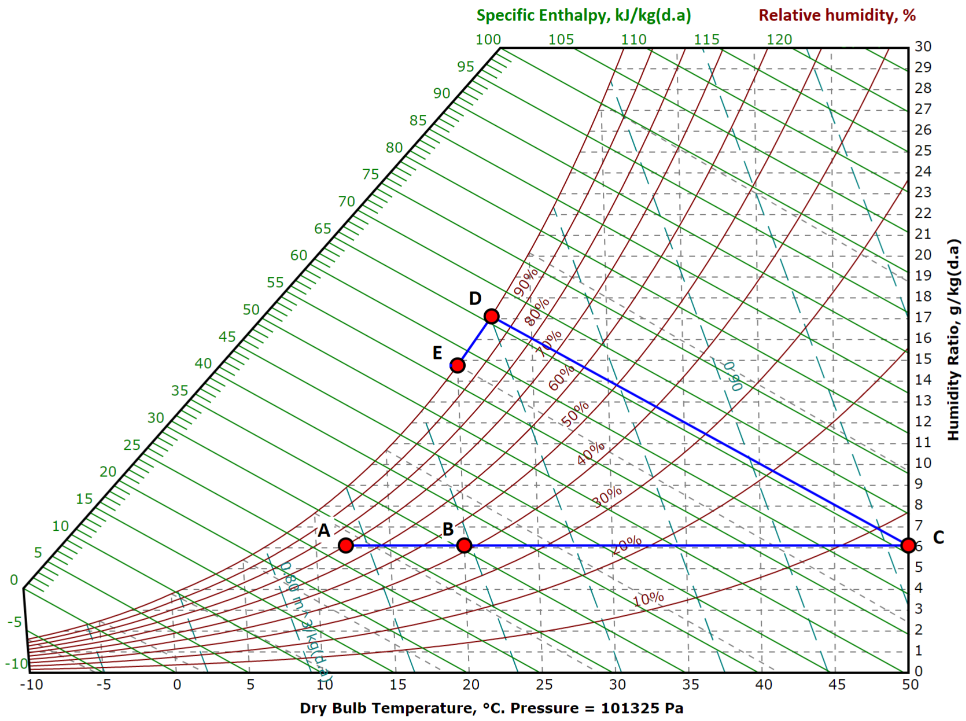


Figure 3.3: Idealized processes of drying air in a single-deck kiln (an example, created using [7])

- **A** - the point represents the fresh air incoming into the kiln:
  - Dry bulb tepmerature $T_{\text{drybulb}} = 12$ °C
  - Relative humidity $\phi = 70$ %

  - Humidity ratio (moisture content) $\chi = 6.11$ g·kg^{-1}
  - Specific enthalpy $h = 27.48$ kJ·kg^{-1}

- **A-B** - the process represents the fresh air heating without changing the moisture content (on the chart, humidity ratio) by the exhaust air in a glass tube heat exchanger. The obtained heat per kilogram of dry air can be calculated as: $\Delta h_{AB} = h_B - h_A = 35.62 - 27.48 = 8.14$ kJ·kg^{-1}.

- **B** - the point represents the pre-heated air:

  - Dry bulb tepmerature $T_{\text{drybulb}} = 20$ °C
  - Relative humidity $\phi = 41.98$ %
  - Humidity ratio (moisture content) $\chi = 6.11$ g·kg^{-1}
  - Specific enthalpy $h = 35.62$ kJ·kg^{-1}

- **B-C** - the process represents the pre-heated air heating to 50 °C without changing the moisture content (on the chart, humidity ratio) by indirect air heater (the air has to be heated more, to 55-60 °C for lowering the relative humidity and thus increasing the drying ability). The obtained heat per kilogram of dry air can be calculated as: $\Delta h_{BC} = h_C - h_B = 66.13 - 35.62 = 30.51$ kJ·kg^{-1}.

- **C** - the point represents the air-on:

  - Dry bulb tepmerature $T_{\text{drybulb}} = 50$ °C
  - Relative humidity $\phi = 7.95$ %
  - Humidity ratio (moisture content) $\chi = 6.11$ g·kg^{-1}
  - Specific enthalpy $h = 66.13$ kJ·kg^{-1}

- **C-D** - the process represents evaporative cooling: the air passing through the green malt. The water absorbed by the air per kilogram of dry air can be calculated as: $\Delta\chi_{CD} = \chi_D - \chi_C = 17.15 - 6.11 = 11.04$ g·kg^{-1}.

- **D** - the point represents the saturated air-off:

  - Dry bulb tepmerature $T_{\text{drybulb}} = 22.42$ °C
  - Relative humidity $\phi = 100$ %
  - Humidity ratio (moisture content) $\chi = 17.15$ g·kg^{-1}
  - Specific enthalpy $h = 66.13$ kJ·kg^{-1}

- **D-E** - the process represents the air-off cooling by the fresh air in a glass tube heat exchanger. Since the air-off is saturated, it condensates. The water condensed per kilogram of dry air can be calculated as: $-\Delta\chi_{DE} = \chi_D - \chi_E = 17.15 - 14.76 = 2.39$ g·kg^{-1}.

- **E** - the point represents the waste air:

  - Dry bulb tepmerature $T_{\text{drybulb}} = 20$ °C

- Relative humidity $\phi = 100$ %
- Humidity ratio (moisture content) $\chi = 14.76$ g·kg^{-1}
- Specific enthalpy $h = 57.55$ kJ·kg^{-1}

3.3 Kiln structure

Kilns can be divided according to different aspects [4]:

- By the type of loading: horizontal or vertical kilns, deep-loaded or shallow-loaded kiln
- By the number and shape of the kiln deck (floor): single-, double- or triple-deck kilns, rectangular or circular in plan
- By the capacity: normal or high-capacity kilns
- By the type of heating and heat transfer medium: directly or indirectly fired kilns with heat exchangers heated with flue gases, hot water, steam or special oils [2]
- By the process continuity: periodic, semi-continuous or continuous kilns

3.3.1 Kiln equipment

The kiln equipment includes a high amount of temperature, pressure, humidity and other sensors, encoders, various valves, flaps, louvres, dampers, motors and other monitor and control elements. Besides that, there are four complex devices which are described below:

- Air heater
- Heat recovery and saving equipment
- Fan
- Loading and unloading device

Air heaters

Nowadays, kilns have indirect heating, it avoids the formation of nitrosamines. Nitrosamines (nitrosodimethylamine, NDMA) are carcinogenic substances, which were formed in directly fired kilns by the reactions of amines with nitrogen oxides from the flue gases. So, the products of combustion were carried with the heated air and were into contact with the malt. Various types of fuels were used: wood, straw, furze, bracken, peat, charcoal, coke, coal, anthracite, special oils or natural gas. [2]

With indirect heating, the nitrogen oxide NOx-rich combustion gases are no longer passing through the drying grain. However, in industrial zones, the incoming air can be contaminated with nitrogen oxides. In this case, it is necessary to permanently burn sulphur during kilning in order to keep under control the nitrosamines content in malt. The limit value for NDMA is 2.5 μg/kg malt [6]. Now, direct-fired heater may be used for the production of special smoked malt, when beechwood is burnt in a kiln and the smoke passes through the malt to form a smoky flavour. [2], [4], [6]

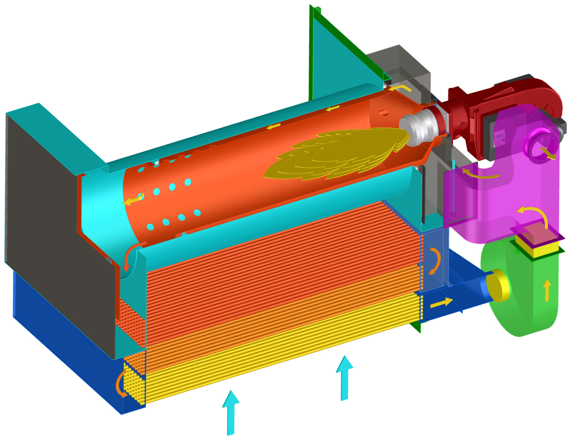


Figure 3.4: ANOX high performance air heater (Air Fröhlich) [8]

The ANOX air heater manufactured by Air Fröhlich is a high-performance indirect heater with a built-in flue gases-air heat exchanger (Figure 3.4). This type of heater is commonly used in malt kilns. The heater is typically fired with natural gas and the flame is contained in a combustion tube. The flue gases (the red and orange arrows) pass through the set of stainless steel heat-exchange tubes and then over glass heat-exchange tubes. The flue gases are cooled by the incoming air and partly recirculated to the combustion tube. In addition, if the flue gases are cooled below the dew point, the latent heat is recovered by water condensation. Therefore, the efficiency of such heaters can exceed 100 % of the net caloric value. The incoming air (the blue arrows) flows counter-current to the flue gases and is heated by passage over the heat-exchange tubes and then over the combustion tube [2], [8].

The VARINOX high performance air heater manufactured by Flucorrex has a similar design. Figure 3.5 shows the VARINOX heating system with heat recovery: 1 - heat-exchange tubes, 2 - combustion tube, 3 - burner with fuel supply, 4 - flue gases fan, 5 - recirculation damper, 6, 7 and 8 - pressure sensors, 9 and 10 - temperature sensors, 11 - kiln fan, 12 - bed with loaded malt, 13 - glass tube heat exchanger for heat recovery, 14 - condensate. The capacity of VARINOX is from 100 to 6000 kW and it can be fuelled with natural gas, LPG (liquefied petroleum gas) or Diesel fuel [9].

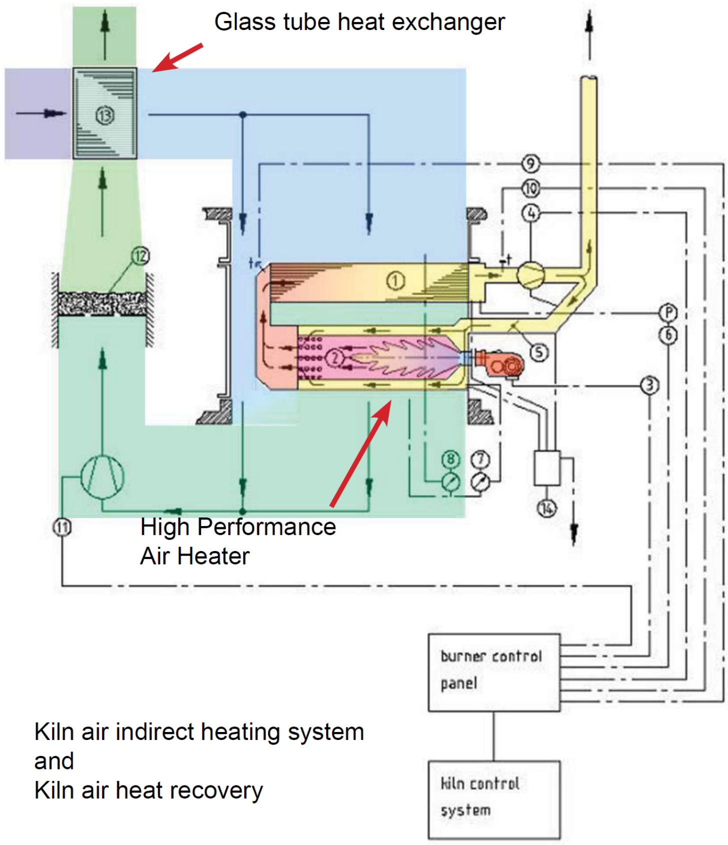


Figure 3.5: VARINOX indirect heating system with heat recovery (Flucorrex) [9]

Other indirect-fired systems also use as a heat transfer medium pressurized hot water, special oils or steam.

Heat recovery and heat saving equipment

Kilning is the most energy-intensive process of malt production and accounts for up to 90 % of malting costs [4]. Therefore, great efforts are made to reduce kilning costs.

Basically, there are several options for the heat recovery and saving:

- Heat recovery systems, including preheating of the incoming air by the outgoing air or using heat pumps
- Recirculating the outgoing air and mixing with the fresh air
- Reusing the outgoing air for the withering stage in another kiln or deck (generally, more energy can be reused in a double-deck kiln than in a single-deck kiln) [6]

- Lowering of moisture content of the incoming air (chemically pre-drying of the incoming air with lithium chloride to reduce the time required for the withering phase, this solution is no longer used) [4], [2]
- Better thermal insulation of a kiln (for a single-deck kiln, heat losses may be from 4 % to 12 %) [4]

Glass tube heat exchanger. This is a huge cross-flow air-air heat exchanger for preheating of the incoming fresh air by the leaving exhaust air (the air-off). The heater is installed in every modern kiln, if it can be beneficial for the particular climatic conditions and useful for the kiln type. The heater is constructed with hundreds of horizontally arranged glass tubes through which the fresh air passes into the kiln. Figure 3.6 shows a schema of the heat exchanger: 1 - incoming fresh air, 2 - preheated fresh air, 3 - warm exhaust air, 4 - cooled exhaust air. A kiln should also have a bypass not to suck the air through the heat exchanger during the cooling phase of kilning, because it will extend the cooling process. In addition, the heat exchanger, as well as the air heater, is a pressure loss for a fan. Glass is a suitable material for the conditions of high humidity and high temperatures of exhaust air. It is non-corrosive and can be easily cleaned to avoid development of fungus and other bacterial organisms. Typically, the thermal efficiency of the heat exchanger is 80 % [8]. The energy savings are up to 35 % and are higher in winter than in summer due to lower ambient temperatures [6].

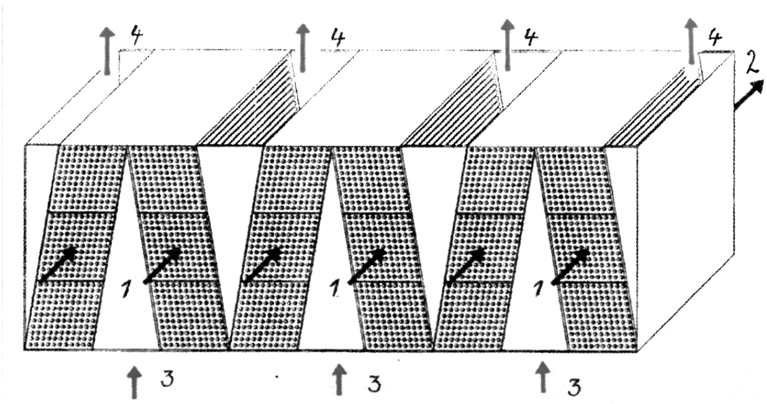


Figure 3.6: Glass tube heat exchanger [6]

Sometimes, due to the kiln construction (for example, when the ducts for the incoming and exhaust air are located on different sides of the kiln) an air-liquid-air system can be used. The heat transfer medium is the antifreeze liquid, energy savings are reduced by the additional power for a fan, as well as by the energy for the liquid circulation pumps [4].

Heat pump. This is an expensive investment, but the heat savings for kilning can reach 50 % [4]. Heat pump systems have varying degrees of complexity.

Recirculation damper. Recirculating of the outgoing air and mixing it with the incoming air is a simple and inexpensive option for heat saving. Although this solution increases the amount of air necessary for kilning, it reduces total heat consumption. The heat savings are greater at low ambient air temperatures (up to 16 % [4]). The air is partly recirculated and mixed during the post-break phase of the kilning process (see Section 3.2.3).

Fans

Circulation of air in traditional kilns was carried out by a top fan in a chimney. In modern deep-loaded kilns, the air is circulated by high-performance centrifugal fans (typically, two fans running in parallel) powered by electric induction motors. Generally, a centrifugal fan generates a higher pressure air flow than an axial fan, therefore such design is used for the drying application [20]. The axial-flow fans may be used in some special kiln designs. The fan is usually installed before the plenum chamber. The kiln equipment and structure should provide a minimum possible resistance to the airflow to use the fan power efficiently. As it was already mentioned, this is one of the reasons for installation of the special flap for the cooling phase of kilning (not to suck air through the heat exchanger and the air heater). The deeper the malt bed, the higher must be the performance of the fan to generate enough pressure and ensure relatively low temperature difference between the top and bottom layers of the malt. [2], [6], [4]

During the first phase of kilning, the large amount of air is required (from 4300 to 5000 m^3 of air per hour and per ton of malt [6]). When the breakpoint is reached, the resistance to airflow decreases and the airflow rate can be reduced to 50-60 %. In the past, the airflow rate was controlled inefficiently by throttling [2]. Nowadays, variable airflows are achieved by adjusting the speed of induction motor using a frequency converter.

Loading and unloading devices

Modern deep-loaded kilns are equipped with a special device for loading and levelling of green malt and unloading of kilned malt from the kiln. The device consists of a cross screw conveyor which can be raised or lowered over the deck (typically, by two electric motors). In case of circular kiln, the device rotates about the kiln axis. Another design is a fixed device and rotating floor (deck). In rectangular kilns, the screw moves along one side of the kiln and a second conveyor is needed to transport the kilned malt away. [6]

Also, there is another solution of malt unloading used in old or small kilns. Unloading is performed with tripping floors. The falling kilned malt is caught by a hopper (or hoppers) and then is transported away by a conveyor. The disadvantage of such design is a less even distribution of airflow due to the malt hoppers installed under the deck. [2], [4]

3.3.2 Single-deck kiln

In the past, first shallow-loaded kilns were directly heated. Then, they were replaced by indirectly heated kilns, that allowed to avoid the formation of nitrosamines (see Section 3.3.1). With increasing demand of malt, first deep-loaded kilns were developed. In comparison with old shallow-loaded kilns, such kilns are compact and have high capacities. Mostly, the kilns were rectangular in cross-section and some of them had helical-screw turners (similarly to the germination units, see Section 2.4.2). Typically, they had tipping floors for easy malt unloading. [2]

Figure 3.7 shows a schema of the deep-loaded single-deck kiln with tipping floor: 1 - hot air chamber, 2 - kiln chamber, 3 - hot air inlet, 4 - hot air spreader, 5 - malt conveyor, 6 - collecting plates, 7 - two-part tipping floor, 8 - side wall, 9 - pull rods, 10 - worm drive, 11 - green malt inlet, 12 - exhaust air. [6], [2]

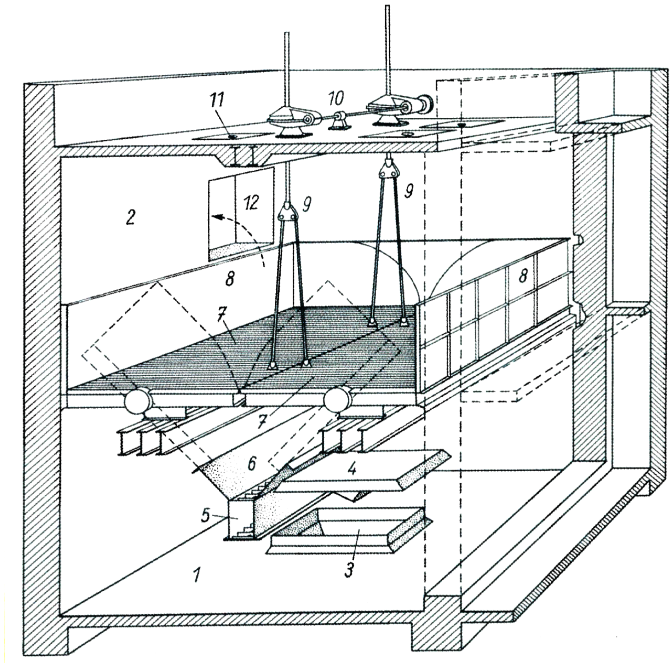
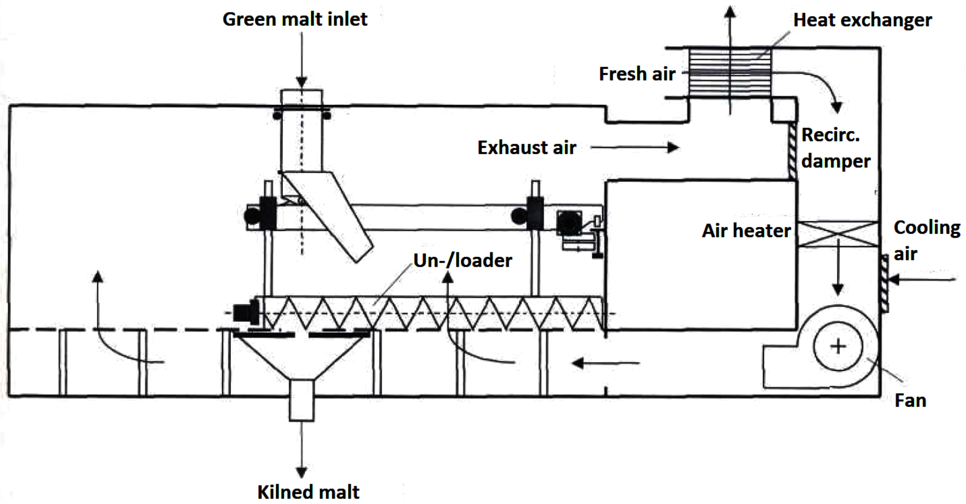


Figure 3.7: Single-deck tipping kiln [6]

Modern kilns work in a different way, the most common type is a high-capacity single-deck circular kiln. (Figure 3.8). The circular design of the kiln ensures better air distribution under the deck. The deep of bed varies from 0.8 to 1.2 m, this corresponds with loading of from 300 to 450 kg per m^2 of kilned malt [4]. A special device, un-/loader, is used for loading, levelling and unloading of malt (the kiln equipment is described in Section 3.3.1). There are two designs of such kilns: fixed floor with rotating un-/loader or rotating floor with fixed un-/loader. The deck (floor) is constructed of perforated or slit plate sections. [4], [6]



(own translation)

Figure 3.8: Single-deck circular kiln (Bühler) [4]

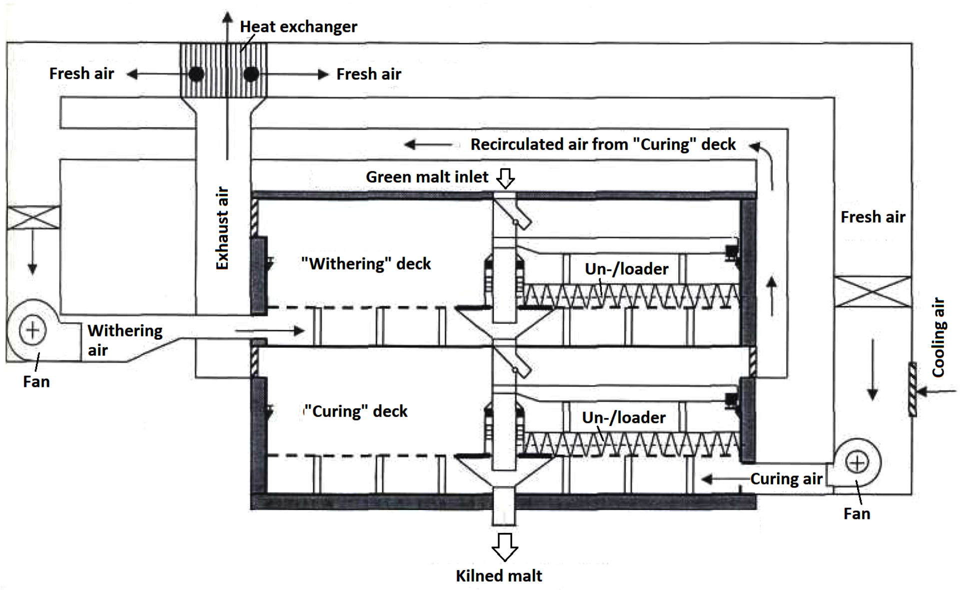
The black arrows (Figure 3.8) show the airflow: the fresh air is sucked into the kiln through the heat exchanger, then it passes the air heater. After that, the air is blown by fans to the plenum chamber, where it goes upward through a perforated deck and the green malt. Finally, the exhaust air continues through the heat exchanger, also it can be partly recirculated and mixed with the fresh air during the post-break phase (see Section 3.2.3). The flap for the cooling air is used during the cooling phase of kilning. In case of high ambient temperatures (15 °C and higher), there should be a possibility to suck and heat the fresh air without passing through the heat exchanger during the withering phase, because of the low efficiency of heat recovery. In an extreme case, the exhaust air would cool the fresh air. The single-deck circular kiln is usually built separately, but it also can be a part of tower malting plant. [4], [6]

Figure 3.9: Single-deck circular kiln (MOPOS) [10]

The single-deck kiln has the following advantages: low investment costs in comparison with the double-deck kiln, fully automated operation. The disadvantages are: higher energy consumption, inhomogeneity of malt due to the deep loading. [4]

3.3.3 Double-deck kiln

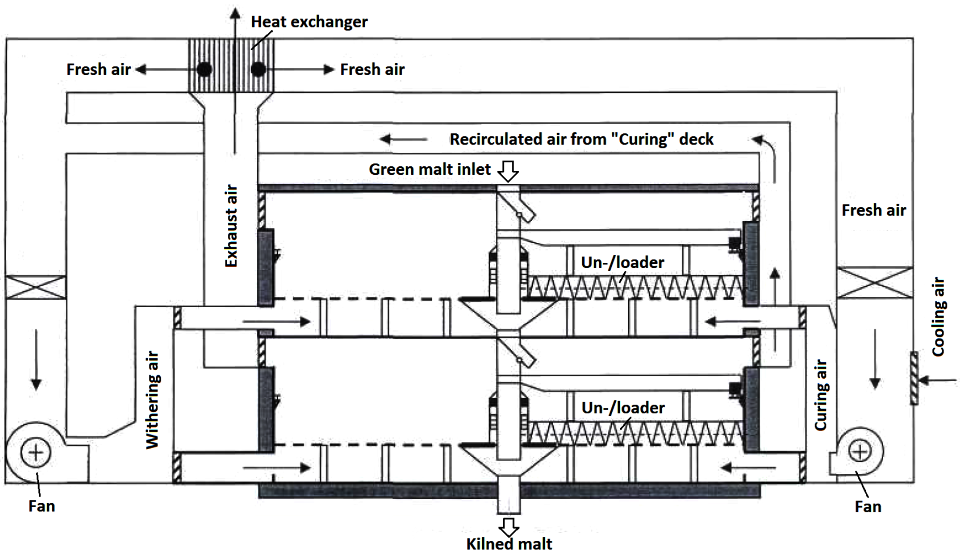
Recently, double-deck (two-floor) kilns were widely used. From the technological point of view, the double-deck kiln is suitable for the production of pale malt: the withering phase (to 10-12 % of moisture content in the malt) is carried out on the upper deck. Then, the upper deck with the pre-dried malt is emptied out onto the lower deck, at which the heating and curing phases take place. Such kilns were equipped with tipping floors and two malt hoppers located in the plenum chamber. The temperature of the air under the upper floor was controlled (to keep it not higher than 60 °C) by the air supplied by cooling ducts. [4], [2]



(own translation)

Figure 3.10: Double-deck circular kiln with shifting the malt (Bühler) [4]

Modern double-deck kilns are circular in plan. There are two designs: with or without shifting the malt from the upper to the lower deck (Figures 3.10 and 3.11). In the first case, the malt is pre-dried on the upper (withering) deck and then loaded to the lower (curing) deck for heating and curing. The exhaust air from the curing deck is recirculated and mixed with the fresh air for use in the witherng part of kiln. Another design of double-deck is without shifting malt, so the whole kilning process is carried out on the same deck. The fans for the withering and the curing air works periodically for different floors. The advantage of such solution is no need for shifting the malt, which lasts about two hours [6]. Two single-deck kilns built next to each other can be operated as a double-deck kiln, if their air-handling equipments are interconnected. [4], [6]



(own translation)

Figure 3.11: Double-deck circular kiln without shifting the malt (Bühler) [4]

Loading, levelling and unloading of malt is performed by an un-/loader (the kiln equipment is described in Section 3.3.1). The withering phase requires a large amount of drying air, therefore the fan for the withering air is more powerful than the fan for the curing air. The double-deck kilns are also equipped with a heat exchanger for heat recovery from the outgoing exhaust air. [4], [6]

The double-deck kiln has the following advantages: low energy consumption, higher homogeneity of malt due to the less deep layer of malt. The main disadvantages are: high investment costs, more complex maintenance, control and automation of the process. [4]

3.3.4 Vertical kiln

In vertical kilns, the malt is held between vertical perforated plates (20 cm apart) and the hot air is passed through them laterally, from bottom to top and from side to side. The air ducts are 80 cm wide. The kiln is divided into two or three sections (floors). The malt falls to the lower section by gravity, when the slide valves open. The desirable temperature of the airflow is achieved by additional cool ducts. The withering phase is carried out at the top of the rectangular malt column and the curing phase at the bottom. Nowadays, vertical kilns are not widely used because of high energy consumption. [2], [6].

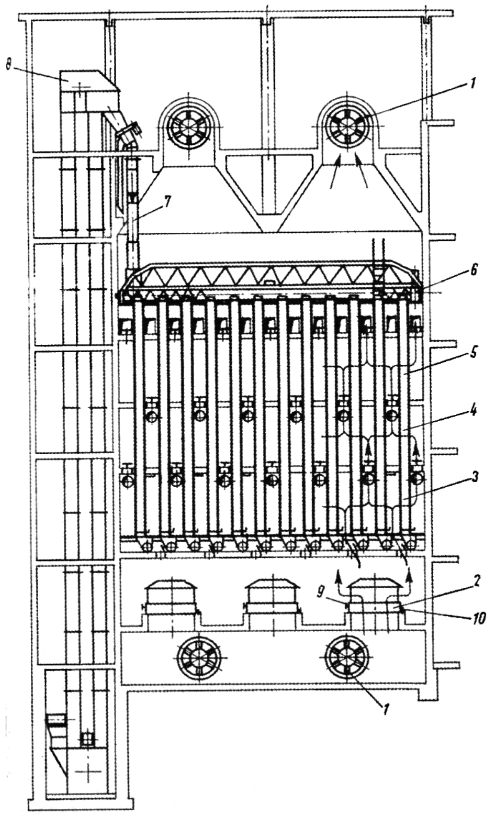


Figure 3.12: A three-floor vertical kiln [6]

Figure 3.12 shows a schema of the three-floor vertical kiln: 1 - axial fan, 2 - steam air heater, 3 - lower floor, 4 - middle floor, 5 - upper floor, 6 - loading screw, 7 - telescopic pipe, 8 - elevator, 9 - steam distribution, 10 - condensate drain [6].

3.3.5 Other types of kilns

Besides various types of circular and rectangular kilns and multifunction malting systems, there are also less common continuous kilns that may be horizontal (Domalt, Saturn) or vertical (Frauenheim, LSCHA). The basic principle of continuous kilns is the malt moving through the different temperature zones. For example: in the first zone the drying air temperature is 50 °C, in the second zone 67 °C, in the third zone 81 °C and in the fourth zone 85 °C, in each zone the malt is held for 6 hours. [2], [4], [6]

Part II

Practical Part

Chapter 4

Simulation

4.1 Introduction

The simulation model (Figure 4.1) of the kilning process belongs to Bühler GmbH (hereinafter Bühler) [21]. The model was developed in Matlab & Simulink environment [22] by a third party in 2013. The model simulates the real process of malt kilning in a single-deck circular kiln (Figure 3.8). The identification of such a complex system was mainly made for analyses of the kilning process from an energy point of view. Since its development, the model has not been practically used. The investigation of the model is necessary for the potential usage of the simulation in future projects. This could yield benefits to Bühler, as the possibility of optimizing the kilning process or dimensioning some of the kiln equipment. The creation of documentation for internal use in English is important to make the simulation usage available within the international company, such as Bühler.

This chapter contains a model description, including modifications and adjustments necessary for the simulation of the chosen real kiln. For the model verification, measured and simulated values are compared.

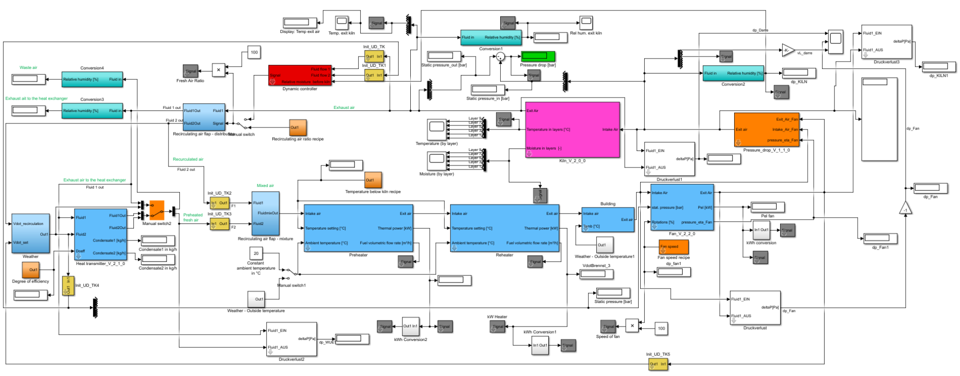


Figure 4.1: Simulation model in Simulink

4.2 Model analysis, modifications and settings

The model consists of sub-models, which represent particular kiln equipment and sub-processes occurring in the kiln. The blocks of the model are: heat exchanger, heaters, fan, recirculating damper, kiln bed, pipeline and air mixing process. The model also includes the recirculation damper controller, which allows to control the damper based on the actual state of the airflow (not by recipe). The fluid (mainly, air) is transferred from block to block, similarly to reality. Figure 4.2 shows a block diagram of the model, the Simulink names appear in italics.

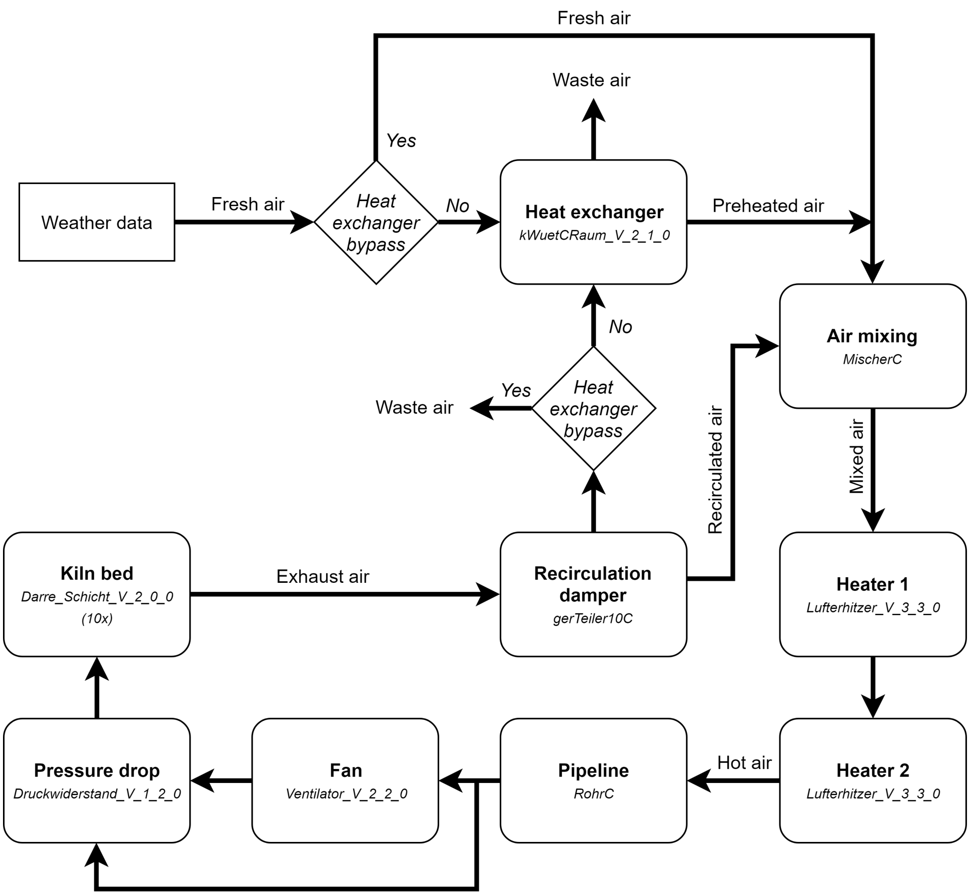


Figure 4.2: Block diagram of the kiln model

Each Simulink sub-model (subsystem, module) contains an S-function block (or several S-functions), which is referred to the particular *mexw32* file (or *mexw64*, depending on platform) containing differential equations for the simulation. These files were created by compiling the source code for the S-functions (written in C, MATLAB (Level-1) or Fortran [22]). The *mexw32* files are owned by Bühler [21], the source code belongs to the third party. The S-function parameters for each sub-model are set through a dialog box.

In the model, the fluid is represented by 9 parameters (Table 4.1).

Parameter	Symb.	Variable	Units
Volumetric flow rate	$\dot{V}$	V_dot	$m^3 \cdot h^{-1}$
Density	ρ	roh	$kg \cdot m^{-3}$
Specific heat capacity (const. press.)	c_p	c_p	$kJ \cdot kg^{-1} \cdot K^{-1}$
Temperature	T	temp	°C
Pressure	p	p	bar
Specific humidity (moisture content)[1]	χ	x	$g_{H_2O} \cdot kg_{air}^{-1}$
Dynamic viscosity	η	eta	Pa·s
Thermal conductivity	λ	lamda	$W \cdot m^{-1} \cdot K^{-1}$
Fluid (type)	-	fluid	-

Table 4.1: Fluid parameters

In the next pages, all the sub-modules are described and set according to the real kiln. The real kiln has slightly different structure, therefore the model should be modified.

4.2.1 Model structure modification

The real kiln is not equipped with air-air heat exchanger, but there is a heat pump system for pre-heating the fresh air incoming into the kiln (Figure 4.4). The model has to be modified to correspond with the real plant (Figure 4.3).

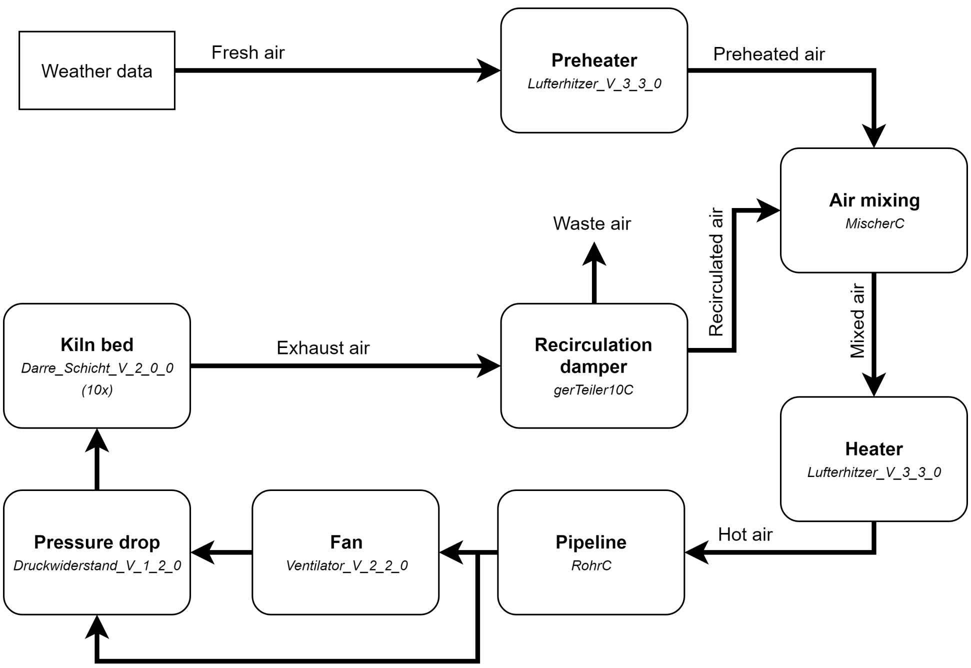


Figure 4.3: Block diagram of the modified kiln model

[1]The name of the parameter in Simulink is *Absolute humidity*

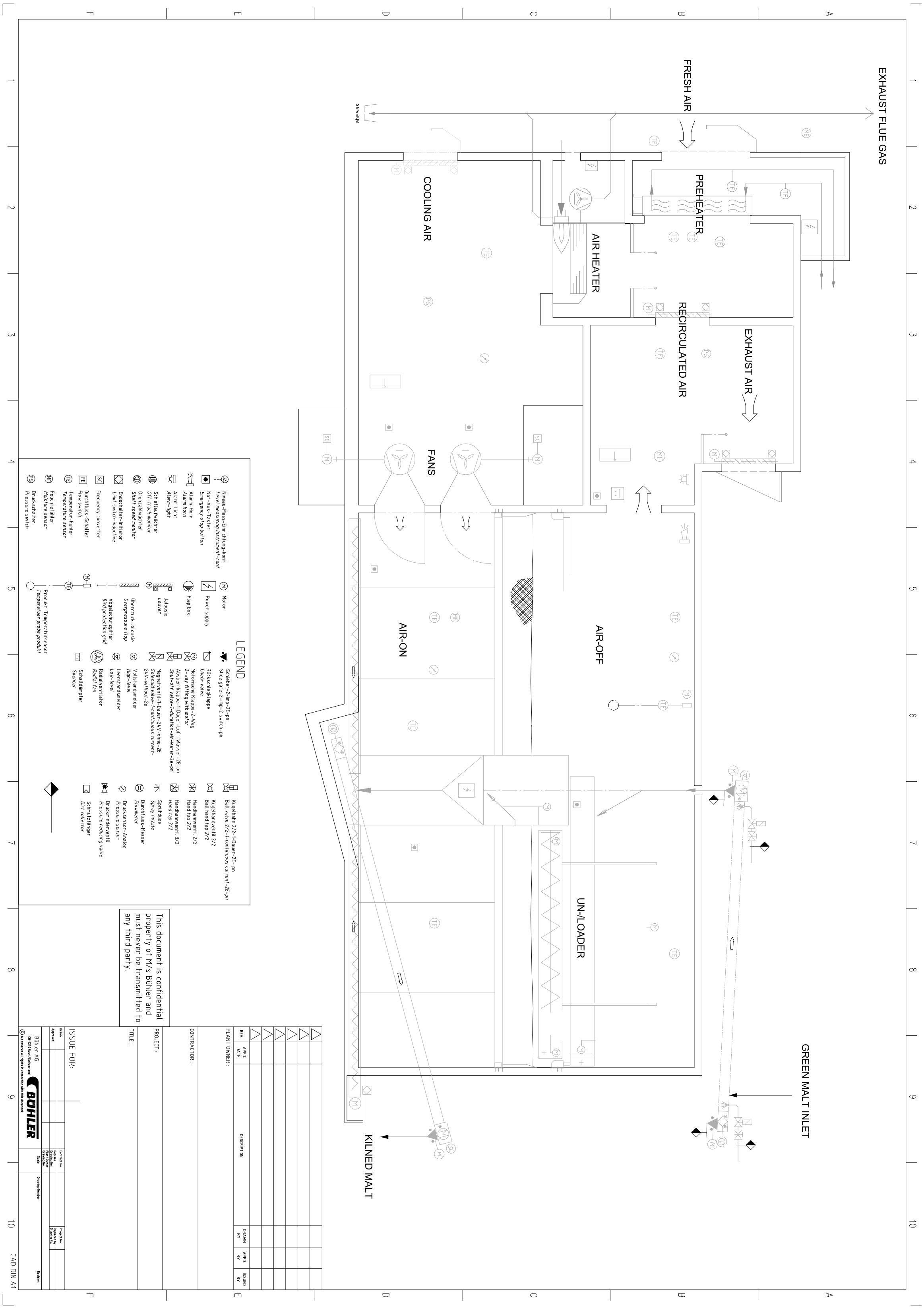


Figure 4.4: Kiln flowsheet (Bühler) [11]

4.2.2 Weather data

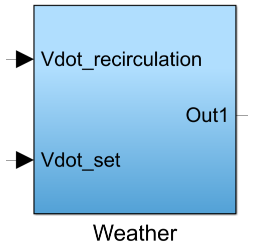


Figure 4.5: Weather block

The fresh air parameters are determined by the weather block (Figure 4.5). It has 2 inports: *Vdot_recirculation* (the recirculated air connected) and *Vdot_set* (the air from fan connected). The necessary amount of the fresh air is calculated as a difference between the volumetric flow rate generated by fan and the volumetric flow rate of recirculated air, but firstly the values are recalculated according to weather conditions by S-function *Vdot_Temp*. The specific humidity of air is calculated by S-function *relinabsFeuchteC* based on the air temperature, pressure and relative humidity. The weather data are read from the Workspace (*Wetter_Aussentemperatur*, *Wetter_Umgebungsdruck*, *Wetter_RelativeAussenfeuchte*). The outport *Out1* represents the fresh air incoming into the kiln, all the air parameters are determined by S-function *UmgebungsbedingungenC*.

4.2.3 Heat exchanger

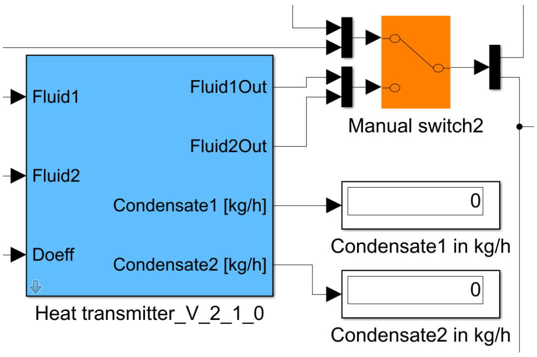


Figure 4.6: Heat exchanger block (bypassed by *Manual switch2*)

The model of the heat exchanger (Figure 4.6) simulates the real glass tube heat exchanger, which is used for heat recovery from the exhaust air (see Section 3.3.1). This block has 3 inports: *Fluid1* (the exhaust air connected), *Fluid2* (the fresh air connected) and *Doeff*, which represents the degree of efficiency of the heat exchanger. The degree of efficiency is an input data from *Daten.mat*, the value is read from the Workspace (*WirkungsgradWUET*).

The outports are: *Fluid1Out* (the waste air), *Fluid2Out* (the preheated air), *Condensate1* [kg·h^{-1}] (a mass flow rate of condensate from the exhaust air) and *Condensate2* [kg·h^{-1}] (from the fresh air, zero during the process).

The block contains S-function *kWuetCRaum_V_2_1_0*. The S-function parameters, which should be set in the block mask, are shown in the Table 4.2. The parameters can be found in manufacturer's documentation. Since the simulated kiln is not equipped with a heat exchanger, the parameters are not set. In that case, it is necessary to bypass the heat exchanger block using *Manual switch2* (see Figure 4.6).

Parameter	Variable	Unit	Value
Transmission area	A	m^2	*not set*
Transmission capacity	k	$W{\cdot}m^{-2}{\cdot}K^{-1}$	*not set*
Nominal volumetric flow rate	VdotNenn	$m^3{\cdot}h^{-1}$	*not set*
Nominal pressure loss	deltapNenn	Pa	*not set*

Table 4.2: Parameters of the heat exchanger block

- *Transmission area* - the heat transfer surface area
- *Transmission capacity* - the overall heat transfer coefficient
- *Nominal volumetric flow rate* - the flow rate of the air passing through the exchanger
- *Nominal pressure loss* - the additional pressure drop for the fan

4.2.4 Air mixing

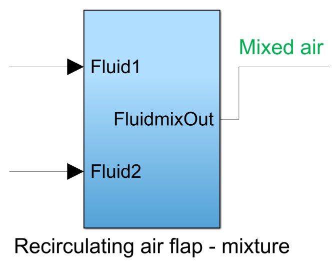


Figure 4.7: Air mixing block

Mixing of recirculated and preheated air is simulated by the air mixing block (Figure 4.7). It has 2 inports: *Fluid1* (the recirculated air connected) and *Fluid2* (the preheated air connected). The fluid parameters of mixed air are calculated by S-function *MischerC*. The outport *FluidmixOut* represents the mixed air.

4.2.5 Air heater

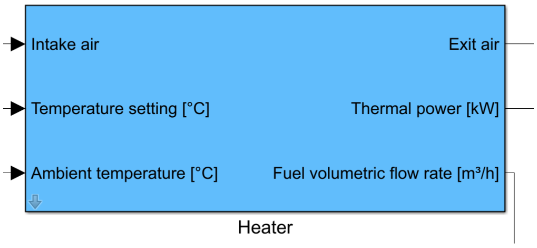


Figure 4.8: Air heater block

The model of air heater (Figure 4.8) simulates the real indirect air heater, which is used for air heating in the kiln (see Section 3.3.1). This block has 3 inports: *Intake air* (the mixed air connected), *Temperature setting* [°C] (the air-on temperature given by recipe) and *Ambient temperature* [°C]. The air-on temperature and ambient temperature are input data from *Daten.mat*, they are read from the Workspace (*Rezept_Temperatur_unterHorde* and *Wetter_Aussentemperatur*). Also, there is a possibility to chose a constant ambient temperature using *Manual switch1*.

The outports are: *Exit air* (the hot air), *Thermal power* [kW], *Fuel volumetric flow rate* [$m^3 \cdot h^{-1}$]. The thermal power and the fuel amount required to maintain the target temperature are calculated in this block.

The block contains S-functions *Lufterhitzer_V_3_3_0* (air heater) and *Regelung_V_4_3_0* (built-in controller). The model was developed with the assumption of 100 % efficiency [12]. The S-function parameters, which should be set in the block mask, are shown in the Table 4.3. Some of the parameters can be found in manufacturer's documentation, the rest can be estimated, measured or calculated.

Parameter	Variable	Unit	Value
Parallel switched modules	AnzParallel	1	4
Nominal thermal output	Nennleistung	kW	*conf.*[2]
Maximum thermal output	maxLeistung	kW	*conf.*
Nominal volumetric flow rate	VdotNenn	$m^3 \cdot h^{-1}$	*conf.*
Nominal pressure loss	deltapNenn	Pa	*conf.*
Aggregate mass	Volumeninhalt	kg	*conf.*
Initial temperature of the boiler	Tstart	°C	25
k*A value for boiler losses	kAWert	$W \cdot K^{-1}$	10
Influence coeff. of the aggr. mass	Einflussfaktor	1	1
Heating value (Hu)	Hu	$kW \cdot h \cdot m^{-3}$	11

Table 4.3: Parameters of the air heater block

[2]Hereinafter confidential information

- *Parallel switched modules* - the number of air heaters installed (in parallel)
- *Nominal and Maximum thermal output* - the thermal output of the air heater, provided by manufacturer
- *Nominal volumetric flow rate* - provided by manufacturer, however it is common to have the **mass** flow provided instead (in that case, assumption of average air density $\rho \doteq 1$ kg·m^{-3} can be made)
- *Nominal pressure loss* - the additional pressure drop for the fan, provided by manufacturer
- *Aggregate mass* - the total weight of the air heater, provided by manufacturer
- *Initial temperature of the boiler* - the estimated temperature at the beginning of simulation (an initial condition for the differential equation)
- *$k \cdot A$ value for boiler losses* - k represents the overall heat transfer coefficient [W·m^{-2}·K^{-1}], and A is a heat transfer surface area [m^2]
- *Influence coefficient of the aggregate mass* - the correction factor (the default value is 1)
- *Heating value (Hu)* - the average caloric value of the fuel used (Table 4.4 gives an overview of such values)

Fuel	Density[3]	Higher Heating Value			Lower Heating Value		
	$\left[\frac{kg}{m^3}\right]$	$\left[\frac{MJ}{kg}\right]$	$\left[\frac{kWh}{kg}\right]$	$\left[\frac{kWh}{m^3}\right]$	$\left[\frac{MJ}{kg}\right]$	$\left[\frac{kWh}{kg}\right]$	$\left[\frac{kWh}{m^3}\right]$
Natural gas	0.777	52.2	14.5	**11.3**	47.1	13.1	**10.2**
Diesel fuel	0.846	45.6	12.7	**10.7**	42.6	11.8	**10.0**
LPG	0.537	49.3	13.7	**7.4**	45.5	12.6	**6.8**

Table 4.4: Higher and Lower Heating (Calorific) Values (average values) [14]

4.2.6 Pipeline (Building)

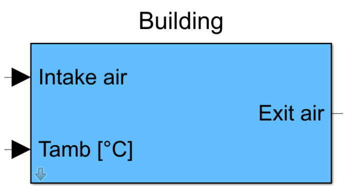


Figure 4.9: Pipeline (building) block

Pressure and thermal losses during the air circulation through the chambers and ducts in the kiln are calculated in the block named *Building* (Figure 4.9).

[3]At 0 °C, 1 bar

The simulation was made with the assumption of the pipeline with constant cross-section. The block is placed between the air heater and fan block. It has 2 inports: *Intake air* (the hot air connected) and *Tamb* [°C] (the ambient temperature). The ambient temperature is an input data from *Daten.mat*, it is read from the Workspace (*Wetter_Aussentemperatur*). The only outport is *Exit air* connected to the fan block.

The block contains S-function *RohrC*. The S-function parameters to be set in the block mask are shown in Table 4.5.

Parameter	Variable	Unit	Value
Length	Rohrlaenge	m	10
Diameter	Flanschfluid1	m	6
Cross-section	Rohrquerschnitt	-	Square
Total pressure loss coefficient	xsieinbau	1	*conf.*
U coefficient of the pipeline	Uwert	$W{\cdot}m^{-1}{\cdot}K^{-1}$	*conf.*

Table 4.5: Parameters of the pipeline block

- *Length* - the total length of the pipeline
- *Diameter* - the average diameter of the pipeline (edge length in case of square cross-section)
- *Cross-section* - the cross-section type, two possibilities: round or square
- *Total pressure loss coefficient of various installations* - the pressure loss coefficient of the pipeline. For the existing kilns, the value can be measured. In either case, it has to be estimated. The analytical calculation is practically impossible, the finite element analysis software can be theoretically used.
- *U coefficient of the pipeline* - the overall heat transfer coefficient per 1 m of pipe length. Similarly to the previous parameter, the value can hardly be calculated. The simplest way is to estimate the value based on the measurements from the existing kilns.

4.2.7 Fan

The model of fan (Figure 4.10) simulates the real fan operation, which ensures air circulation in the kiln (see Section 3.3.1). The pressure drop is calculated separately in the next block. The fan block has 3 inports: *Intake air* (the hot air connected), *stat. pressure* [bar] (from the weather data) and *Rotations* [%] (the fan speed given by recipe). The static pressure and fan speed are input data from *Daten.mat*, they are read from the Workspace (*Wetter_Umgebungsdruck* and *Rezept_Ventilatordrehzahl*).

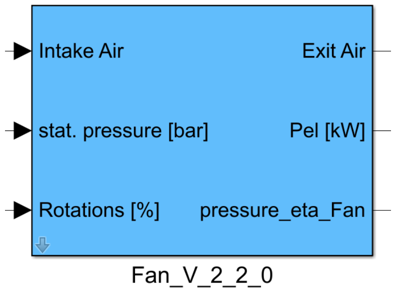


Figure 4.10: Fan block

The outports are: *Exit air* (connected to the Pressure drop block), *Pel* [kW] (actual electrical power consumption), *pressure_eta_Fan* (actual efficiency of the fan).

The block contains S-function *Ventilator_V_2_2_0*. The S-function parameters are to be set in the block mask. The General tab has 3 parameter (Table 4.6). The Interpolation tab has 12 parameters, which are set using the fan performance curves from manufacturer (described below).

Parameter	Variable	Unit	Value
Parallel switched modules	AnzParallel	1	2
Minimal vol. flow rate possible	VdotMIN	$m^3 \cdot h^{-1}$	*conf.*
Degree of efficiency of the powertrain	etaMotor	%	*conf.*

Table 4.6: Parameters of the fan block

- *Parallel switched modules* - the number of fans installed in the kiln
- *Minimal vol. flow rate possible* - from the fan curves (described below)
- *Degree of efficiency of the powertrain* - determined by power transmission from the electric motor to the fan shaft

The shaft power P_{shaft} [kW] for the particular operating point can be calculated as:

$$P_{\text{shaft}} = \frac{\dot{V} \cdot \Delta p}{\eta} \cdot \frac{1}{36 \cdot 10^3} \tag{4.1}$$

where $\dot{V}$ [$m^3 \cdot h^{-1}$], Δp [Pa] and η [%] are given by the graph with fan performance curves (Figure 4.11), constant $\frac{1}{36 \cdot 10^3}$ represents unit conversions.

Then, the electric power P_{electric} [kW] is expressed as:

$$P_{\text{electric}} = \frac{P_{\text{shaft}}}{\eta_{\text{powertrain}}} \cdot 100 \tag{4.2}$$

The powertrain efficiency $\eta_{\text{powertrain}}$ [%] is a parameter for the fan block and can be calculated as:

$$\eta_{\text{powertrain}} = \eta_{\text{freqconverter}} \cdot \eta_{\text{motor}} \cdot \eta_{\text{mech}} \tag{4.3}$$

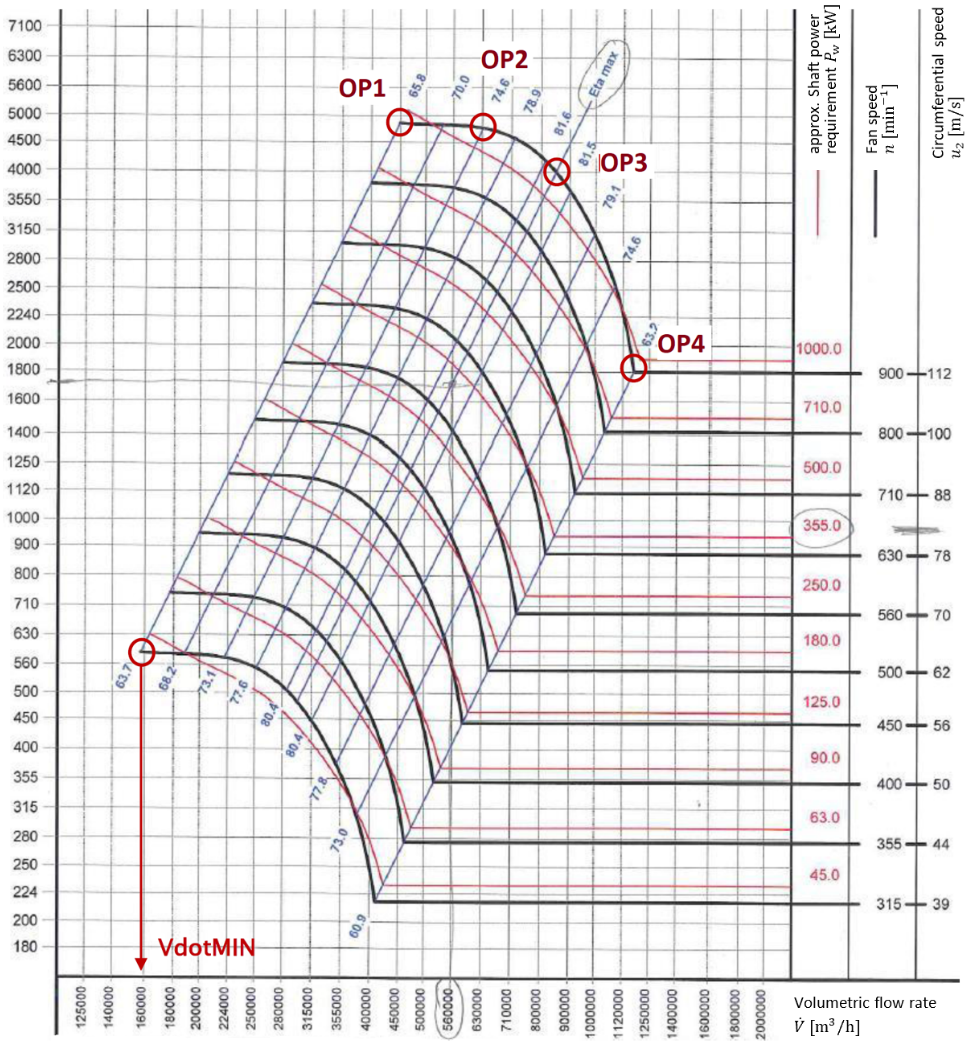
where $\eta_{\text{freqconverter}}$ [%] is an average efficiency of the frequency converter, η_{motor} [%] is an average efficiency of the motor and η_{mech} [%] is an efficiency of mechanical transmission from the motor shaft to the fan shaft.

The simulation of fan is based on the graph with fan performance curves provided by manufacturer. The graph interpolation in Simulink is implemented by setting of 13 parameters. An example of such setting is given below.

Example of interpolation settings

Four operating points are to be specified, each point is represented by three parameters: pressure increase Δp [Pa], volumetric flow rate $\dot{V}$ [m^3/h] and degree of efficiency η [%]. Also, setting of the minimal volumetric flow rate is necessary for the interpolation. These parameters can be found on the graph with fan performance curves (Figure 4.11).

- *Minimal vol. flow rate possible* $\dot{V} = 160\ 000\ \text{m}^3{\cdot}\text{h}^{-1}$
- *OP1*: minimal volumetric flow rate and maximal pressure increase at 100 % fan speed (the surge line)
  - pressure increase $\Delta p = 4850$ Pa
  - volumetric flow rate $\dot{V} = 450\ 000\ \text{m}^3{\cdot}\text{h}^{-1}$
  - degree of efficiency $\eta = 65.8$ %
- *OP2*: a point between OP1 and OP3 at 100 % fan speed
  - pressure increase $\Delta p = 4800$ Pa
  - volumetric flow rate $\dot{V} = 630\ 000\ \text{m}^3{\cdot}\text{h}^{-1}$
  - degree of efficiency $\eta = 74.6$ %
- *OP3*: maximal efficiency at 100 % fan speed
  - pressure increase $\Delta p = 4000$ Pa
  - volumetric flow rate $\dot{V} = 850\ 000\ \text{m}^3{\cdot}\text{h}^{-1}$
  - degree of efficiency $\eta = 81.6$ %
- *OP4*: maximal volumetric flow rate and minimal pressure increase at 100 % fan speed (the suction line)
  - pressure increase $\Delta p = 1800$ Pa
  - volumetric flow rate $\dot{V} = 1\ 180\ 000\ \text{m}^3{\cdot}\text{h}^{-1}$
  - degree of efficiency $\eta = 63.2$ %



(own translation)

Figure 4.11: Fan performance curves [12]

4.2.8 Pressure drop

Pressure drop of the system is calculated in a separate block, which is placed after the fan block (Figure 4.12). It has 3 inports: *Exit_Air_Fan*, *Intake_Air_Fan* and *pressure_eta_Fan* (degree of efficiency at the current operating point of the fan). The only outport is *Exit air* connected to the kiln bed block.

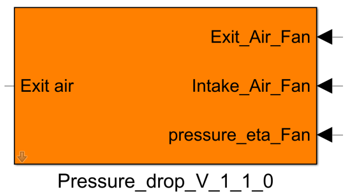


Figure 4.12: Pressure drop block

The block contains S-function *Druckwiderstand_V_1_2_0*. The only S-function parameter to be set is *Initial meassured static pressuredrop of system*, which is necessary as an initial condition for the differential equation (Table 4.7). The parameter represents the pressure drop of the building and green malt at the beginning of the process.

Parameter	Variable	Unit	Value
Initial meas. stat. pressuredrop of system	DeltaPGesamt	Pa	1480

Table 4.7: Parameters of the pressure drop block

4.2.9 Kiln bed

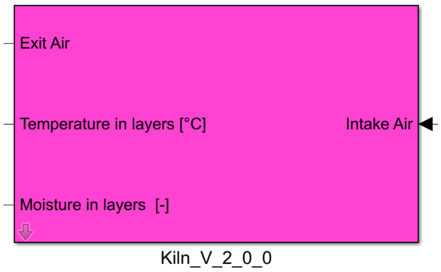


Figure 4.13: Kiln bed block

The model of kiln bed (Figure 4.13) simulates the kiln bed loaded with green malt, which is being dried during the kilning process. A piece (batch) of malt is represented by 10 layers, through which the drying air is passed (Figure 4.14) The malt temperature and moisture content of each layer are calculated during the simulation.

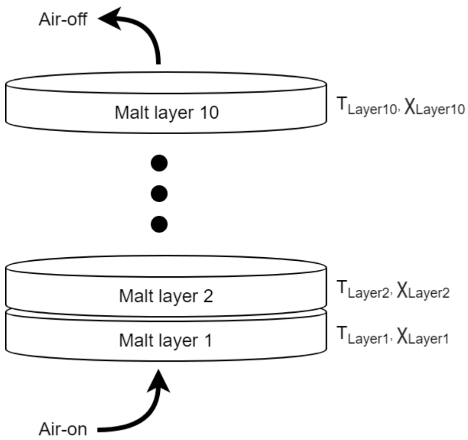


Figure 4.14: A piece of malt represented by ten layers

The kiln bed block has only one inport *Intake Air* representing the air-on from the kiln fans. The outports are: *Exit Air* (the exhaust air), *Temperature in layers* [°C] (the malt temperature of each layer), *Moisture in layers* (the moisture content in the malt, for each layer).

The block contains ten S-functions *Darre_Schicht_V_2_0_0* (malt layers) and two S-functions *BetonWaermespeicher* to take into account the kiln structure (building thermal inertia). The block diagram of the kiln bed model is presented in Figure 4.15.

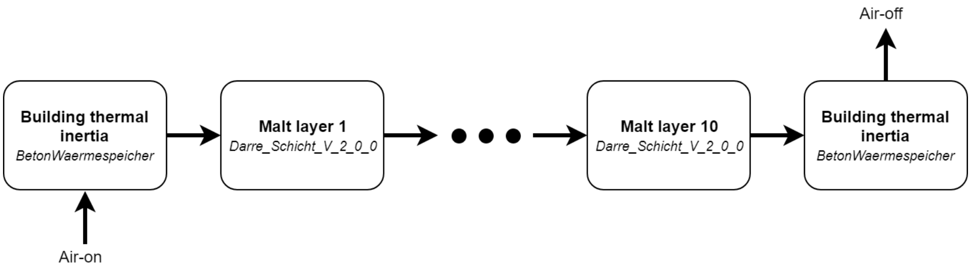


Figure 4.15: Block diagram of the kiln bed model

The model was developed with the following assumptions [12]:

- The specific heat capacity of malt $c_{p\_\mathrm{malt}} = 2\ \mathrm{kJ{\cdot}kg^{-1}{\cdot}K^{-1}}$
- Thermal resistance between air and building structure was calculated using ISO 6946 [23]
- Neglecting the stationary heat losses
- Neglecting the thermal conduction within the grains between the layers
- Uniform temperature distribution in the layers
- Neglecting the water movement against the air flow
- The void fraction ϕ is proportional to the relative humidity
- The grain shrinkage of 8 %

The S-function parameters, which should be set in the block mask, are shown in the Table 4.3.

Parameter	Variable	Unit	Value
Tons of barley	M	t	360
Initial moisture of barley	XBarley0	%	12
Initial moisture of green malt	XMalt0	%	44
Initial temp. of the product to be dried	TMalt0	°C	30
Fill depth	hs	m	*conf.*
Through-flow cross sectional area	A	m^2	*conf.*
Height of kiln building	HeightKILN	m	*conf.*
Thickness of kiln building wall	dWall	m	*conf.*
Thickness of kiln buidling ceiling	dCeiling	m	*conf.*
Thickness of kiln buidling floor	dFloor	m	*conf.*
Initial void fraction ϕ[4]	psiein	1	0.37
Number of layers	AnzS	1	10
Average grain diameter	DurchmKorn	mm	2.0
Shape factor	Formfaktor	-	Sphere

Table 4.8: Parameters of the kiln bed block

- *Tons of barley* - the initial mass of the barley piece (batch)
- *Initial moisture of barley* - the grain moisture content before steeping
- *Initial moisture* and *Temperature of green malt* - the average values at the beginning of the kilning process (initial conditions for the differential equations)
- *Fill depth* - the height of the green malt piece loaded in the kiln
- *Through-flow cross sectional area* - the kiln deck area, through which the air passes upward
- *Height of kiln building, thickness of walls, ceilng* and *floor* - the average values of the kiln building dimensions
- *Initial void fraction* ϕ - described below, the default value is 0.37
- *Number of layers* - the number of malt layers representing the piece - see Figure 4.14 (the default value 10 cannot be changed)
- *Average grain diameter* - the value in the range from 2.0 to 2.5 mm
- *Shape factor* - the approximation of the grain geometry (sphere or cylinder)

[4]The name of the parameter in Simulink is *Initial void ratio psi*

Void ratio and void fraction calculation

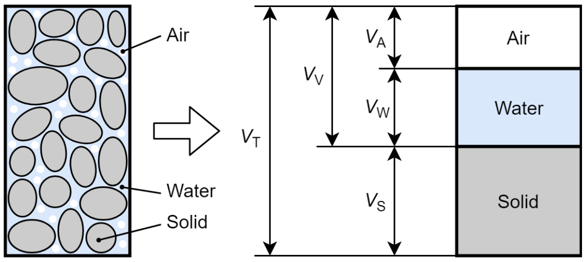


Figure 4.16: Void ratio and void fraction calculation

The void ratio e [1] is the ratio of the volume of voids (i.e. air and water) to the volume of solids:

$$e = \frac{V_V}{V_S} = \frac{V_A + V_W}{V_S} = \frac{V_V}{V_T - V_V} = \frac{\phi}{1 - \phi} \tag{4.4}$$

where V_A is the volume of air, V_W is the volume of water, V_S is the volume of solids, V_V is the volume of void-space, V_T is the total volume, and ϕ is the void fraction (porosity) - see Figure 4.16 [24].

The void fraction or porosity ϕ [1] is the ratio of the void volume to the total volume:

$$\phi = \frac{V_V}{V_T} = \frac{V_A + V_W}{V_T} = \frac{V_V}{V_V + V_S} = \frac{e}{1 + e} \tag{4.5}$$

Building thermal inertia block

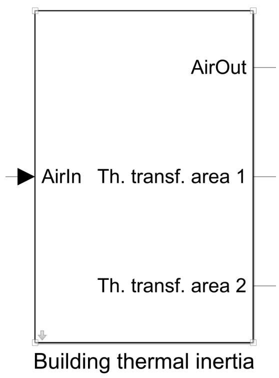


Figure 4.17: Building thermal inertia block

As it was already mentioned, there are two *Building thermal inertia* blocks inside the kiln bed block (Figure 4.17). Table 4.9 shows the S-function parameters, which are to be set. The first block represents the thermal inertia between the floor and the walls of the kiln, the second block - between the ceiling and the walls.

Parameter	Variable	Unit	Value 1	Value 2
Transfer area floor/ceiling	A1	m^2	A	A
Floor/Ceiling thickness	d1	m	dFloor	dCeiling
Thermal resis. trans. area 1	Rth1	$m^2 \cdot K \cdot W^{-1}$	0.17	0.04
Initial temp. trans. area 1	T0_1	°C	40	40
Transfer area wall	A2	m^2	AWall	AWall
Wall thickness	d2	m	dWall	dWall
Thermal resis. trans. area 2	Rth2	$m^2 \cdot K \cdot W^{-1}$	0.13	0.13
Initial temp. trans. area 2	T0_1	°C	30	30
Material	matpop	-	concrete	concrete

Table 4.9: Parameters of thermal inertia blocks

- *Transfer area floor/ceiling* and *Floor/Ceiling thickness* - these parameters of the floor/ceiling are specified automatically from the kiln bed block
- *Thermal resistance transfer area 1* - the value was set according to ISO 6946 [23]
- *Initial temperature transfer area 1* - the estimated temperature of the floor/ceiling at the beginning of the kilning process (an initial condition for the differential equation)
- *Transfer area wall* and *Wall thickness* - these parameters of the wall are specified automatically from the kiln bed block
- *Thermal resistance transfer area 2* - the value was set according to ISO 6946 [23]
- *Initial temperature transfer area 2* - the estimated temperature of the walls at the beginning of the kilning process (an initial condition for the differential equation)
- *Material* - two possibilities: reinforced concrete or steel.

4.2.10 Recirculation damper (flap)

The air-off from the kiln bed can be partly recirculated, this is simulated by the recirculation damper block (Figure 4.18). It has 2 inports: *Fluid1* (the air-off from kiln bed connected) and *Signal* (the ratio of the fresh air to be used[5]). The outports are: *Fluid1Out* (the exhaust air to a heat exchanger or to waste) and *Fluid2Out* (the recirculated air connected). The parameters of both fluids are calculated by S-function *gerTeiler10C*.

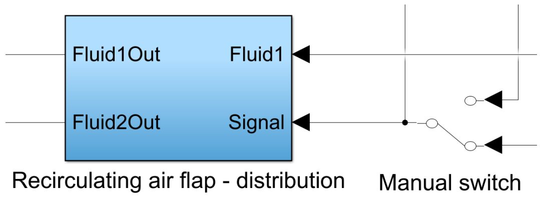


Figure 4.18: Recirculation damper (flap) block

The ratio of air to be recirculated is defined by the recipe recirculation damper position, which is read from the Workspace (*Rezept_Umluftanteil* from *Daten.mat*). Another possibility is to use the dynamic controller by switching *Manual switch* to another position (Figure 4.18) - see Section 4.2.11.

4.2.11 Dynamic controller

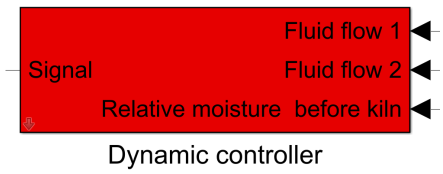


Figure 4.19: Dynamic controller block

The recirculation damper controller (Figure 4.19) can be used for dynamic calculating the optimal ratio of the fresh air, which defines the ratio of air to be recirculated. The block has 3 inports: *Fluid flow 1* (the air-off from the kiln bed connected), *Fluid flow 2* (the fresh air connected) and *Relative moisture before kiln* (the air-on relative humidity). The outport *Signal* represents an optimal ratio of the fresh air to be used.

The optimal ratio is calculated by S-function *RegelungEnthalpieC_TK*. The controller has two operation modes:

- **Relative humidity of exhaust air (the air-off) *mode*** - the optimal ratio is calculated according to the following two S-function parameters:
  - *Target value humidity* [%] - the desired value of the air-off relative humidity (normally, 100 %)
  - *Maximum rel. humidity before kiln* [%] - the maximum air-on relative humidity, which must not be exceed during the kilning process (for example, 15 %)
- **Heat content *mode*** - the optimal ratio is calculated based on the enthalpy and relative humidity of the air-off and the fresh air.

[5]The value between 0 (the air-off is fully recirculated) and 1 (the air-off is not recirculated)

The S-function parameter *Time constant* [s] represents the system inertia and is necessary for the output signal stabilizing.

All the S-function parameters should be set in the input mask of the block (Table 4.10). For the simulated kilning process, the recirculation damper position is adjusted by recipe, therefore the parameters are not set.

Parameter	Variable	Unit	Value
Type of controller	reglerart	-	*not set*
Time constant (system inertia)	zeitk	s	*not set*
Target value humidity	xSoll	%	*not set*
Maximum rel. humidity before kiln	relFvD	%	*not set*

Table 4.10: Parameters of the kiln bed block

4.2.12 Input data

When the kiln model is modified and set to correspond with the real plant, the input data can be inserted into the file *Daten.mat*, which is automatically loaded when the simulation starts (however, it can be changed in the tab *Callbacks* in the model properties in Simulink). The input data include:

- *Rezept_Temperatur_unterHorde* - the time series of the target air-on temperature [°C] (recipe)
- *Rezept_Umluftanteil* - the time series of the recirculation damper position [%] (recipe)
- *Rezept_Ventilatordrehzahl* - the time series of the fan speed [%] (recipe)
- *Wetter_Aussentemperatur* - the time series of the ambient temperature [°C] (weather)
- *Wetter_RelativeAussenfeuchte* - the time series of the fresh air relative humidity [%] (weather)
- *Wetter_Umgebungsdruck* - the time series of the ambient pressure [bar] (weather)
- *WirkungsgradWUET* - the time series of the heat exchanger efficiency [%] (not set for the simulated kiln, since it is not equipped with a glass tube heat exchanger)
- *Zeitintervall_fuer_Ausgabe* - time interval for the simulation results

Time series are presented as a matrix, where the first column is time in seconds, and the second column contains particular values.

4.3 Simulation results and model verification

The simulation model was adjusted according to the real kiln (see Section 4.2). The model verification can be made by comparison of simulated values against measurements obtained from WinCoS[6]. For this purpose, different sets of input data were used: different kilning recipes and different weather conditions (summer, autumn and winter).

The simulated kiln location has a tropical climate. The ambient pressure was set according to the historical weather data from internet [25] (the constant value of 1.008 bar). The ambient temperature and relative humidity are measured values, which were obtained from WinCoS. The target air-on temperature, fan speed and recirculation damper position are determined by the particular kilning recipe, which was defined by a SCADA operator.

4.3.1 Summer conditions

The input data (weather and recipe) for simulation are shown in Figure 4.20.

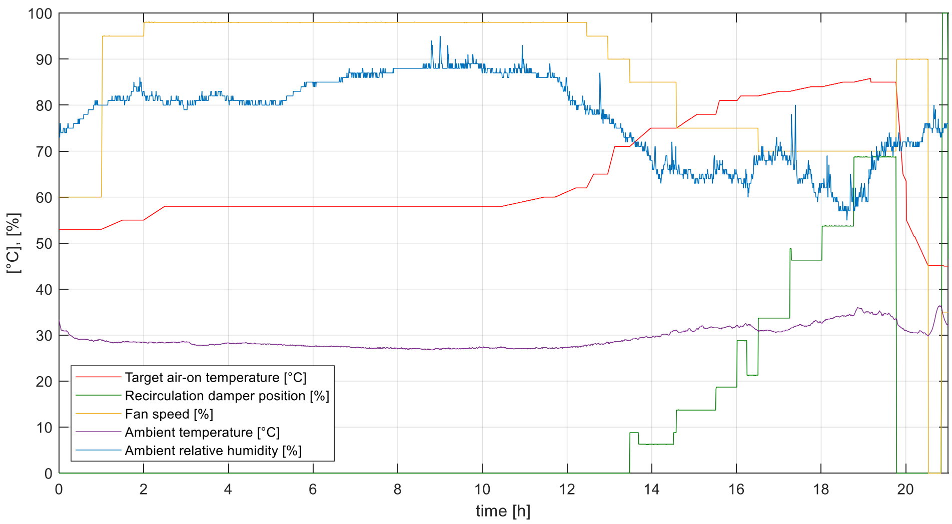


Figure 4.20: Input data (summer conditions)

The simulation results and comparison with measured values are shown in Figure 4.21.

[6]Bühler SCADA system (the name originates from Window Control System)

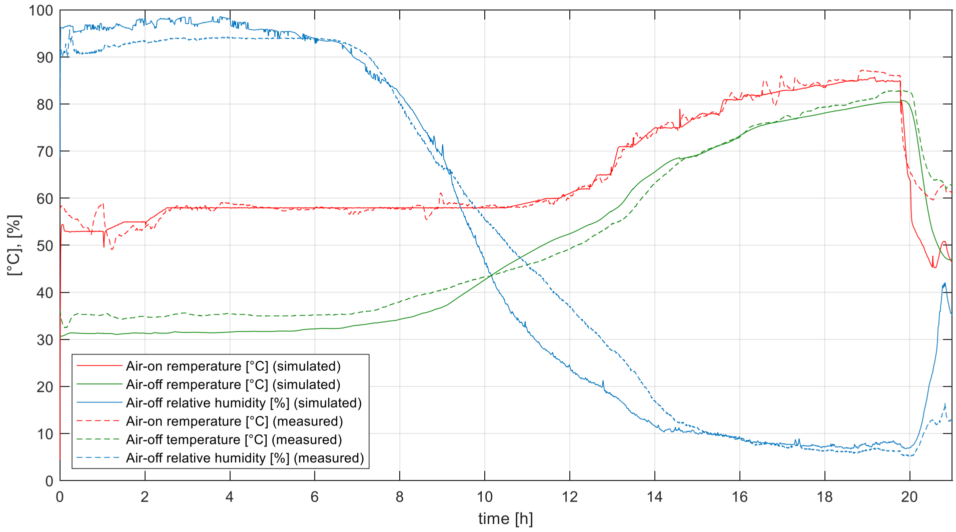


Figure 4.21: Comparison of simulated and measured data (summer conditions)

The simulation results fit the measurements well, except of the cooling phase, where the more significant differences can be observed. It can be caused by different measured and simulated air-on temperatures for cooling: in the real process, the target air-on temperature (see Figure 4.20) was not reached. The prediction of the air-on and air-off temperatures is relatively accurate. The simulated air-off relative humidity fits the measurements worse during the heating phase, the reason can be found in the imperfect simulation of the fan operation.

As it was already mentioned, the model was developed with 10 layers according to Figure 4.14, the simulated malt temperature and moisture content in layers are shown in Figure 4.22.

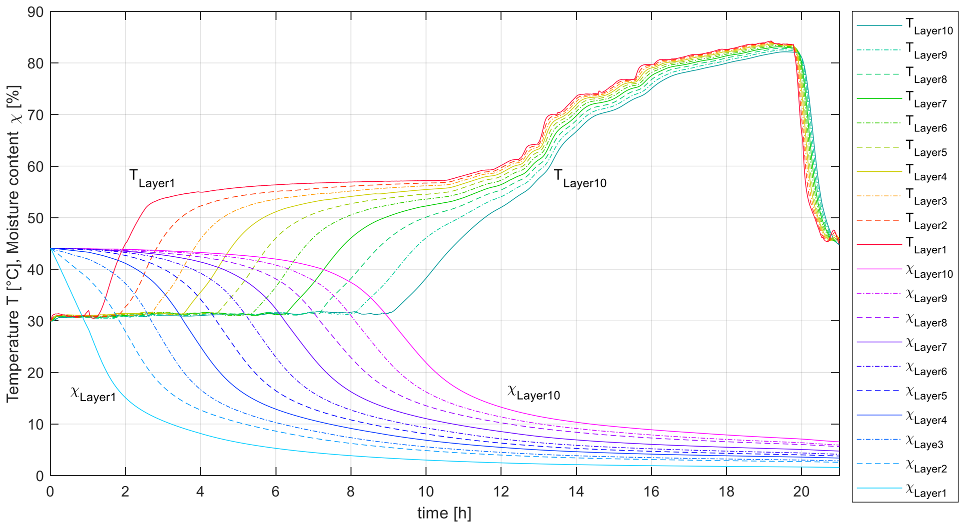


Figure 4.22: Malt temperature and moisture content in layers (summer conditions)

The final average moisture content is about 4 %. The final malt temperature is 45 °C.

The simulated kiln bed pressure drop is presented in Figure 4.23. The maximum pressure drop is at the beginning of the process, and during the withering phase it decreases due to evaporating of the unbound moisture in the malt, which ensures lowering of the resistance to the passing air.

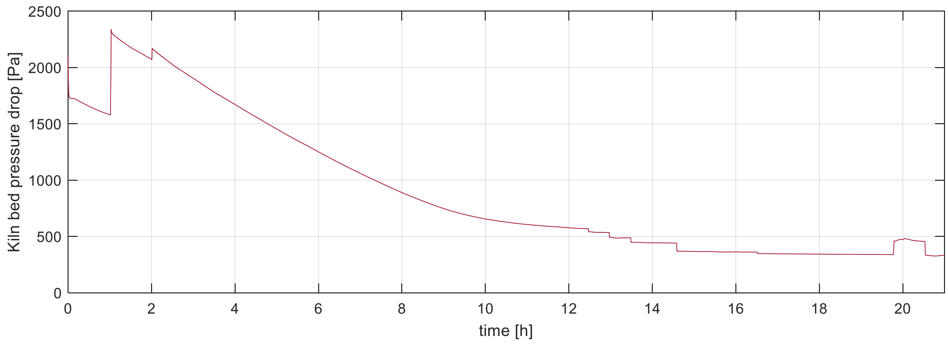


Figure 4.23: Kiln bed pressure drop (summer conditions)

4.3.2 Autumn conditions

The input data (weather and recipe) for simulation are shown in Figure 4.24.

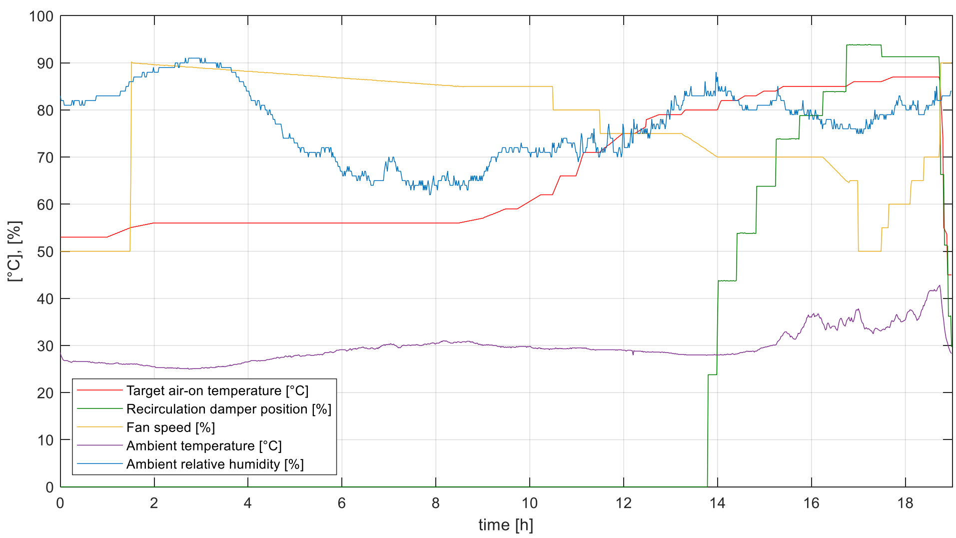


Figure 4.24: Input data (autumn conditions)

The simulation results and comparison with measured values are shown in Figure 4.25.

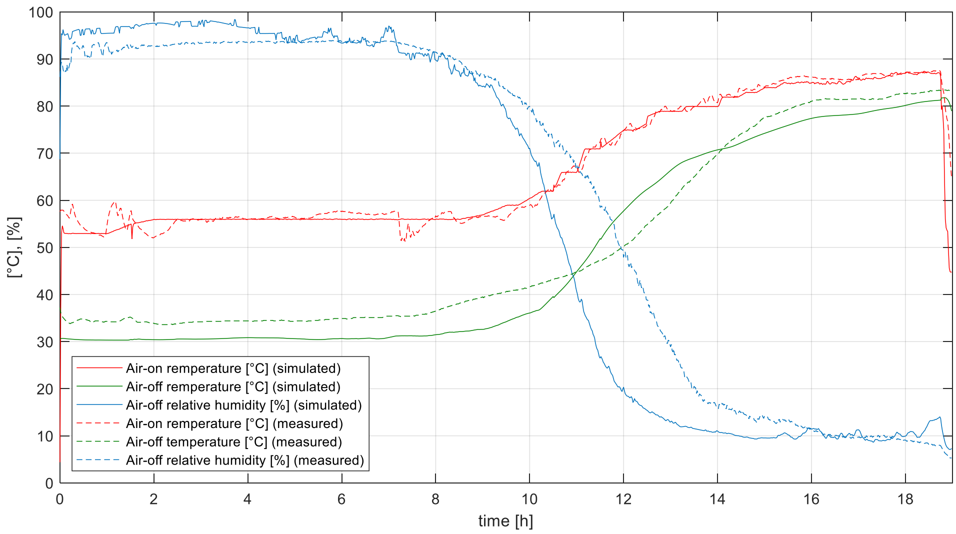


Figure 4.25: Comparison of simulated and measured data (autumn conditions)

The simulation results for the autumn conditions fit the measurements worse than the results in Section 4.3.1. The simulated air-off relative humidity decreases earlier and faster than in reality. This means, that the malt drying rate is higher, the reason can be also found in the imperfect simulation of the fan operation.

The simulated malt temperature and moisture content in layers are shown in Figure 4.26. The final average moisture content is about 5 %. Since the cooling phase was not properly finished (see Figure 4.24 and 4.25), the final malt temperatures have a significant differential between the lower and upper layers.

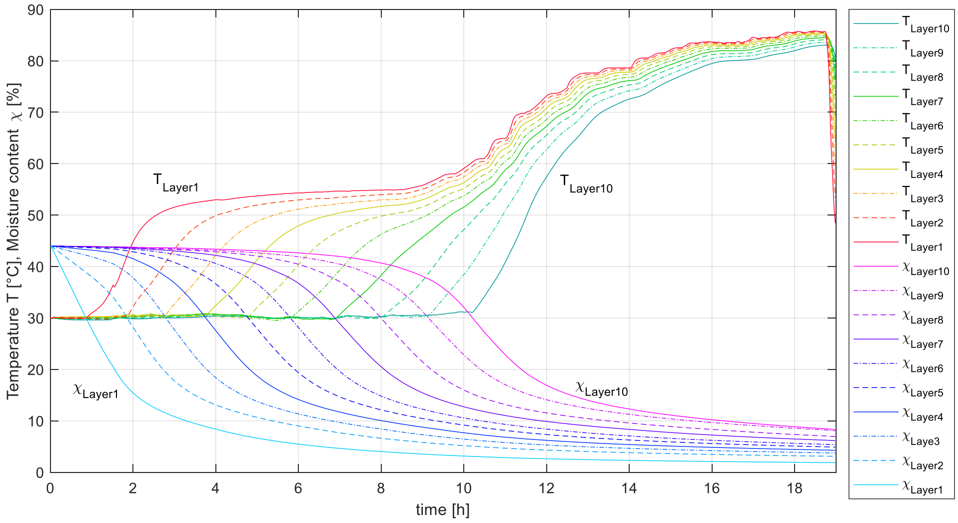


Figure 4.26: Malt temperature and moisture content in layers (autumn conditions)

The simulated kiln bed pressure drop is presented in Figure 4.27.

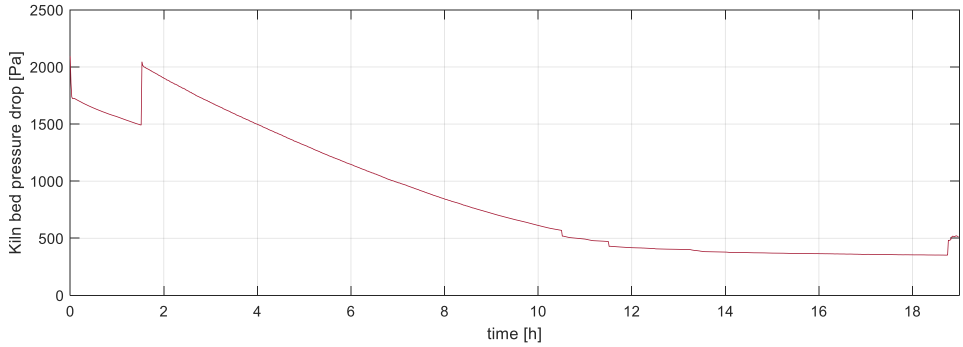


Figure 4.27: Kiln bed pressure drop (autumn conditions)

4.3.3 Winter conditions

The input data (weather and recipe) for simulation are shown in Figure 4.28.

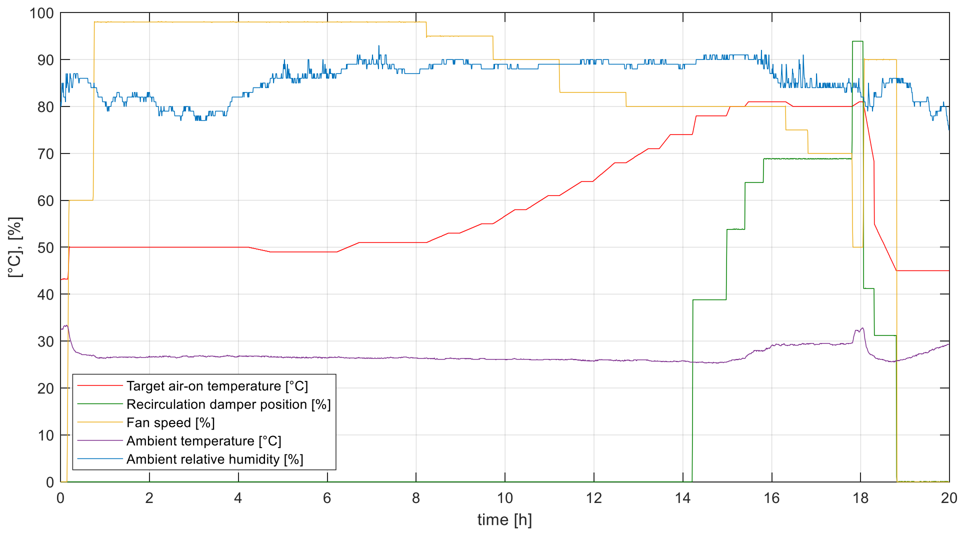


Figure 4.28: Input data (winter conditions)

The simulation results and comparison with measured values are shown in Figure 4.29.

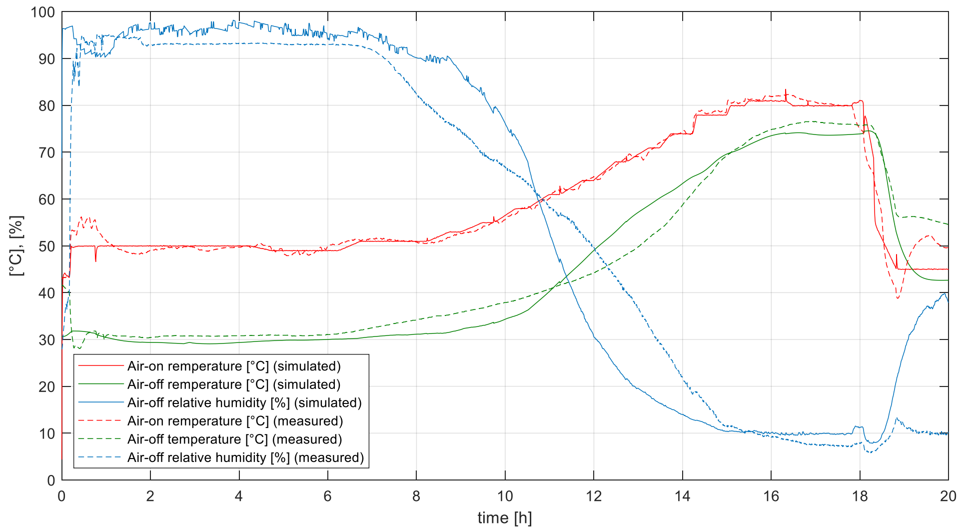


Figure 4.29: Comparison of simulated and measured data (winter conditions)

Except of the cooling phase, the simulation results for the winter conditions fit the measurements better than the results in Section 4.3.2, and worse than the results in Section 4.3.1. The prediction of the air-on and air-off temperatures is relatively accurate. The simulated air-off relative humidity decreases with higher rates than in reality, the reason can be also found in the imperfect simulation of the fan operation.

The simulated malt temperature and moisture content in layers are shown in Figure 4.30. The final average moisture content is about 5 %. The final average malt temperature is 45 °C.

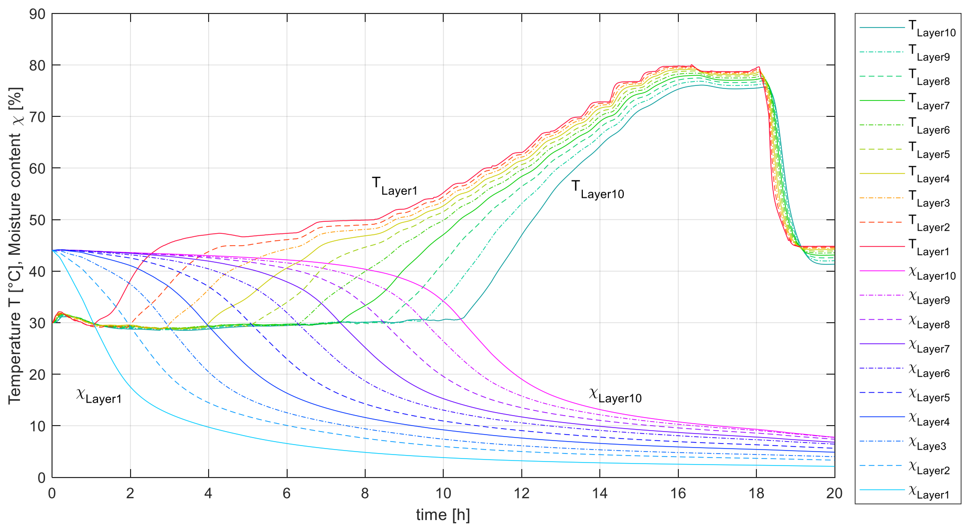


Figure 4.30: Malt temperature and moisture content in layers (winter conditions)

The simulated kiln bed pressure drop is presented in Figure 4.31.

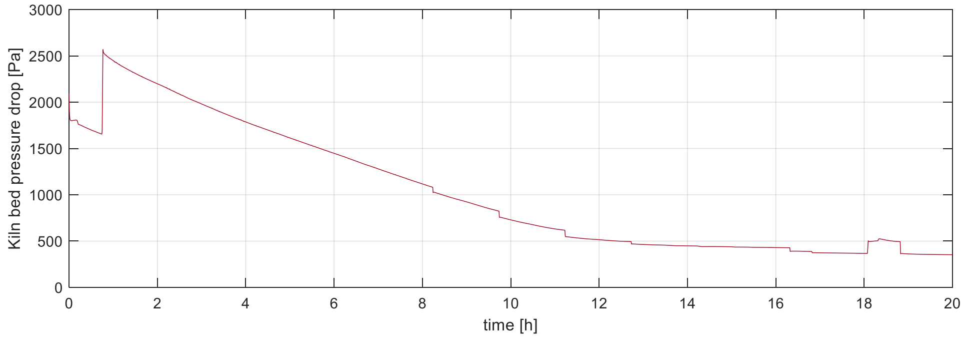


Figure 4.31: Kiln bed pressure drop (winter conditions)

4.4 Model usage for the equipment dimensioning

This section contains suggestions, how the simulation model can be used for the air heater and fan dimensioning for a specific kiln.

4.4.1 Air heater

Since the performance of air heaters is calculated during the simulation, the model can be used to determine the required thermal output of heaters. For this purpose, when setting up the model, the thermal output of the heater has to be set to the fictitious large value (for example, 10^5 kW) - see Section 4.2.5. Input data should contain unfavourable weather conditions possible for the kiln location, which determine the drying ability (the moisture content of the drying air) and the thermal energy consumption for heating. After the simulation, a graph with the thermal output of heaters can be created. Particular air heater should be selected considering a sufficient power (thermal output) margin, for example 20 % power margin.

To give an example of suggested solution using the model of the simulated kiln (Figure 4.4), two simulations were made:

Heater dimensioning with a predetermined pre-heater

An example: *If the pre-heater heat capacity is 5000 kW, what heat capacity of the heater should be?*

The fictitious heat capacity of 10^5 kW is set for the heater block in Simulink. Figure 4.32 shows the simulation results: the thermal output of both air heaters to keep the air-on temperature according to the recipe (see Input data, Figure 4.20, *this is an example without air recirculation*).

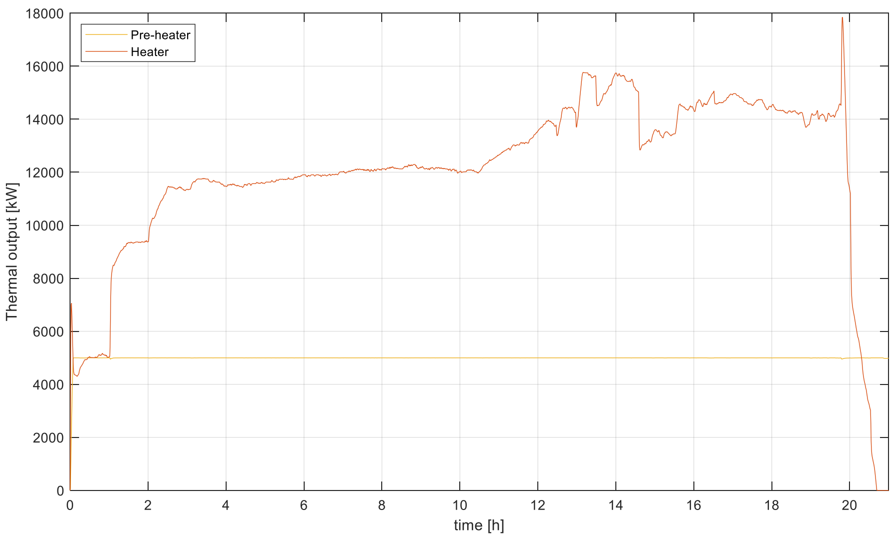


Figure 4.32: Thermal output of air heaters (predetermined pre-heater)

As you can observe, the thermal output of the pre-heater is constantly at its maximum. The maximum value for the heater is around 18000 kW - it represents the overall required heat capacity of air heater. If the heat capacity of air heater supplied by manufacturer is 5500 kW [9], the number of units to be installed can be calculated as:

$$\frac{18000 \cdot 1.2}{5500} = 3.93 \Rightarrow 4 \text{ units required} \tag{4.6}$$

where the coefficient 1.2 represents the power margin of 20 %.

Pre-heater dimensioning with a predetermined heater

An example: *If 4 units of heaters with the heat capacity of 5000 kW are installed, what heat capacity of the pre-heater should be?*

The fictitious heat capacity of 10^5 kW is now set for the pre-heater block in Simulink. Figure 4.33 shows the simulation results: the thermal output of both air heaters to keep the air-on temperature according to the recipe (see Input data, Figure 4.20, *this is an example without air recirculation*).

As you can observe, the air heating is mainly provided by pre-heater, the maximum thermal output of the pre-heater is approx. $2.3 \cdot 10^4$ kW. At the same time, the main heater (4 units) is almost not used during the kilning procees (with maximum thermal output of approx. 650 kW). Such solution for the pre-heater dimensioning **cannot** be used, because the pre-heater does not heat the mixed air. It means that the air-on temperature would not be controlled (installation of the heater with thermal output of 650 kW would be enough). Therefore, it is firstly necessary to select a pre-heater to be installed and subsequently to use the simulation model to determine the required thermal output of the main heater.

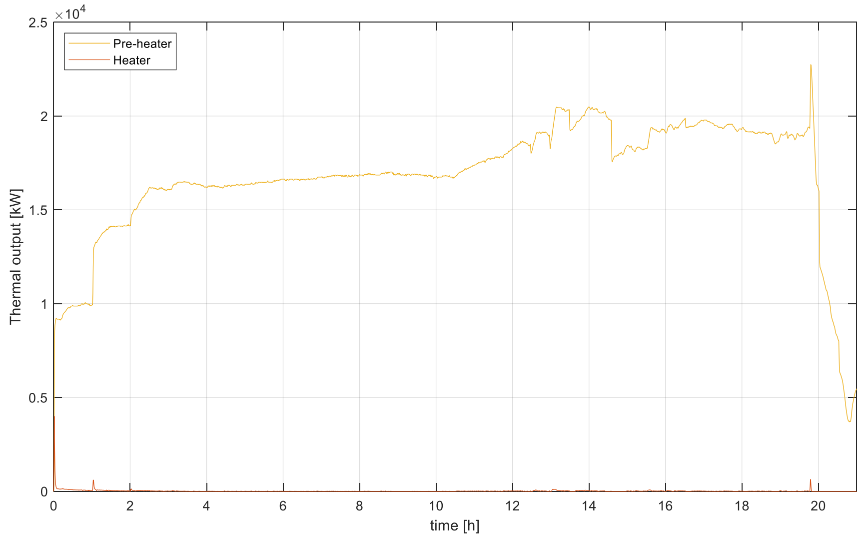


Figure 4.33: Thermal output of air heaters (predetermined heater)

4.4.2 Fan

A large amount of air is required during the withering phase of kilning. Therefore, a fan should be dimensioned to generate the necessary air volume flow in these critical conditions. Using the standard values from the literature [4], [6], the following assumptions can be made to calculate the required volume flow during the withering phase:

- The air volume flow of the fan (fans) has to be from 4300 to 5000 m^3 per hour per ton of malt [6].
- Approximately 82 kg of malt is produced from 100 kg of barley (yield of 82 %, Bühler kilns).
- The batch size of the malting plant is 360 t of barley (see Table 4.8).

Then, the required volumetric flow rate during the withering phase can be calculated as:

$$\dot{V}_{\text{withering}} = 5000 \cdot 360 \cdot 0.82 = 1.476 \cdot 10^6 \; [\text{m}^3 \cdot \text{h}^{-1}] \tag{4.7}$$

The required volumetric flow rate during the withering phase can be higher due to the different kilning technology (for example, for reducing the time needed to reach the break point - see Section 3.2.3). Another factor to be considered is the approximated yield used.

The simulation model can be used for checking the fan performance during the process. When the fan parameters (mainly, the performance curves) from manufacturer are set in Simulink (see Section 4.2.7), the simulation can be started. If the results show, that the fan doesn't generate enough volume flow, another fan has to be chosen and checked again by the simulation model. The final fan is determined, when the desired results of kilning are achieved.

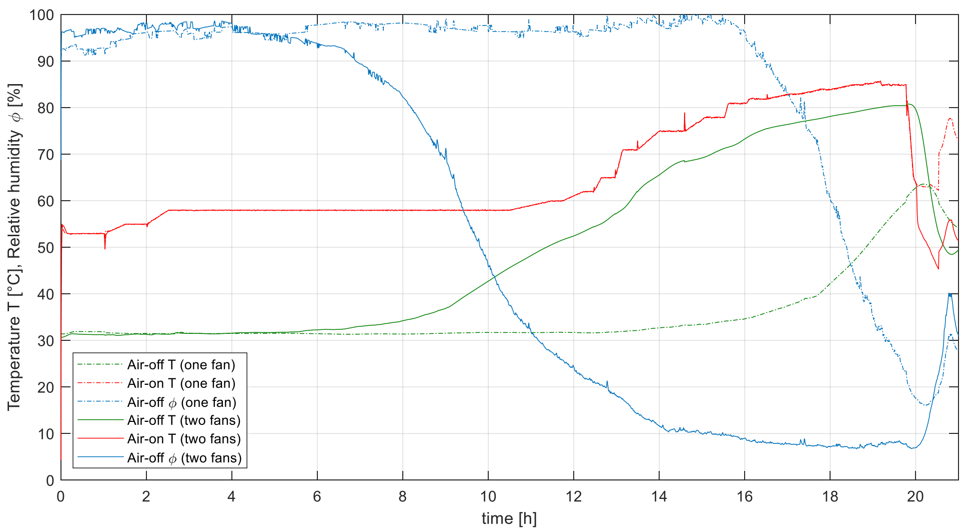


Figure 4.34: Simulation results with one and two fans operating

To give an example of suggested solution using the model of the simulated kiln (Figure 4.4), two simulations were made: with one and two fans operation during the process. Figure 4.34 shows the results of both simulations. As you can observe, the two fans operation ensures the desired kilning process. But one fan cannot generate enough volumetric flow rate, the consequences are:

- The break point is reached too late. The withering phase lasts more than 17 hours

- The curing phase is not occurred, it means that flavour, aroma and colour substances in malt were not formed. It follows that such malt cannot be used in brewing.

- The final moisture content of malt is too high, the upper layer has more than 12 % (Figure 4.35). It follow that such malt is not storable.

- The significant difference of the final malt temperature and moisture content between the lower and upper layers (Figure 4.35). The values during the desired kilning process are shown in Figure 4.22.

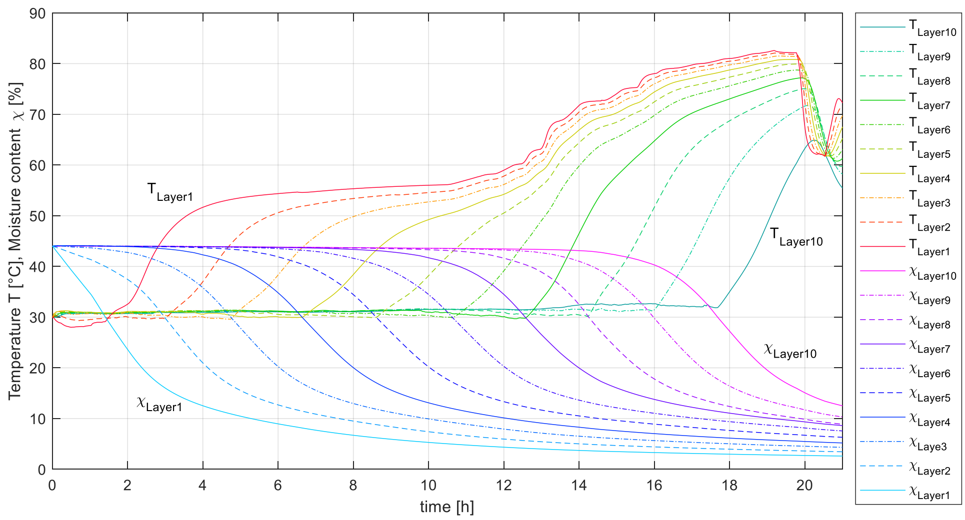


Figure 4.35: Grain temperature and moisture content in layers (one fan operation)

4.5 Optimization of the kilning process

The simulation model can be also used for creation and optimization of the kilning recipes. This section contains the sequence of actions to create an optimized kilning recipe for the simulated kiln. For this purpose, the weather data from Figure 4.20 were used. Figure 4.36 shows overall thermal output and electric power for the original recipe.

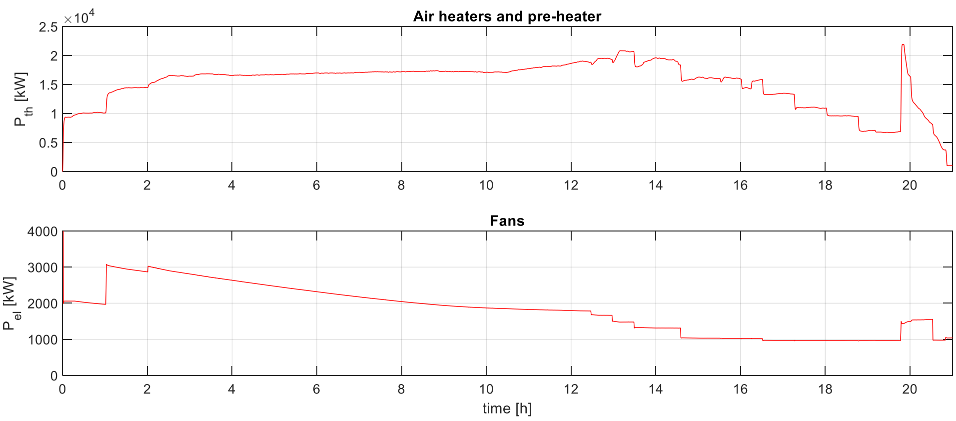


Figure 4.36: Overall thermal output and electric power (original recipe)

4.5.1 Break point identification

The first step is to identify the break point, which determines, how long the withering (free drying) phase lasts. For the pale malt production, the withering phase is typically carried out at 55 °C temperature of the air-on [4]. This stage requires a high amount of air - the fans have to be at maximum speed. The air-off cannot be recirculated, because of its high moisture content and low temperature - the damper position is 0 %. For the detailed process description, see Section 3.2.3.

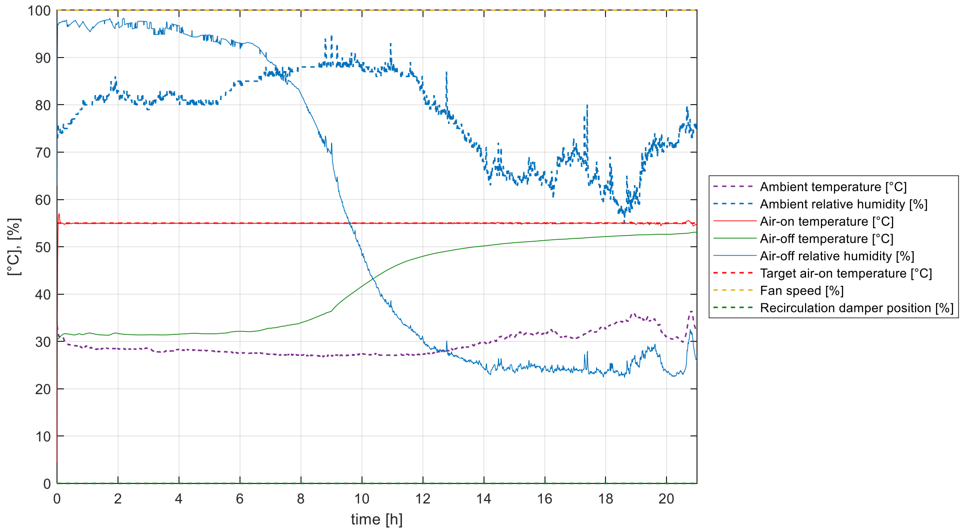


Figure 4.37: Break point identification

Figure 4.37 shows the simulation results: the dashed lines represent input data (weather and recipe), the solid lines represent simulated values. As you can observe, the break point is at approx. 8 hours.

4.5.2 Heating and curing phases

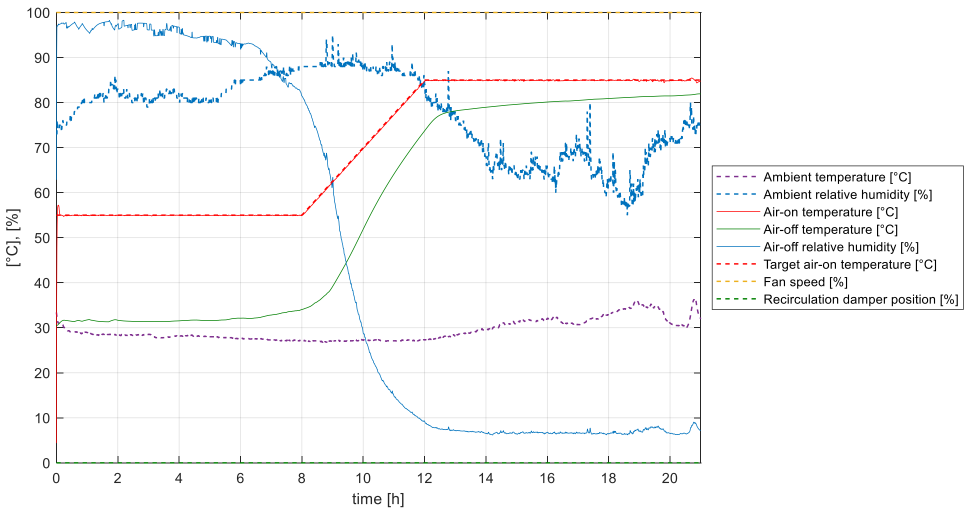


Figure 4.38: Input data and simulation results (no optimization)

The heating phase follows after the break point - the air-on temperature is gradually increased up to the curing temperature (typically, 85 °C for pale malt) during 3-4 hours (see Section 3.2.3). The simulation results are shown in Figure 4.38.

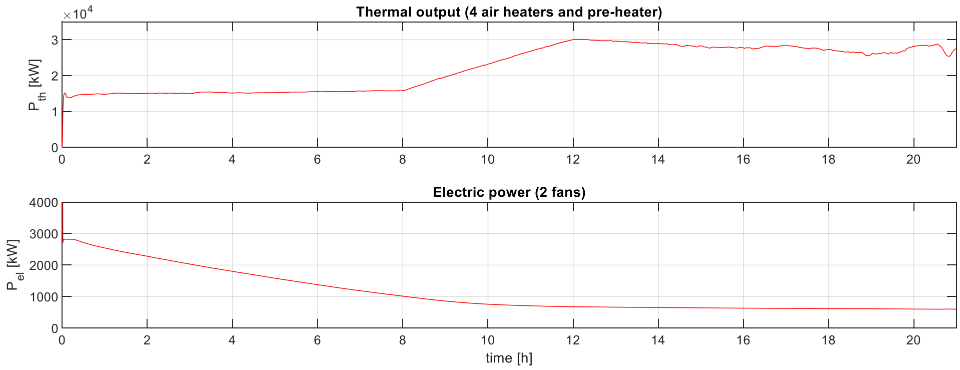


Figure 4.39: Overall thermal and electric power (no optimization)

Thermal output of all air heaters (pre-heater and 4 heaters) and electric power of 2 fans during the simulation are shown in Figure 4.39. As you can observe, the thermal output during curing is very high with its peak of 30 MW at 12 hours. The energy consumption is shown in Table 4.11.

	Energy [kWh]	Energy [MJ]	per ton of barley $[\frac{\text{kWh}}{\text{t}}]$
Electric	23 578	84 881	65.5
Thermal	466 050	1 677 780	1 294.6

Table 4.11: Overall thermal and electric energy consumption (no optimization)

4.5.3 Fan speed adjustments

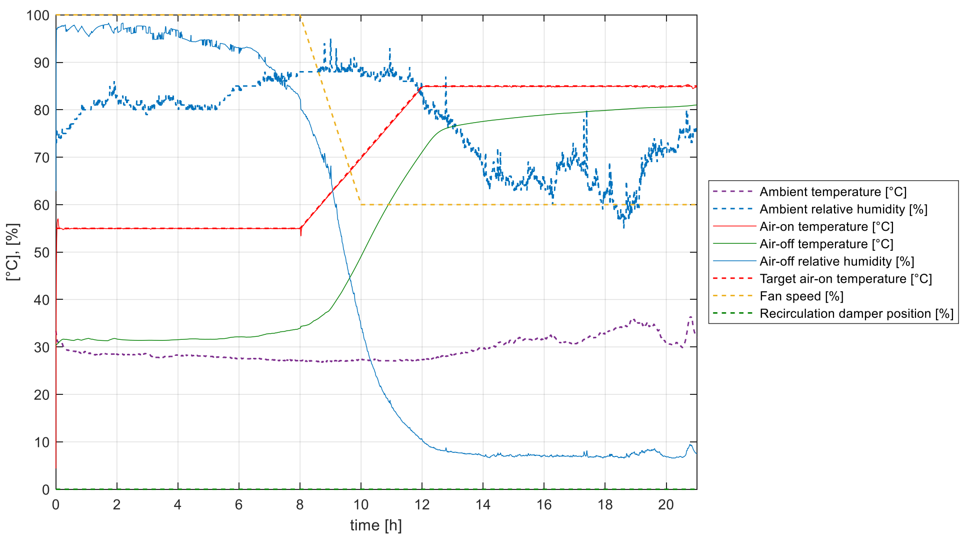


Figure 4.40: Input data and simulation results (with fan speed optimization)

When the break point is reached, the fan speed has to be reduced to 50-60 % for energy saving. The kiln bed pressure drop is less then before, and the moisture removing rate is no longer constant, it is decreasing (see Section 3.2.3).

The simulation results are shown in Figure 4.40. As you can observe in comparison with Figure 4.38, the air-off temperature has not significantly changed with reducing the fan speed after the break point.

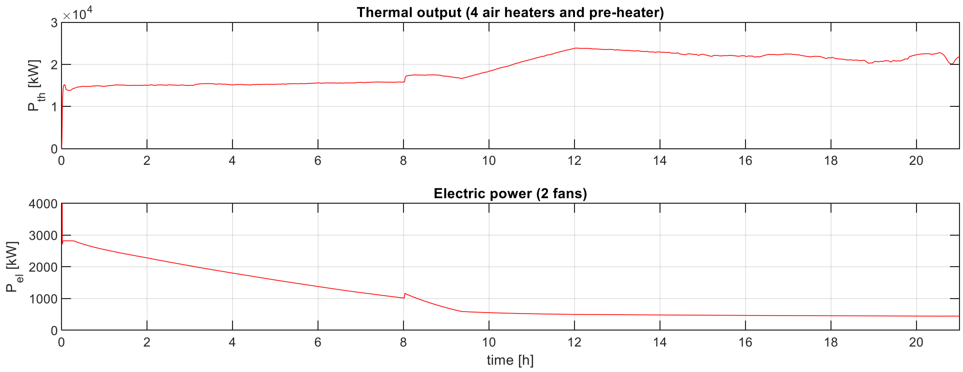


Figure 4.41: Overall thermal and electric power (with fan speed optimization)

Thermal output of all air heaters and electric power of fans during the simulation are shown in Figure 4.41. The energy consumption is shown in Table 4.12: the fan speed reducing after the break point allowed to save 8.9 % of electric energy and 14.6 % of thermal energy in comparison with the previous simulation (Table 4.11).

	Energy [kWh]	Energy [MJ]	per ton of barley $[\frac{kWh}{t}]$
Electric	21 484	77 342	59.7
Thermal	398 000	1 432 800	1 105.6

Table 4.12: Overall thermal and electric energy consumption (with fan speed optimization)

4.5.4 Process time reduction and cooling phase

The curing phase should take about 3-5 hours to allow flavour and colour substances formation in malt (see Section 3.2.3). Due to the faster withering phase in the optimized recipe, the original time of process (21 hours) is excessive, and the curing phase lasts too long (9 hours). Therefore, the time of curing should be reduced to 5 hours. The cooling phase follows after curing to stop further malt colouring and enzyme activity impairment: the malt is cooled at 45 °C (similarly to the original recipe) with high air volume rate (100 % of fan speed).

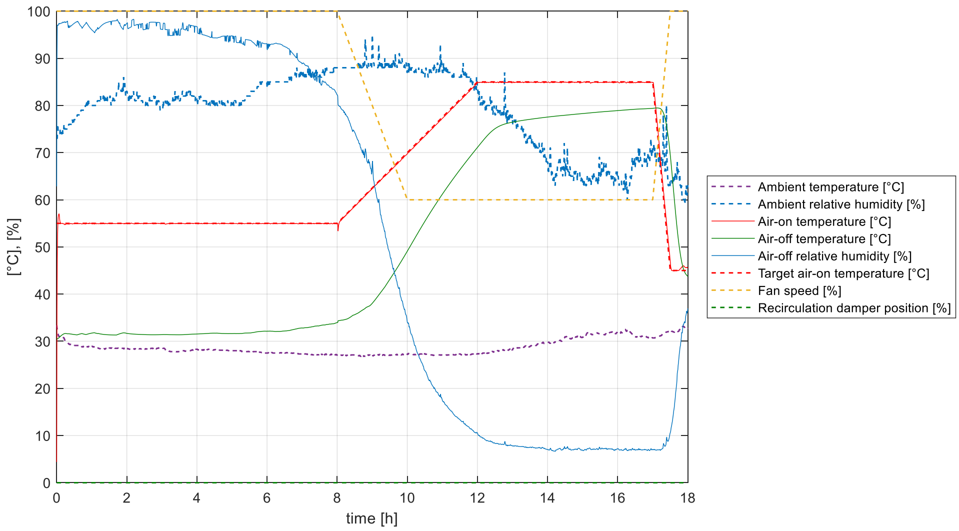


Figure 4.42: Input data and simulation results (with process time reduction and cooling)

The simulation results are shown in Figure 4.42. As you can observe, the process time was reduced to 18 hours.

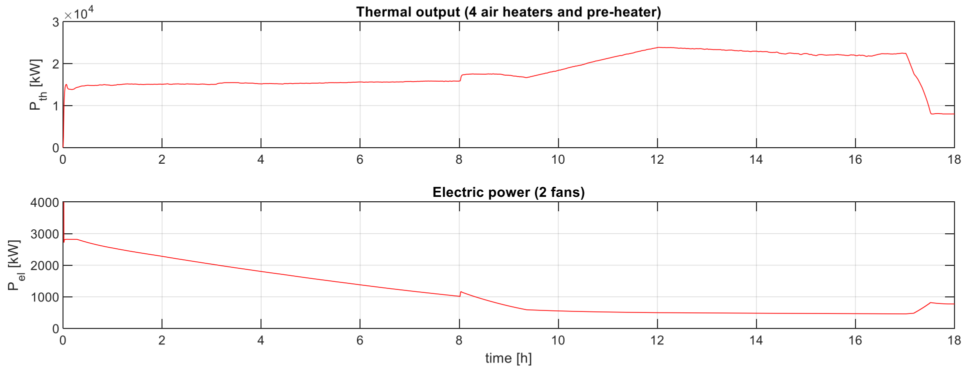


Figure 4.43: Overall thermal and electric power (with process time reduction and cooling)

Thermal output of all air heaters and electric power of fans during the simulation are shown in Figure 4.43.

	Energy [kWh]	Energy [MJ]	per ton of barley $[\frac{kWh}{t}]$
Electric	20 338	73 217	56.5
Thermal	324 940	1 166 400	902.6

Table 4.13: Overall thermal and electric energy consumption (with process time reduction and cooling)

The energy consumption is shown in Table 4.13: the process time reducing allowed to save 5.3 % of electric energy and 18.4 % of thermal energy in comparison with the previous simulation (Table 4.12).

4.5.5 Recirculated air

After the break point, when the air-off relative humidity decreases under 15 %, the air can be partly recirculated or reused for withering in another kiln or deck (see Section 3.2.3 and 3.3.1). The recirculation damper position is gradually increasing to 80 % and during cooling it has to to be closed.

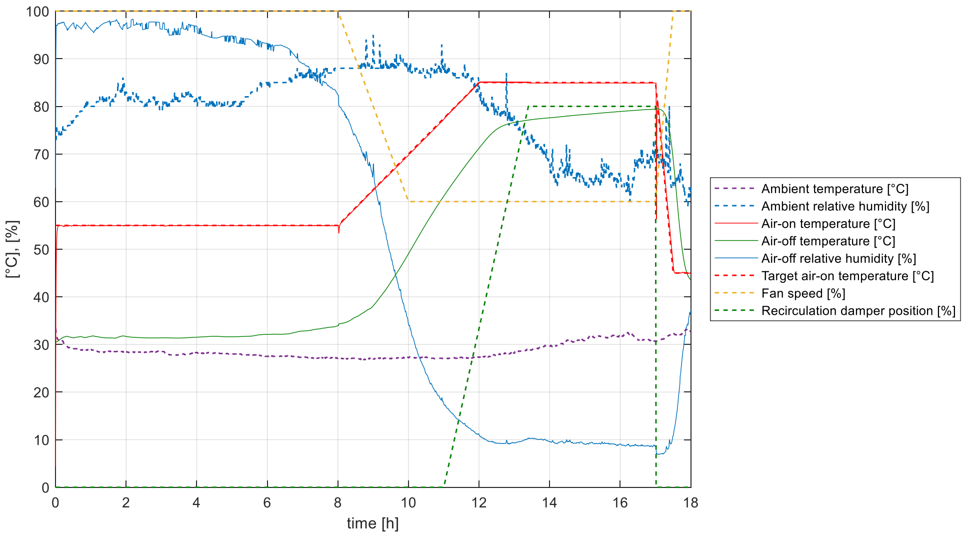


Figure 4.44: Input data and simulation results (with recirculated air)

The simulation results are shown in Figure 4.44. As you can observe, the air recirculation has no impact on the air-off temperature and relative humidity, but it allows to reduce thermal output of air heaters during heating and curing (Figure 4.45).

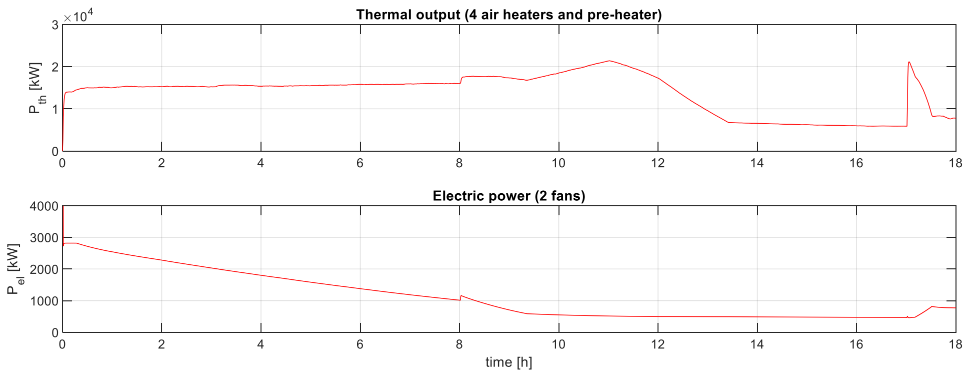


Figure 4.45: Overall thermal and electric power (with recirculated air)

Thermal output of all air heaters and electric power of fans during the simulation are shown in Figure 4.45. The energy consumption is shown in Table 4.14: the air recirculation caused a negligible increase of electric energy (0.2 %), but allowed to save 23.6 % of thermal energy in comparison with the previous simulation (Table 4.13).

	Energy [kWh]	Energy [MJ]	per ton of barley $[\frac{kWh}{t}]$
Electric	20 373	73 343	56.6
Thermal	248 340	894 024	689.8

Table 4.14: Overall thermal and electric energy consumption (with recirculated air)

4.5.6 Final recipe

As you can observe in Figure 4.45, the overall thermal output exceeds 2 kW at 11 hours (at the beginning of the recirculated air using) and at 17 hours (when the damper is abruptly closed). The better solution would be to use the recirculated air earlier (at 10 hours) and to close the damper gradually with the fan speed increasing.

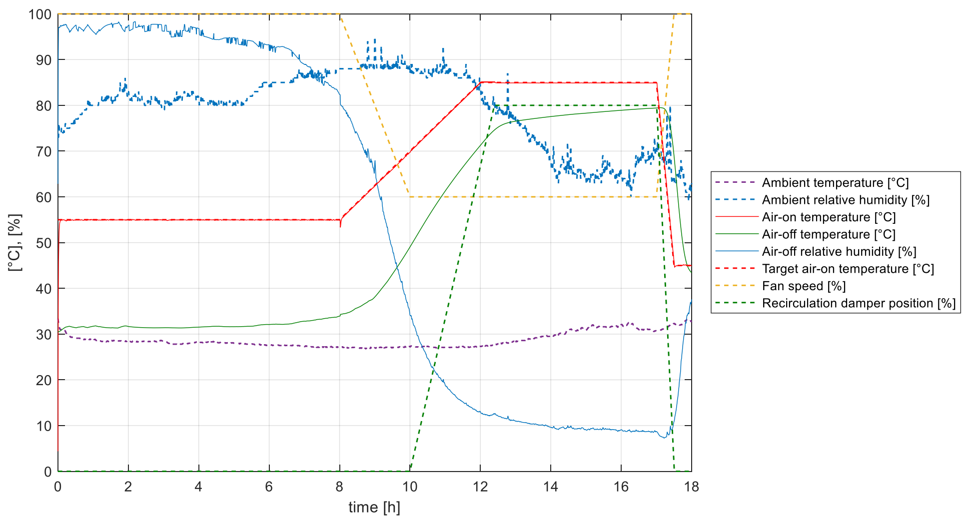


Figure 4.46: Input data and simulation results (final recipe)

The simulation results are shown in Figure 4.46. As you can observe, the results were not influenced, but the overall thermal output of air heaters during heating and curing was reduced (Figure 4.47).

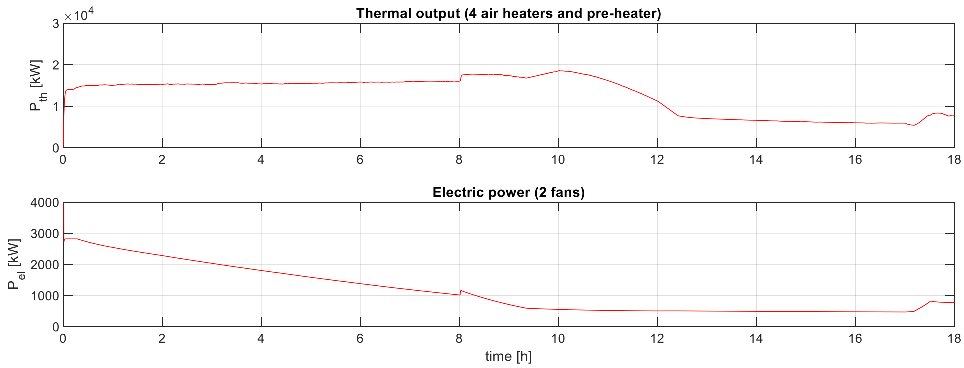


Figure 4.47: Overall thermal and electric power (final recipe)

Thermal output of all air heaters and electric power of fans during the simulation are shown in Figure 4.45. The energy consumption is shown in Table 4.14: the electric energy consumption were almost not influenced, but the recipe changes allowed to save further 7.4 % of thermal energy in comparison with the previous simulation (Table 4.14).

	Energy [kWh]	**Energy [MJ]**	**per ton of barley** $[\frac{\mathbf{kWh}}{\mathbf{t}}]$
Electric	20 383	73 379	56.6
Thermal	230 050	828 180	639.0

Table 4.15: Overall thermal and electric energy consumption (final recipe)

Figure 4.48 shows the malt temperature and moisture content for the optimized recipe: the process takes only 18 hours and the target malt temperature and moisture content are achieved.

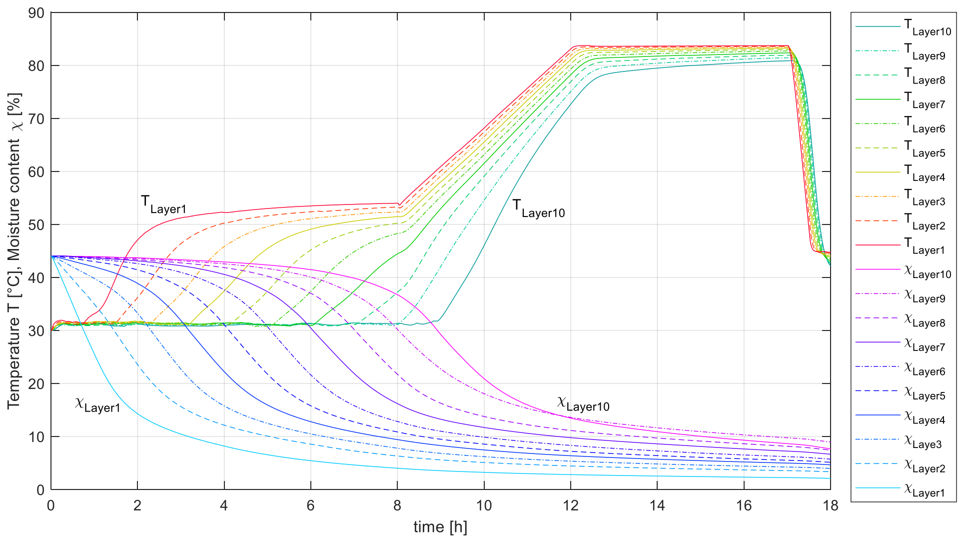


Figure 4.48: Malt temperature and moisture content in layers (final recipe)

4.5.7 Process time and energy consumption

When the kilning recipe is optimized, the highest thermal and electric energy consumption is for the withering phase. The time required to reach the break point mainly depends on the amount of the air passing through the malt and the moisture content in the air. During withering, the air temperature is not a decisive factor for the pale malt production, but it affects the enzyme activity (see Section 3.2.3).

The amount of air is defined by fan speed, therefore the process time can be extended with the fan speed reduction. Five simulations with different fan speeds were done to find out the relation between withering time and energy consumption. For this experiment, the withering time was defined as the time, when the air-off relative humidity decreases under 80 %. To equalize the weather conditions, the constant average values for the kiln location were set:

- Ambient temperature $T_{amb} = 30$ °C
- Ambient relative humidity $\phi_{amb} = 80$ %
- Atmospheric pressure $p_a = 1.008$ bar

The relation between withering time and energy consumption for withering is shown in Figure 4.49.

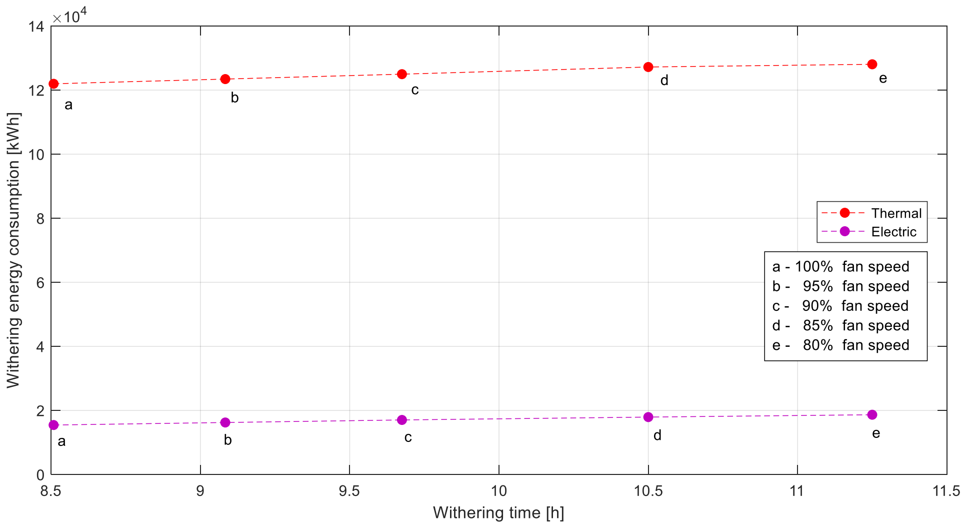


Figure 4.49: Withering energy consumption

The results show, that minimum thermal and electric energy consumption for the withering phase is reached with the 100 % fan speed ensuring the shortest process time. The reason can be found in the higher amount of thermal losses for a longer kiln operation. The duration and temperatures of the curing phase is defined by the technology of the malt being produced. Therefore, to reach the highest kiln efficiency, the kilning process has to be finished in the shortest possible time, which the malt technology could allow. The shorter the process time, the more the amount of malt can be produced during a typical 24 hours cycle in a malting plant.

Chapter 5

Conclusions

Malting is a complex and lengthy technological process. To understand the specific content, the theoretical part provides with the theory of malting and the equipment used in a modern malting plant (Chapter 2). Firstly, all the steps of the malt production are described:

- Intake, cleaning, grading and storage
- Steeping
- Germination
- *Kilning*
- Finishing, storage, blending, dispatch

The kilning process is described in detail in the separate chapter (Chapter 3), where you can find the theory of the kilning process including four phases: withering, heating, curing and cooling. The kiln equipment is described, then description of the most widely used types of kilns follows.

The practical part is dedicated to the simulation of the kilning process in a single-deck circular kiln. Firstly, the practical part is focused on analysing the model, its modification and setting according to the selected real kiln (Figure 4.4). The model parameters were set using the Bühler data, documentation from manufacturers and ISO standards.

The simulation model verification was done by comparison of simulated values against measurements (see Section 4.3). For this purpose, three different sets of input data were used: different kilning recipes and different weather conditions (summer, autumn and winter). In my opinion, the model predicts the measurements well, taking into account the complexity of the system. However, some improvements are needed. The simulated heating phase has higher drying rates of the malt than in reality. The reason can be found in the imperfect simulation of the fan operation. The most significant differences were observed for the cooling phase of the process. It is worth noting, that the cooling phase is the shortest phase of the kilning, which is not energy intensive. Even though some inaccuracies, the model can be used as a tool for the prediction of the approximate energy consumption.

A batch (piece) of malt is represented by 10 discrete layers (Figure 4.14). The moisture content and temperature of each layer is calculated with the uniform distribution within the layer. The model does not take in account the universal un-/loading and levelling machine (see Section 3.3.1), which is not used during the kilning process, but is still presented in the kiln. During loading, the un-/loader may press the malt in a certain position, which will cause an increase of the product resistance to the drying air. The air follows a path of least resistance, and the pressed areas remain wet. The imperfect air distribution in the plenum chamber can also be a reason of wet areas.

Besides the changes in moisture content and temperature, malt has also other important characteristics and changes occurring during the kilning process: termination of grain germination and modification, enzyme activity, formation of flavour and colour substances in malt. Precise simulation of these characteristics is not possible, due to numerous influencing factors: barley variety, climatic conditions of the year and the previous steps of malting: mainly, steeping and germination. Therefore, the simulation model cannot be used for the prediction of the malt quality and its character. The main use of the model can be for the kilning process investigation from the energy point of view, based on the changes of the malt temperature and moisture content.

The practical part continues with suggestions how the model can be used for the air heater and fan dimensioning. Since the model calculates the air heaters thermal output, the required overall thermal output can be determined using the fictitious large value of the heater thermal output. The power margin has to be taken into account. For this simulation, unfavourable weather conditions (possible for the kiln location) has to be set. The weather data influences the drying ability (the moisture content of the drying air) and thermal energy consumption for heating - see Section 4.4.1.

The model usage for the fan dimensioning is more complicated. Firstly, an approximate value of the required volumetric flow rate for the withering phase has to be manually calculated. Then a fan is selected and its operation can be checked by simulation after setting the fan block in Simulink according to the documentation from manufacturer. The fan is determined using an iterative method, when the desired results of the kilning process are achieved - see Section 4.4.2.

Finally, the practical part describes different possibilities to reduce thermal and electric energy consumption for the kilning process (see Section 4.5). The following possibilities were simulated:

- Fan speed adjustment - lowering of the fan speed after the break point reduces thermal and electric energy consumption
- Process time reducing - possible higher rates of malt drying during the withering phase with a higher amount of air

- Air recirculation - since the air-off contains less moisture content after the break point, it can be reused to reduce thermal energy consumption

The results of simulations with modified recipes are compared. The final energy savings achieved are 13.6 % of electric energy and 50.6 % of thermal energy in comparison with the recipe without any optimization.

Once the unbound moisture in the lower layer is removed, the drying rate decreases and the layer temperature starts to increase. At this point, the air-on temperature could be increased gradually to the curing temperatures to reduce the process time. At the same time, it should be taken into account, that higher air-on temperature can damage the enzyme activity in the upper layers, which are still in stewing conditions.

In future, investigation can be continued with researching an optimal course of the withering air-on temperature. It would allow to minimize the process time. The shorter the process time, the higher the kiln efficiency (see Section 4.5.7). Productivity is a crucial parameter for the malting plants. In many cases, production schedule is planned according to the full capacity run 360 days per year. Considering this, minimizing the process time would have a direct positive relation with the generated income, and is an important point of interest for malting process optimization.

Appendices

Appendix A

Symbols

$\dot{V}$	Volumetric flow rate	$[m^3 \cdot h^{-1}]$
ρ	Density	$[kg \cdot m^{-3}]$
c_p	Specific heat capacity (at constant pressure)	$[kJ \cdot kg^{-1} \cdot K^{-1}]$
T	Temperature	[°C]
p	Pressure	[bar]
χ	Specific humidity (moisture content, humidity ratio)[1]	$[g \cdot kg^{-1}]$, [%]
ϕ	Relative humidity, void fraction[1]	[%], [1]
η	Dynamic viscosity, efficiency[1]	$[Pa \cdot s]$, [%]
λ	Thermal conductivity	$[W \cdot m^{-1} \cdot K^{-1}]$
u	Moisture content	[%]
m	Mass	[kg]
h	Specific enthalpy	$[kJ \cdot kg^{-1}]$
P	Power	[kW]
k	Overall heat transfer coefficient	$[W \cdot m^{-2} \cdot K^{-1}]$
A	Area	$[m^2]$
e	Void ratio	[1]

[1] depends on the context

Appendix B

Bibliography

[1] PIERRE-ALAIN DORANGE. Malt en grain. In: *Wikimedia Commons* [online]. 2013 [cit. 2019-06-05]. Available at: https://commons.wikimedia.org/wiki/File:Malt_en_grain.JPG.

[2] BRIGGS, Dennis E. *Malts and Malting.* New York: Springer US, 1998. ISBN 978-0-412-29800-4.

[3] Máčírna - napouštění náduvníku. In: *MOPOS* [online]. Olomouc: Moravské potravinářské strojírny, ©2019 [cit. 2019-08-10]. Available at: https://www.mopos.com/data/filecache/43/macirnaA.jpg.

[4] KOSAŘ, Karel a Stanislav PROCHÁZKA. *Technologie výroby sladu a piva.* 3. vyd., 2. na CD-ROM. Praha: Výzkumný ústav pivovarský a sladařský, 2012. ISBN 978-80-86576-52-7.

[5] Kruhová klíčírna. In: *MOPOS* [online]. Olomouc: Moravské potravinářské strojírny, ©2019 [cit. 2019-08-10]. Available at: https://www.mopos.com/data/filecache/46/obrazek_131.jpg.

[6] KUNZE, Wolfgang. *Technology Brewing & Malting.* 5th edition. Berlin: VLB Berlin, 2014. ISBN 978-3-921690-77-2.

[7] Free Online Interactive Psychrometric Chart. *FlyCarpet* [online]. Fresh Meadows (NY): FlyCarpet, ©2019 [cit. 2019-08-10]. Available at: http://www.flycarpet.net/en/PsyOnline.

[8] ANOX-crosssection. In: *Air Fröhlich – Wärmetauscher* [online]. Oberaach: Air Fröhlich Engineering, ©2012-2019 [cit. 2019-07-10]. Available at: https://www.afe.swiss/en/malzbereich-2/.

[9] Flucorrex: Heat Technology for Malting and Drying Processes. In: *[Taniplan Oy | Ventilation equipments...]* [online]. 2011 [cit. 2019-06-15]. Available at: https://www.taniplan.fi/userData/taniplan/tiedostot/prosessilammonsiirtimet/eng/Malting-and-drying-process-2011.pdf.

[10] Kruhový hvozd. In: *MOPOS* [online]. Olomouc: Moravské potravinářské strojírny, ©2019 [cit. 2019-08-10]. Available at: `https://www.mopos.com/data/filecache/f8/obrazek_130.jpg`.

[11] BÜHLER. *KILN PLANT: Flowsheet.* Uzwil, ©2019.

[12] *Bühler. Simulationsmodell für den Malztrocknungsprozess: Documentation.* 2013.

[13] SLAD: Sladování ječmene - výrobní postup. *[Sladovna Bruntál - tradiční dodavatel sladu...]* [online]. Bruntál: SLADOVNA, ©2019 [cit. 2019-06-05]. Available at: `http://www.sladovnabruntal.cz/slad/`.

[14] Fuels - Higher and Lower Calorific Values. *Engineering ToolBox* [online]. 2003 [cit. 2019-07-15]. Available at: `https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html`.

[15] Malt. In: *Wikipedia: the free encyclopedia* [online]. San Francisco (CA): Wikimedia Foundation, 2019 [cit. 2019-05-12]. Available at: `https://en.wikipedia.org/wiki/Malt`.

[16] HOFFMANN, Pavel a Iva FILKOVÁ. *Výrobní linky potravinářské.* 2. vyd. Praha: Vydavatelství ČVUT, 1999. ISBN 80-01-02003-7.

[17] BASAŘOVÁ, Gabriela. *Sladařství: teorie a praxe výroby sladu.* Praha: Havlíček Brain Team, 2015. ISBN 978-80-87109-47-2.

[18] GOLDER, Animes Kr. and Vaibhav V. GOUD. *Chemical Engineering Design - II* [online]. Guwahati: Indian Institute of Technology Guwahati [cit. 2019-06-10]. Available at: `https://nptel.ac.in/courses/103103027/16`.

[19] MAIANTI, Rafael. *Kilning.* 2018.

[20] BOLL, Chris. Axial Vs Centrifugal Blowers: Which Is Best For You? *OPE Reviews: Reviews of landscaping tools and outdoor power equipment* [online]. Lakeland (FL): OPE Reviews, ©2016-2019 [cit. 2019-07-12]. Available at: `https://opereviews.com/news/axial-vs-centrifugal-blowers-best/`.

[21] *Home. - BUHLERGROUP.com* [online]. Uzwil: Bühler Holding, ©2019 [cit. 2019-07-15]. Available at: `https://www.buhlergroup.com/`.

[22] *Simulink® User's Guide* [online]. Natick (Massachusetts): The MathWorks, 2019 [cit. 2019-06-15]. Available at: `https://www.mathworks.com/help/pdf_doc/simulink/sl_using.pdf`.

[23] ISO 6946. *Building components and building elements - Thermal resistance and thermal transmittance - Calculation method.* Second edition. Geneva: ISO, ©2007.

[24] ROSEKE, Bernie. How to Calculate Void Ratio. *ProjectEngineer — Building Better Project Managers* [online]. Calgary: Rivergreen Software, ©2019 [cit. 2019-07-20]. Available at: https://www.projectengineer.net/how-to-calculate-void-ratio/.

[25] *Timeanddate.com* [online]. Stavanger: Time and Date, ©1995-2019 [cit. 2019-07-16]. Available at: https://www.timeanddate.com/.