CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY OF ELECTRICAL ENGINEERING

DIPLOMA THESIS

Modelling and Control of Tunnel Pasteurizers

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České vysoké učení technické v Praze
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Katedra řídicí techniky

ZADÁNÍ DIPLOMOVÉ PRÁCE

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Studijní program: Elektrotechnika a informatika (magisterský), strukturovaný
Obor: Kybernetika a měření, blok KM1 - Řídicí technika

Název tématu: **Modelování a řízení tunelových pasterizátorů**

Pokyny pro vypracování:

1. Seznamte se s procesem průmyslové pasterizace pro tepelnou úpravu nápojů.
2. Prostudujte a popište běžně používané principy konstrukce a řízení tunelových pasterizátorů.
3. Navrhněte simulační model zvoleného typu tunelového pasterizátoru.
4. Formulujte úlohu řízení využívající konstrukční možnosti moderních tunelových pasterizátorů.
5. Navrhněte algoritmus řízení.
6. Otestujte navržený algoritmus na simulačním modelu procesu a porovnejte jeho vlastnosti s algoritmem běžně užívaným.

Seznam odborné literatury:

Dodá vedoucí práce

Vedoucí: Doc.Ing. Petr Horáček, CSc.

Platnost zadání: do konce letního semestru 2009/10

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děkan

V Praze dne 27. 2. 2009

Declaration

I declare that I have created my Diploma Thesis on my own and I have used only literature (literature, projects, SW etc.) cited in the included reference list.

In Prague, 22. 5. 2009

Signature

Acknowledgement

I have the honour to thank my supervisor Doc. Ing. Petr Horáček, CSc. for guidance and for useful comments. I would also like to thank my family for their support during the whole five years of my studies.

Abstract

Pasteurization is a temperature treatment of food whereby microbiological organisms are destroyed. The main goals of pasteurization are to make the product safe for human consumption and to promote biological stability of the food and thereby improve its shelf life. One of means how to achieve pasteurization of the product is tunnel pasteurizers. They are integral part of production lines of many breweries and other producers of beverages all over the world. Tunnel pasteurizers consist of a long enclosed chamber typically 15 – 30 m long, in which water is sprayed onto the packages (typically bottles and cans) which are moved through by a conveyor. The quality of control of pasteurizers has cardinal impact on flavour and biological safety of the product and not least on the economy of the plant operation. The goal of this thesis is to design a simulation model of a tunnel pasteurizer and a suitable control algorithm.

First, it is necessary to get acquainted with pasteurization process and pasteurizers. In the next step, the simulation model of tunnel pasteurizer is developed. Linearized model is used as a basis for design of predictive control algorithm, formulated using mixed integer programming. The controller is then tested using model situations of tunnel pasteurizer operation.

Abstrakt

Pasterizace je tepelná úprava potravin, při které dochází ke zničení mikroorganismů. Hlavním účelem pasterizace je vytvoření produktu bezpečného pro lidskou spotřebu a také zvýšení biologické stability dané potraviny a tím pádem prodloužení její doby trvanlivosti. Jedním z prostředků, jak dosáhnout pasterizace potravinových produktů, je tunelový pasterizátor. Tunelové pasterizátory jsou nedílnou součástí výrobních linek pivovarů a dalších výrobců nápojů na celém světě. Tunelový pasterizátor sestává z uzavřeného tunelu typicky 15 – 30 m dlouhého, ve kterém jsou vodou postřikovány lahve nebo plechovky, které jsou unášeny pásovým dopravníkem. Kvalita řízení pasterizátoru má zásadní vliv na chuť a biologickou bezpečnost produktu a v neposlední řadě také na ekonomiku provozu celého podniku. Cílem této diplomové práce je navrhnout simulační model tunelového pasterizátoru a vhodný řídicí algoritmus.

Nejdříve je třeba se seznámit s procesem pasterizace a pasterizátory. Dalším krokem je vytvoření simulačního modelu tunelového pasterizátoru. Linearizovaný model bude sloužit jako základ k návrhu prediktivního řídicího algoritmu, formulovaného pomocí lineárního programování s celočíselnými proměnnými, který bude otestován na modelových provozních situacích.

Contents

1 Introduction

This thesis deals with modelling and control of the pasteurization process in tunnel pasteurizers. These machines are integral part of production lines of many breweries and other producers of beverages all over the world. The quality of control of pasteurizers has cardinal impact on flavour and biological safety of their products and not least on the economy of the plant operation.

The thesis is divided into 6 chapters. The preliminary parts are intended to state basic facts about pasteurization. In Chapter 2 are described two methods of pasteurization, namely batch pasteurization and flow pasteurization. Chapter 3 treats at large of tunnel pasteurization and among others features comparison of conventional and modern pasteurizers in the areas of construction and control and brings a list of problems involved in tunnel pasteurizers. Chapter 4 contains design of models of single deck and double deck pasteurizer, identification of the model parameters and finally linearization of model of a container, which is further used in control algorithm. Chapter 5 is devoted to formulation of an optimization problem of pasteurizer control. Two types of optimization tasks are presented – static and dynamic. Result of static optimization is operating point under normal operation. The dynamic optimization is predictive control task and is applied when the pasteurizer operates under exceptional conditions. Finally, the results are presented and discussed in Chapter 6.

1.1 Invention of Pasteurization

The process of pasteurization is named after its inventor Louis Pasteur, the founder of discipline of microbiology. Around year 1856, Pasteur was approached with a contamination problem in alcoholic fermentation, which was thought to be an entirely chemical process at the time. After careful examination, he found that the fermentation was a biological process carried out by microorganisms. This hypothesis, called the germ theory, was followed by many elegant experiments that showed unequivocally the existence of microorganisms and their effect on fermentation.

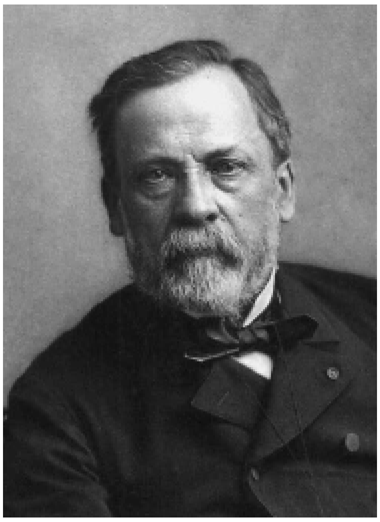

Figure 1.1: Louis Pasteur

Based on these findings, Pasteur determined that such microorganisms could be killed by heat. This simple process became known as pasteurization, a process used today for milk and many other beverages.

1.2 Definition of Pasteurization

Pasteurization is a temperature treatment of food whereby microbiological organisms are destroyed. The first main goal of pasteurization is to make the product safe for human consumption the other is to promote biological stability of food and thereby improve its shelf life. Not all the microorganisms are destroyed during the process, because the food is exposed to such temperatures, which take minimum effect on physical stability and flavour of the food. That makes the difference between pasteurization and sterilization, because during sterilization, all the microorganisms contained in the food are destroyed, but typically on the expense of flavour.

2 Pasteurization techniques

There are basically two methods of pasteurization in use today: batch and continuous. In the majority of industrial processes, the continuous pasteurization has replaced the batch method. However, the batch processing is still in use in smaller plants or for some specific products (1). Just before the start of description of the pasteurization methods, it would be useful to enlighten how pasteurization is measured for better orientation in the text.

2.1 Pasteurization Measurement

To quantify the amount of pasteurization, two main units are used: Pasteurization Unit and Time above Temperature.

2.1.1 Pasteurization Units

The amount of pasteurization is quantified using term Pasteurization Units. It is a nonlinear measurement of time and temperature which reflects the kill rate of the bacteria within the product (2).

One Pasteurization Unit (PU) is defined as 1 minute of heating at 60°C. The formula for computing PU is

$$\frac{dPU(t)}{dt} = 10^{\frac{T(t)-T_{ref}}{Z}}, \qquad \text{for} \;\; T(t) \geq T_x,$$
$$\frac{dPU(t)}{dt} = 0, \qquad \text{for} \;\; T(t) < T_x, \tag{2.1}$$

where T is the temperature of the product, T_{ref} is 60°C, T_x is temperature below which no contribution is made to PU and Z is temperature change required to reduce bacteria by a factor of 10 (3).

2.1.2 Time above Temperature

Time above temperature (TAT) is another quantity that characterizes pasteurization. It is defined as the amount of time during which the temperature of the product is equal or higher than 60°C.

$$\frac{dTAT(t)}{dt} = k, \qquad \begin{matrix} k = 1 \text{ for } T(t) \geq 60 \\ k = 0 \text{ for } T(t) < 60' \end{matrix} \tag{2.2}$$

where T is the temperature of the product.

2.2 Batch Method

Batch method uses a vat pasteurizer which consists of a jacketed vat surrounded by either circulating water, steam or heating coils of water or steam. The vat is provided with an agitator to ensure uniform heating of its content. The heating period (typically 30 minutes) is followed by rapid cooling. Batch pasteurization is used in the dairy industry, especially for milk by-products like creams or chocolate, and extensively in the ice cream industry rather because of mix quality reasons than microbial reasons (4).

2.3 Continuous Method

Continuous method has several advantages over the vat method; the most important ones are time and energy savings. Two types of continuous pasteurization are distinguished; flow pasteurization and tunnel pasteurization, which will be discussed separately in Chapter 3. The main difference between them is that by the flow pasteurization the product is pasteurized before bottling, whereas by the tunnel pasteurization the product is bottled firstly and then pasteurized in the tunnel pasteurizer.

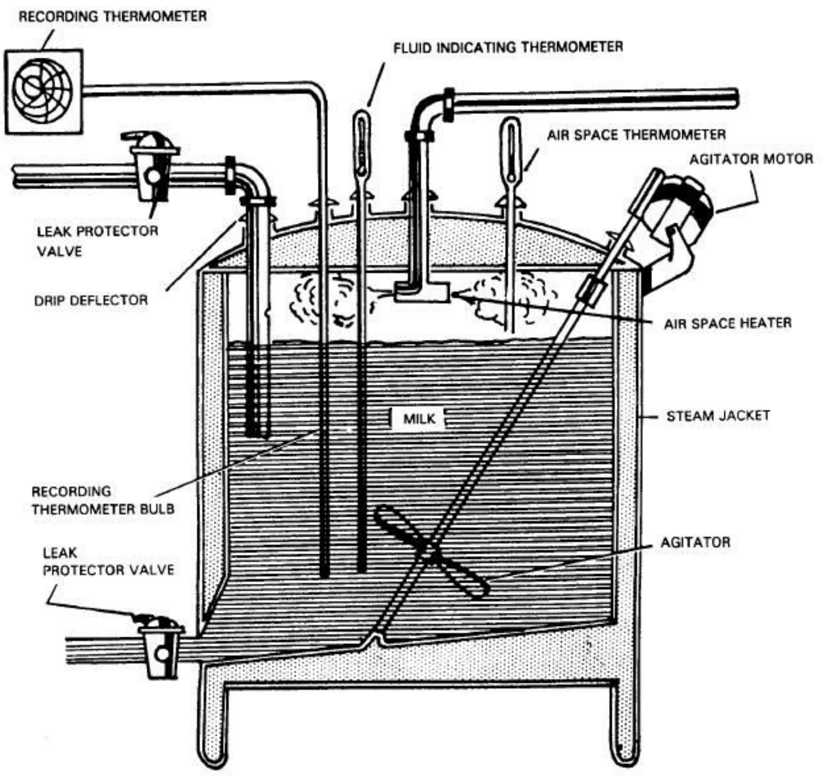

Figure 2.1: Sketch of a batch pasteurizer (5)

2.3.1 Flow Pasteurization

For most continuous flow processing, a HTST – high temperature short time pasteurization (which is also called flash pasteurization) is used. The HTST pasteurization standard was designed to achieve 5-log reduction, killing 99.999% of the number of viable microorganisms in pasteurized liquid (6).

The heat treatment is accomplished using a plate heat exchanger. The liquid is forced between metal plates or through pipes heated on the outside by the hot water or vacuum steam. For beer, the pasteurization temperature is at least 71.5°C to 74°C and is held for about 15 to 30 seconds. The heat exchanger is designed so that a particular flow rate will achieve maximum efficiency. Consequently, the flow rate – not the temperature – must be adjusted to alter the number of PU for a given product (7).

Because the flash pasteurization is done prior to filling, it has no effect on microorganisms introduced during filling. Therefore, a well controlled, sterile filling operation to prevent re-introduction of organisms is essential (8).

HTST is very popular with the dairy and juice industry and was also widely adopted by breweries in Europe and Asia, while it is not so frequently used by breweries in North America. In brewery industry is the HTST pasteurization used mostly for kegs, less for bottles and cans (7).

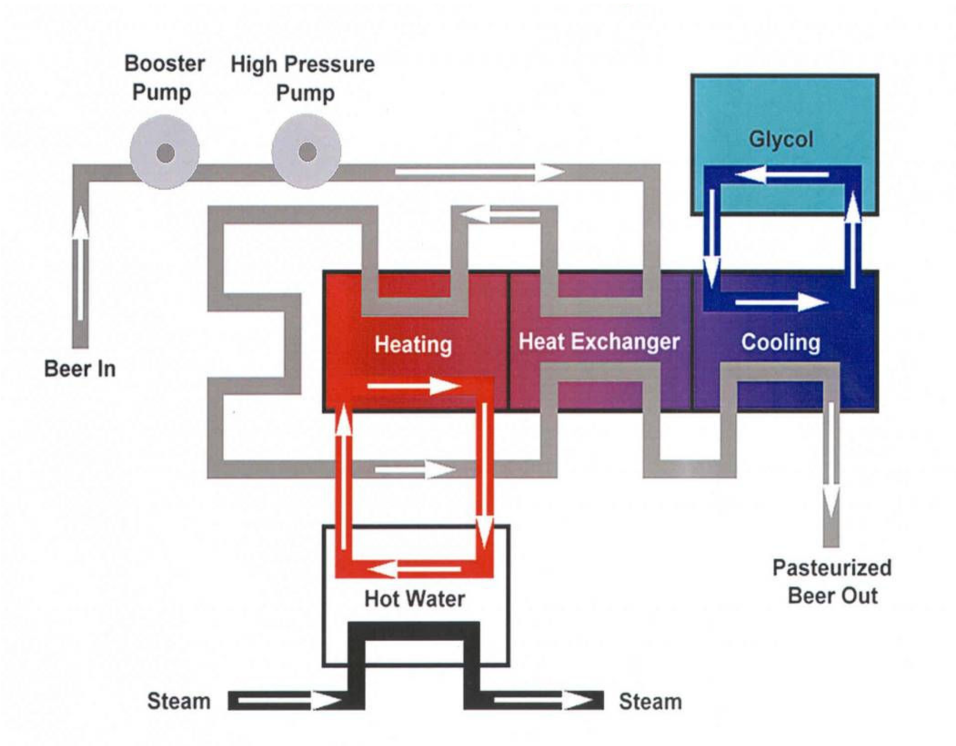

Figure 2.2: Block diagram of a flash pasteurizer (9)

Figure 2.3: Flash pasteurizer (10)

3 Tunnel Pasteurization

Tunnel pasteurization is used for bottles and cans and is employed after filling and crowning. The timescale is much longer than by flash pasteurization, up to 1 hour, and the peak temperature is lower, at about 60°C. There are a number of reasons why this long time span is needed. First, the rate at which the heat is conducted through a container wall and then through the content is quite long. Second, with bottles, a rapid temperature rise would cause thermal stresses that could result in bottle bursting. Third, there is a steep pressure rise when a highly carbonated package is heated and again there is a risk of bursting (11).

Figure 3.1: Tunnel pasteurizer (13)

Tunnel pasteurizers consist of a long enclosed chamber (typically 15 – 30 m, single or double deck configuration), in which water is sprayed onto the packages which are moved through by a conveyor. The tunnel is divided into 7 – 15 spray zones, which are grouped into a heating zone, where the container temperature is progressively raised to desired pasteurization temperature, a pasteurization zone, where the product reaches desired PU, and a cooling zone, where the product is cooled to demanded output temperature (approximately the ambient dew point temperature which will avoid condensation forming on the product container which adversely affects the packer process (12)). The water running off the packages is collected in reservoirs and recycled to the spray pans.

Two main components of the pasteurizer are the water spray and circulation systems and the package transport system.

3.1 Water Spray System

Uniform water distribution is essential to equal PU gain for every container. Different spraying systems are available:

- Spray pans, which distribute water through raised, clog-free holes and work by gravity.
- Spray bars with notched, clog-free orifices.
- Spray nozzles, which provide active pressure spraying, easy maintenance and accurate spray pattern.

a) b)

Figure 3.2: a) Spray pans, b) Spray bars (14)

a) b)

Figure 3.3: a) Spray nozzle, b) Spray nozzles in action (13)

3.2 Water Circulation System

3.2.1 Water Circulation System in Conventional Pasteurizers

In (15), conventional water circulation system is described:

Normally, heat exchangers are used for heating the water in the zones. The heat exchangers are connected to each individual zone, in which the products are to be heated, and water and steam are supplied through their own separate circulation. The steam in most known apparatuses being supplied from a shared steam supply source with the application of so-called analog valves for the control of the steam admission for the heat exchanger provided in the individual zone.

It will be understood that analog valves refer to valves, which can be adjusted to deliver a certain amount of fluid, in contrast to valves, which are either open or closed (on/off valves).

In the application of heating systems with water/steam heat exchangers in each individual zone, the pipe lines and the valves for controlling the sprinkling liquid and the steam become very complex and vulnerable, and the number of analog valves for steam becomes equal to the number of heat exchangers as a minimum.

Leakages in analog valves for steam are frequent after they have been in use for some time. Leakages correspond to uncontrolled heating of the sprinkling fluid passing the heat exchanger, and the result therefore is an inappropriate consumption of cooling water in order to keep the temperature of the sprinkling water down at the predetermined temperature of the zone during a constant and regular movement of the conveyor belt in normal operation.

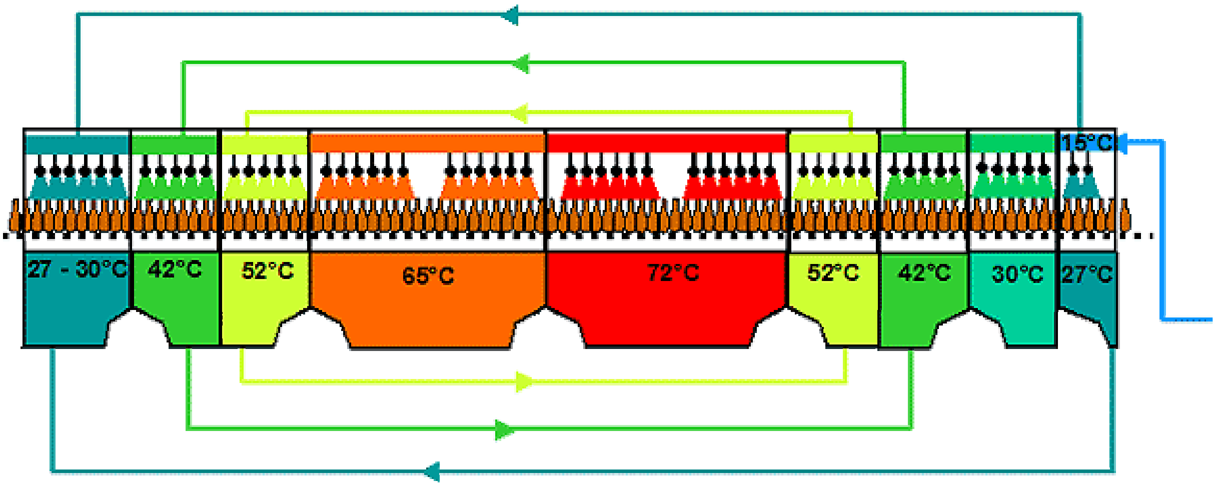

Figure 3.4: Scheme of tunnel pasteurizer with 3 regenerative pairs

Water circulation in conventional pasteurizers is provided by so called regenerative pairs. In (16) is stated:

Each regenerative pair shares the same water and includes a heating zone and a cooling zone coupled into a pumped closed loop. Within a regenerative pair, the spray water which is cooled as it heats up the incoming cool product in the heating zone is collected in a sump, pumped to the cooling zone spray head and used to cool the hot containers entering the zone. The same water, after it has been heated as it cools the outgoing hot product, is collected in the cooling zone sump and returned to the preheat zone sprays for use in heating incoming product. If necessary, the temperature of the water may be raised to a higher temperature using a heat exchanger.

3.2.2 Water Circulation System in Modern Pasteurizers

Modern pasteurizers feature closed water cycle, thereby the heating-up times for individual zones are reduced and vast amounts of energy and water are saved. This is achieved by special design of heating and water circulation system with single heat exchanger and buffer tank.

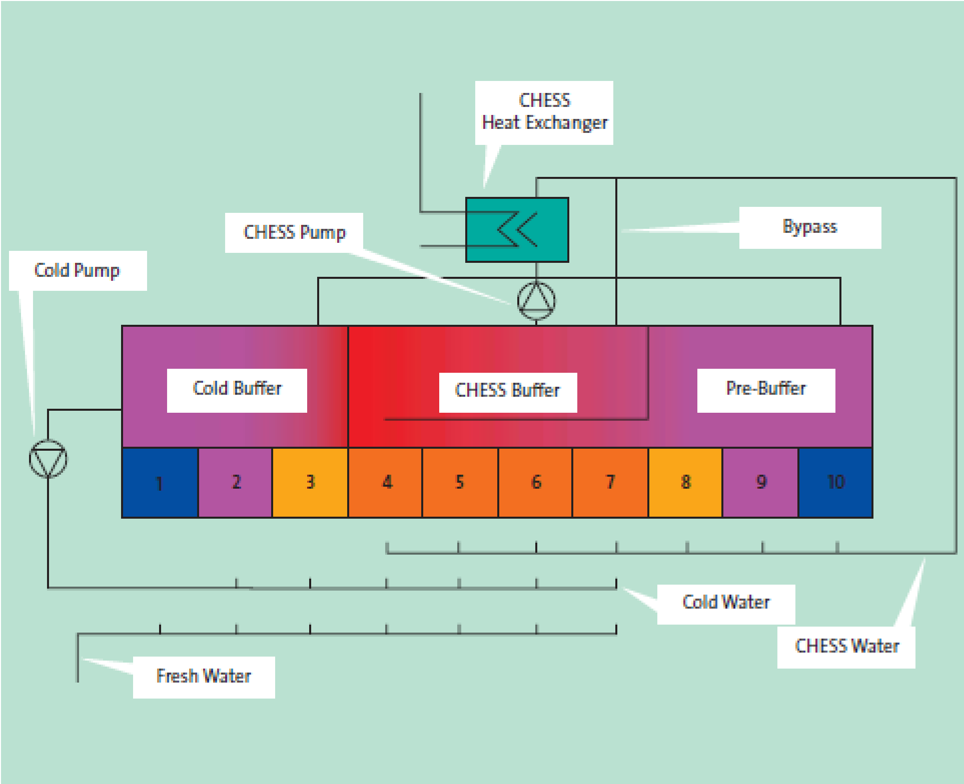

Figure 3.5: Scheme of water circulation system with one heat exchanger and buffer tank (14)

Thanks to common heat exchanger for all zones, it is possible to direct the full heating capacity of the entire pasteurizer to a single specific zone, which improves the heating performance of the machine. Whenever required for regulation of the water temperature, direct injection of hot water into the mixing pipe allows zone higher heat-up speed. The pasteurizer is then able to react quickly on irregularities and secure quick restart or cold start-up.

The next important part of circulation system is a buffer tank, where overflow water from pasteurizer zones is stored. Typically the buffer is composed from hot water tank, cold water tank and warm water tank. Overflow water is then directed to the tank with similar temperature. This system offers better flow characteristics compared to traditional systems since water is automatically recycled and reused in the machine.

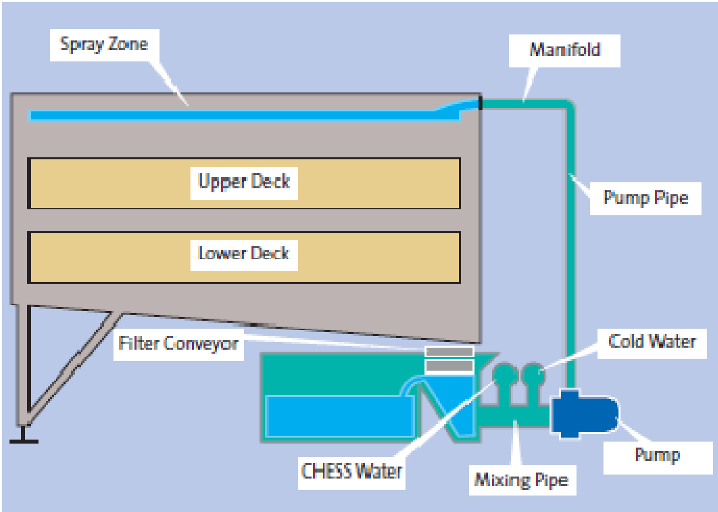

Figure 3.6: Water circulation in modern tunnel pasteurizer, water temperature is adjusted in a mixing pipe (14)

3.3 Container conveying system

Transport of containers through the pasteurizer is provided by a belt conveyor. The conveyor belts have grid structure to permit high water passage. Plastic, stainless steel or hybrid belts are available for all types of the containers and products. Important properties of belts are durability, minimal wear and therefore long service life and simple maintenance.

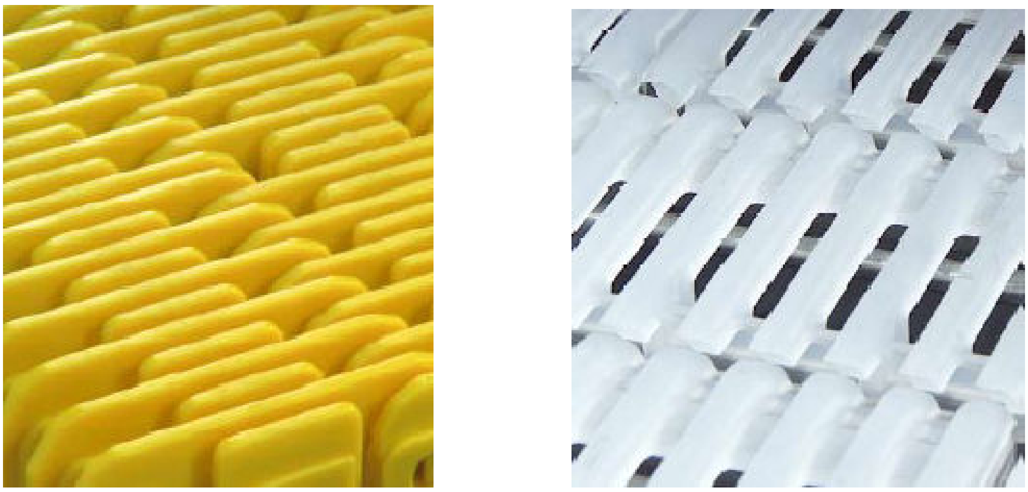

Figure 3.7: Plastic conveyor belts (13), (14)

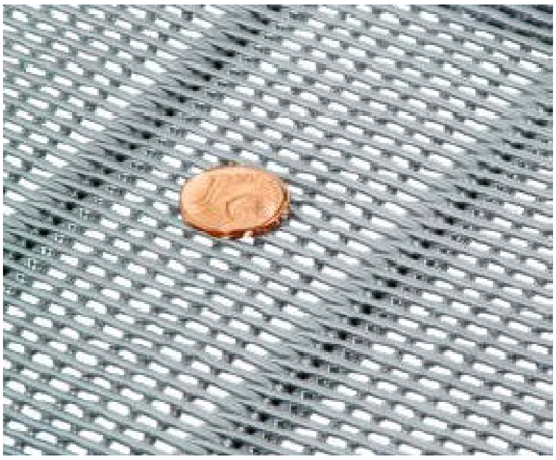

Figure 3.8: Stainless steel conveyor belt (13)

3.4 Pasteurization Units Measurement and Control

3.4.1 PU Measurement in Conventional Pasteurizers

In (12) the conventional measurement is described:

The conventional PU measurements device or "P.U. Box" consists of a container having a thermometer wired therein which is connected to a recorder. The wired container is sent through the pasteurizer tunnel and the beer cold spot temperature is recorded as it progresses through the tunnel. Using the beer cold spot temperature and time, PU input is calculated.

This method of measuring PU takes approximately 25 minutes to run a can and about 45 minutes to run a bottle through the pasteurizer. The set up time results in a total of only four P.U. Box runs being made through a pasteurizer in an 8 hour shift. This is theoretically possible, but the manpower required to run this test 4 times per shift makes it economically unfeasible. Normal testing is only one or two runs per machine per week. Thus, less than 0.1% of the packages can be tested and verified for proper pasteurization.

Additionally, under the conventional system, pasteurizer conditions are set arbitrarily based on operating experience to obtain the desired pasteurization results. These settings are always conservatively high in an attempt to allow for unexpected problems such as pasteurization down time, unstable temperature control, etc., which would adversely affect and change the PU input to the product leaving the pasteurizer. These settings are then checked by running a P.U. Box through the pasteurizer at steady state normal operating conditions to verify that normal operation gives the desired pasteurization. This system provides no way to check or verify results under abnormal conditions and, in fact, it is rare if the exact time and circumstances of the abnormal occurrences are even known.

3.4.2 PU Measurement in Modern Pasteurizers

Modern systems monitor continuously the entire pasteurization process. Water spray temperature in each spray zone is continuously monitored and recorded. From these data and from known speed of the conveyor, PU of each product leaving the pasteurizer is calculated. The formula for PU computation is developed from pilot plant test runs (12).

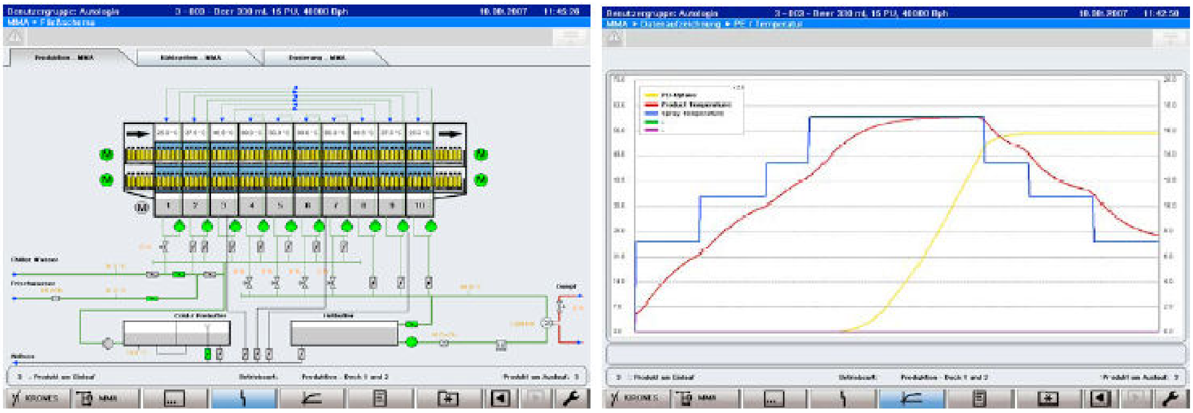

Figure 3.9 Screenshots of pasteurizer control software GUI (17)

The temperatures of the sprays are regulated throughout the entire process. The control system guarantees optimal results even if the machine is stopped. New control systems also enable flying product change, which means that two different product batches are simultaneously pasteurized during the one's run-in and the other's run-out. This increases production throughput and saves up to 85% of the water and 80% of time normally required (14).

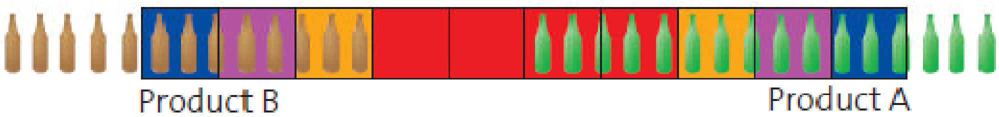

Figure 3.10: Scheme of flying product change

Of course modern monitoring systems offer software for collecting, visualizing and archiving the essential data from the pasteurizer. Real time process data is retrieved from the pasteurizer continuously and can be shown in the form of dynamically updated process diagrams, trends and curves. The data is collected via Ethernet and stored in a database, which is accessible to the user over internet. What is more, some systems enable the manufacturer's engineers to link up remotely to the machine for evaluation or optimization purposes (14).

3.5 Problems with Tunnel Pasteurizers

Next paragraphs contain a description of problems that encounter conventional pasteurizers, which were taken over from (18).Some of them like under and over-pasteurization are caused by obsolete control system. High water consumption and energy losses are consequences of old-fashioned design of water circulation system and heating system, which are today replaced by systems designed with emphasis on the economical efficiency.

3.5.1 Under-pasteurization

Under-pasteurization is a relative term which is dependent on the biological condition of the product being packaged, the cleanliness of the container, and the level of assurance required by the manufacturer (demanded PU). Under-pasteurization most often occurs unknowingly: i.e., failures in the heating controls, product advanced too quickly through the heating and holding zones or faulty spray water distribution.

3.5.2 Over-pasteurization

Over-pasteurization occurs more frequently than under-pasteurization since brewers would rather err on the high side, and control equipment is designed to fail accordingly. When a problem of the filling or packaging line forces the pasteurizer to stop, the product which has been heated to approximately 60°C continues to pasteurize, e.g. a ten minute delay at 63°C will add over 25 PU to the product. Failure of heating controls and faulty calibration also can cause over-pasteurization.

3.5.3 Water Consumption and Waste

The old pasteurizers with three or less regeneration pairs require continuous additions of cooling water. When utilities were cheap, this water was normally injected where needed in the pasteurizer, allowed to overflow from the machine to the sewer. Typically today, this overflowing water is collected and recycled to the pasteurizers.

3.5.4 Heat Waste

Excess water overflowing at a higher temperature than when injected becomes a source of heat waste. Normally, a "balanced" pasteurizer will require continuous addition of heating energy. When no product is in the hot side of a regenerative pair, more heating energy must be provided to compensate for the heating normally accomplished by the hot product which is being cooled. This extra heating is also required if less product is in the hot regenerative pair than is in the cold regenerative pair. This condition is an "unbalanced" machine.

When the pasteurizer is being filled with product (run-in) at the beginning of a day or shift, the hot end is completely empty and the heating normally provided by the hot product must be supplied by steam or heated water. This extra heat required during run-in is eventually lost and is considered a "necessary" waste of heating energy.

3.5.5 Cooling Energy Waste

As stated in previous paragraph, heating energy is wasted during run-in. Conversely, when it is time to empty the machine, large amounts of cooling energy are required to replace the cool product which normally is entering the pasteurizer. This cooling requirement is also eventually lost and is considered a "necessary" waste of cooling energy.

3.5.6 Simultaneous Heating and Cooling Energy Waste

If the supply of product to the pasteurizer is delayed the beginning of a run-out will occur. When product supply resumes, a gap or space void of product will have been formed in the pasteurizer. A series of such gaps frequently results in external heating and cooling being provided simultaneously in a regeneration pair. This situation is a common source of cooling and heating energy waste.

3.5.7 Beer Waste and Losses

The primary causes of beer waste and losses are over and under-pasteurization or tipped and broken containers. Tipped containers caused by the previously mentioned gaps cause machine and conveyor jams and are thus damaged and wasted. Broken bottles normally result from thermal shock which is caused when hot or cold product enters a successive zone that is either too cold or too hot, respectively.

3.6 Physical Phenomena in Containers

During heating and cooling, the content of the container reacts on the temperature changes around. Because the whole content of the container is not heated equally, flows of the beer inside the container occur.

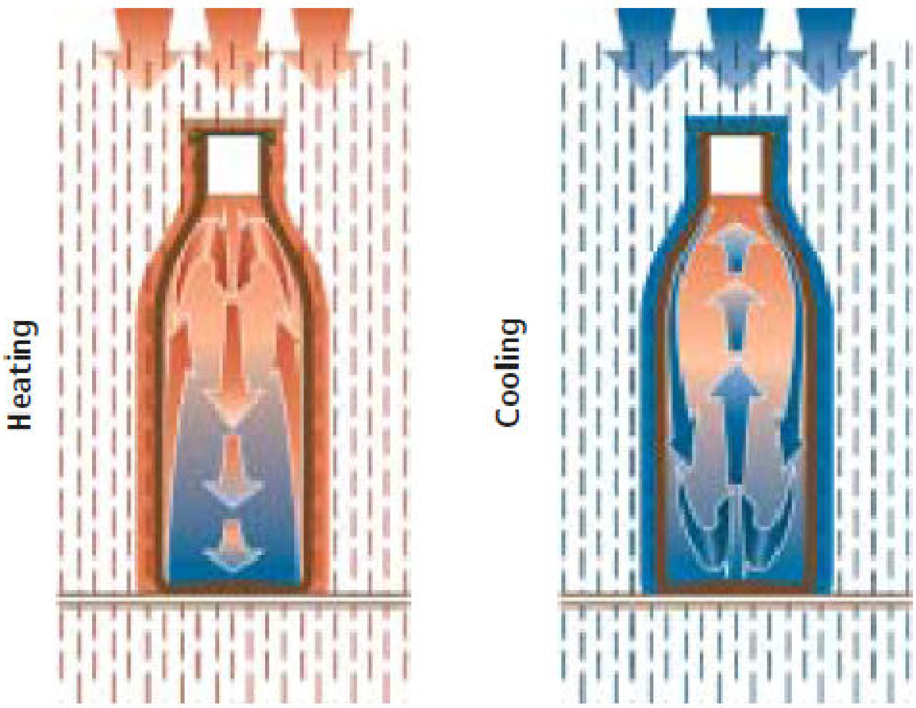

Figure 3.11: Flows in container during heating and cooling (13)

During heating up, the hotter beer flows up along the side of the container and down in the middle. By contrast, during cooling the flow turns and the beer flows upwards in the middle and down along the side of the container (19).

The positive effect of this phenomenon is that the majority of container content obtains the similar amount of PU. Nevertheless, there is an area in the container called “cold spot”, which is situated near the bottom in the centre of the container and where the achieved temperature is lower than in the rest of the container.

4 Simulation Model of Tunnel Pasteurizer

As mentioned in Chapter 3, the whole tunnel pasteurizer has basically two main components: the spray and circulation systems and the package transport system. For the purpose of control of the pasteurization process, it is essential to create a model of the transport system, simple model of the spray system and a model of a container. The scheme of the model is in Figure 4.1. It should be remarked that it is the scheme of single deck pasteurizer. The inputs are conveyor speed v and spray zone temperatures T_z. In dependency on distance s, the container is sprayed by water at temperature T_{up}. The outputs are then temperature of container content T_{in}, temperature of overflow water T_{down}, Pasteurization Units PU and Time above Temperature TAT of each container.

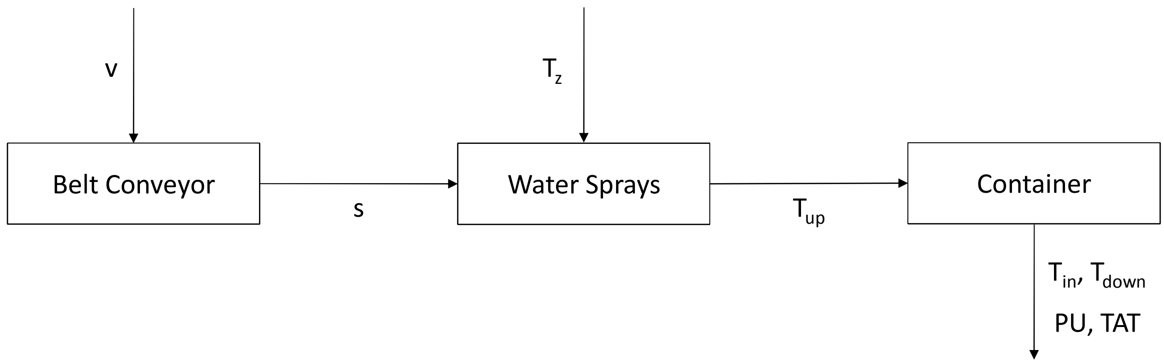

Figure 4.1: Principal scheme of model of single deck pasteurizer

The model of water circulation system is not introduced in this thesis, because it is not necessary for reaching the goals of the thesis. Moreover, the water circulation system can be understood as independent on the rest of the pasteurizer and can be modelled separately. It will be possible to connect both models afterwards, using the spray system as an interface between them. Another reason for not integrating the circulation system in the current model is fact, that the modelled part of pasteurizer is universal for all possible pasteurizers, whereas the water circulation system differs from manufacturer to manufacturer.

4.1 Simplifying Presumptions

Consecutive presumptions were taken into account to simplify the model and lower the computation costs. Let the pasteurizer be observed from the longer side. From this point of view, a transversal row of containers can be represented by a single container, presuming that the spray pattern is uniform and equal for every container in this row.

Next, the gaps between spray zones are omitted, considering the proportions of the spray zones compared to proportions of the gaps. Further, these gaps are negligible from the side of a control system proposed later in the thesis. Though, it is possible the gaps will be included in the model later to refine on the model.

4.2 Model of Belt Conveyor

A conveyor is a system that converts speed of the conveyor into position of the conveyed object. Therefore, the input of the model part representing the conveyor is speed and initial positions of the containers and the output are positions of the containers. This can be written as Equation (4.1)

$$s_i(t) = s_i(t_0) + \int_{t_0}^{t} v(\tau)\, d\tau, \qquad i = 1, \dots, N_c, \tag{4.1}$$

where $s_i(t)$ is position of container i in time t, $s_i(t_0)$ is initial position of container i in time t_0, $v(\tau)$ is the speed of belt conveyor and N_c is the number of containers.

4.3 Model of Spray System

Spray system provides each zone in pasteurizer with water at demanded temperature. As the container travels through the pasteurizer, it passes through the zones and is washed by the water at the appropriate temperature. This temperature is determined in Equation (4.2)

$$b_{z_j} \leq s_i(t) \leq e_{z_j} \Rightarrow T_{up_i}(t) = T_{z_j}(t), \qquad i = 1, \dots, N_c, j = 1, \dots, N_z, \tag{4.2}$$

where $s_i(t)$ is position of container i in time t, b_{z_j} is distance from the beginning of spray zone j to the beginning of the pasteurizer, e_{z_j} is distance from the end of spray zone j to the beginning of the pasteurizer, $T_{up_i}(t)$ is temperature of water being sprayed on container i, $T_{z_j}(t)$ is temperature of water in spray zone j, N_c is the number of containers and N_z is the number of spray zones.

4.4 Model of Container

The container will be modelled as a thermal system. Thermal systems are systems with distributed parameters, but for control purposes they can be modelled as circuits composed of elements with concentrated parameters. The principles of modelling these systems can be found in (20).

In Figure 4.2 is a scheme of a cross section of a container with denoted parameters. The yellow area represents beer; the green rectangle around it stands for container walls and the blue area at the top and on the left side of the container is water being sprayed on the container and then flowing from the upper side down along the container walls. The water is also in contact with ambient air, which causes thermal losses.

During this process, thermal transmittance between and in the mentioned objects takes place. The heat in the flowing water is transmitted by convection. Heat convection rises from movement and mixing of fluid volumes of different temperatures, thus transferring the heat between different parts of the whole mass. The thermal transmittance from water into the ambient air is realized by heat conduction.

Between the flowing water and container walls, the heat is transmitted by conduction, the same way as between container walls and beer in the container. The flows in beer that occur during heating or cooling are omitted; therefore the thermal transmittance in beer can be easily modelled by heat conduction as well. Heat conduction is the transfer of thermal energy between neighbouring molecules in a substance due to a temperature gradient. It always takes place from a region of higher temperature to a region of lower temperature, and acts to equalize temperature differences. Conduction in contrast to convection does not require any bulk motion of matter and takes place in all forms of matter.

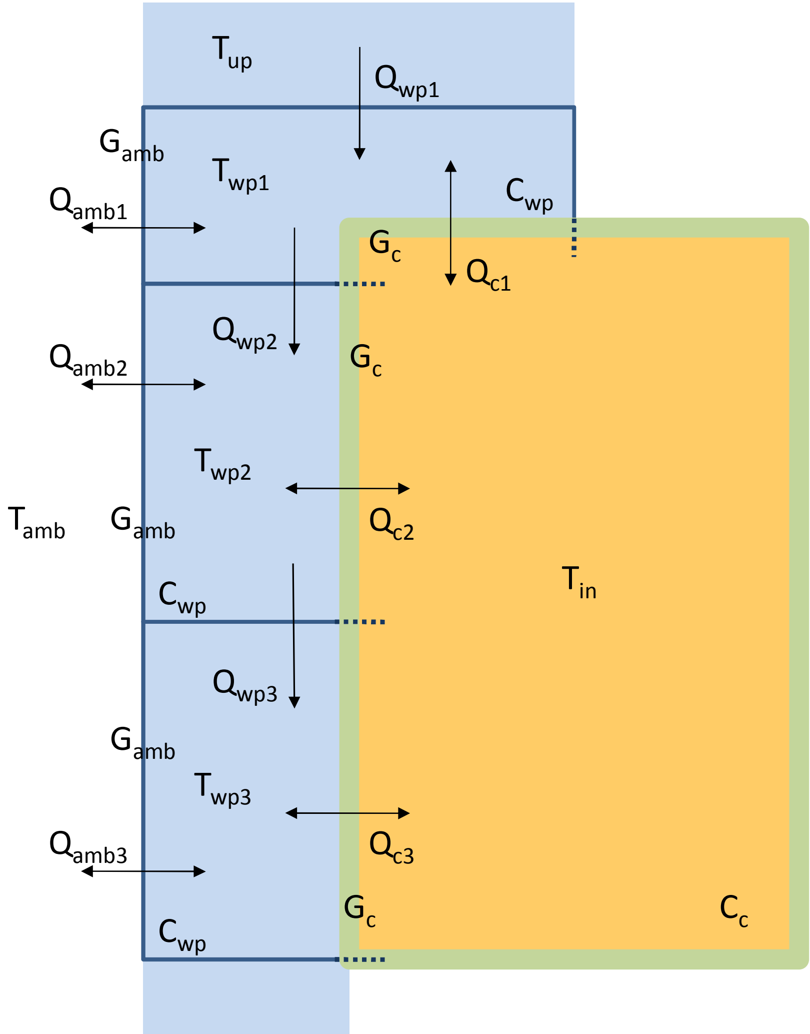

Figure 4.2: Scheme of container with denoted parameters

4.4.1 Heat convection in flowing water

In a model with concentrated parameters, the continuous distribution of temperatures in flowing water is represented by finite number of water volumes N_{wp}, each characterized by its own temperature T_{wp_i}, where $i = 1, \dots, N_{wp}$ and thermal capacitance C_{wp}. Since the volumes are identical, so are their thermal capacitances. These volumes are bound together by heat flow Q_{wp_i} that is dependent on:

- upper volume temperature $T_{wp_{i-1}}$, eventually in case $i = 1$ on spray water temperature T_{up},

- this volume temperature T_{wp_i},
- water flow F_w.

These relations are expressed by Equation (4.3)

$$Q_{wp_i}(t) = (k_1F_w(t) + k_1k_2)\left(T_{wp_i}(t) - T_{wp_{i-1}}(t - T_d)\right) - k_1k_3F_w(t),$$
$$\text{if } k = 1 \Rightarrow T_{wp_{i-1}}\left((t - T_d)\right) = T_{up}(t), \qquad i = 1, \dots, N_{wp}, \tag{4.3}$$

where k_1, k_2, k_3 are constants representing the normal operation point and T_d is time that takes the water to flow through the previous water part. The proposed model contains three volumes, thus $i = 3$. It is a compromise number between model precision and simulation speed.

4.4.2 Heat conduction between water and container

The processes of heat conduction between flowing water and container walls and between the walls and container content were merged. This was possible thanks to omission of thermal capacitance of container wall, which is far smaller than the thermal capacitance of beer in the container C_c. Container wall was divided into 3 sections with respect to location of adjacent water volumes from Section 4.4.1. Each section is characterized by thermal conductance G_c, which represents thermal conductance of the container wall combined together with thermal conductance of adjacent part of beer volume. The heat flow Q_{c_i} through one section is expressed in Equation (4.4)

$$Q_{c_i}(t) = G_c\left(T_{wp_i}(t), T_{in}(t)\right)\left(T_{wp_i}(t) - T_{in}(t)\right), \qquad i = 1, \dots, N_{wp},$$
$$Q_c(t) = \sum_i Q_{c_i}(t). \tag{4.4}$$

Thermal conductance $G_c\left(T_{wp_i}(t), T_{in}(t)\right)$ is nonlinearly dependent on water temperature and beer temperature according to Equation (4.5)

$$T_{mean_i}(t) = \frac{T_{wp_i}(t) + T_{in}(t)}{2}$$
$$G_c\left(T_{wp_i}(t), T_{in}(t)\right) = G_0\left(\alpha_{T2}T_{mean_i}{}^2 + \alpha_{T2}T_{mean_i}(t) + 1\right), \qquad i = 1, \dots, N_{wp}, \tag{4.5}$$

where G_0 is thermal conductance of material (here partially container wall material – glass or metal and partially beer) at 0°C, α_{T1} and α_{T2} are material constants defining the dependence of thermal conductivity on the temperature of the material. This temperature is not explicitly known, but is computed as mean value ${T_{mean}}_i$ of surrounding temperatures ${T_{wp}}_i$ and T_{in}.

4.4.3 Temperature of beer in container

Now all pre-requisites are met to define the Equation (4.6) for inner temperature T_{in}, which is

$$\frac{dT_{in}(t)}{dt} = \frac{1}{C_c\big(T_{in}(t)\big)} \sum_{i=1}^{N_{wp}} {Q_c}_i(t), \tag{4.6}$$

where thermal capacitance of beer C_c depends on beer temperature T_{in} in accordance with Equation (4.7)

$$C_c\big(\,T_{in}(t)\big) = C_0\big(\beta_{T1}{T_{in}}^2(t) + \beta_{T2}T_{in}(t) + 1\big), \tag{4.7}$$

where C_0 is thermal capacitance of beer at 0°C, β_{T1} and β_{T2} are constants defining the dependence of thermal conductivity on the temperature of the beer T_{in}.

Temperature T_{in} is used to derive the values of PU and TAT. How to achieve this is described in Section 2.1.

4.4.4 Heat conduction between water and ambient

Ambient temperature T_{amb} is supposed to be common for all containers. Only heat conduction between spray water and ambient air ${Q_{amb}}_i$ is taken into account; heat conduction between container and ambient can be omitted with no bad effect on performance of the model. The heat conduction ${Q_{amb}}_i$ is defined in Equation (4.8)

$${Q_{amb}}_i(\,t) = G_{amb}\left({T_{wp}}_i(\,t) - T_{amb}(\,t)\right), \qquad i = 1, \dots, N_{wp}, \tag{4.8}$$

where G_{amb} stands for thermal conductance of interface water – ambient air.

4.4.5 Temperature of flowing water

Spray water is medium for heat transfer in pasteurization process. In the model, three kinds of heat flow come together in the water part – heat convected by flowing water discussed in

Section 4.4.1, heat conducted between water part and container introduced in Section 4.4.2 and finally heat conducted between water part and ambient air presented in Section 4.4.4. The Equation (4.9) defines the water part temperature T_{wp_i}

$$\frac{dT_{wp_i}(t)}{dt} = \frac{1}{C_{wp}}\left(Q_{wp_i}(t) - \sum_{i=1}^{N}\left(Q_{c_i}(t) + Q_{amb_i}(t)\right)\right), \qquad i = 1, \dots, N_{wp}. \tag{4.9}$$

4.5 Model of Double Deck Pasteurizer

A double deck pasteurizer is not one single deck pasteurizers superimposed one on the other, but in fact it is still more one pasteurizer. Although it has two conveyor belts, there is one water circulation and heating system and the lower deck has not the spray system similar to the upper deck, but the containers are sprayed with used water from the upper deck that passes through the permeable conveyor belt. After the water passes through the lower deck, it is recycled and sprayed on the containers in the upper deck again.

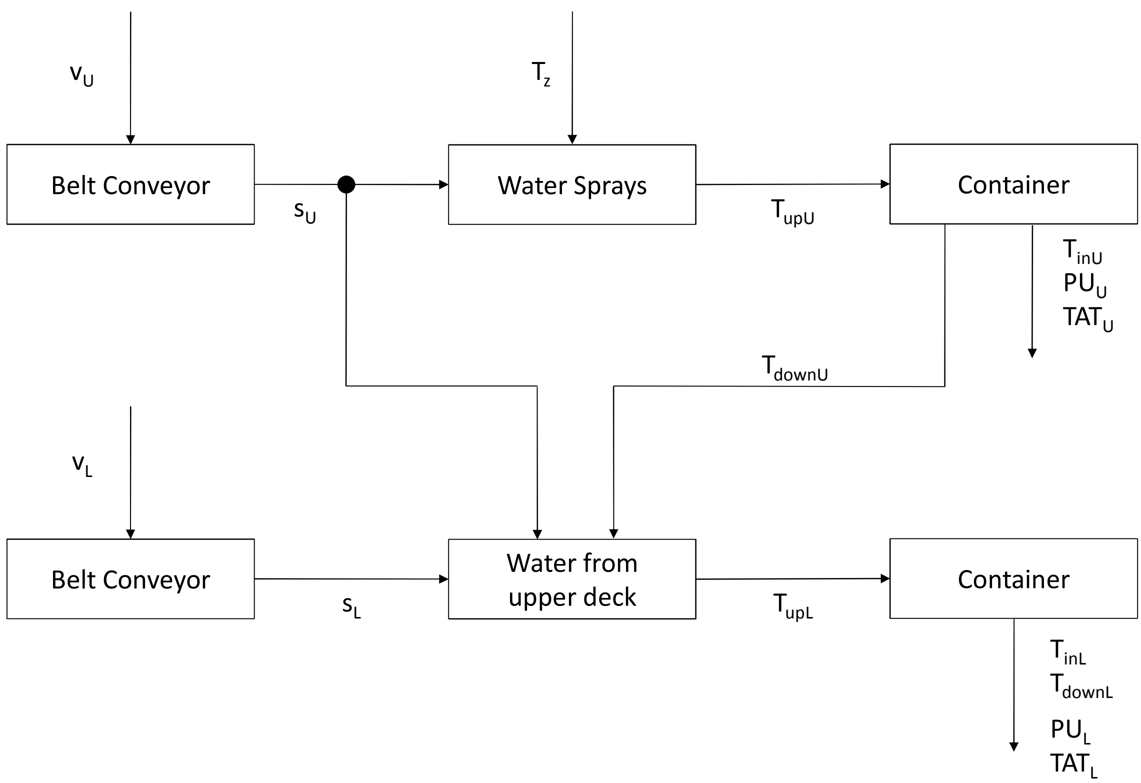

Figure 4.3: Principal scheme of model of double deck pasteurizer

The principal scheme of double deck pasteurizer is in Figure 4.3. The different spray system of the lower deck causes different computation of temperature T_{up_L} from temperature T_{up_U}. Lower deck spray water temperature T_{up_L} is dependent on positions of containers in the upper deck s_U and temperature of used water T_{down_U}. Description of this dependence is in section 4.5.1.

4.5.1 Temperature of lower deck spray water

There are three possible configurations of row of containers on the upper deck considering the effect of this configuration on a container in lower deck (one container means a row of containers):

a) The containers are inline without bigger gaps between them. Above a container in the lower deck may be situated one container at the distance precisely same as the lower container or two containers each covering part of area above the lower container.

b) There are gaps between containers in the upper deck and only one container is situated partially above the container in lower deck.

c) There are no containers in upper deck above the container in lower deck and this container is sprayed directly by water from upper deck sprays.

Firstly, the nearest upper containers to the lower container shall be found. To the nearest upper container b_j that is behind the lower container *j* applies Equation (4.10)

$$s_{b_j}(t) - s_j(t) = \max\{s_i(t) - s_j(t) \leq 0\}, \qquad i = 1, \dots, N_U, j = 1, \dots, N_L, \qquad (4.10)$$

where s_{nb_j}, s_i, s_j stand for distance of the appropriate container to the front of the pasteurizer. A similar principle is used in Equation (4.11) to get the nearest upper container f_j in front of the lower container *j*

$$s_{f_j}(t) - s_j(t) = \min\{s_i(t) - s_j(t) \geq 0\}, \qquad i = 1, \dots, N_U, j = 1, \dots, N_L. \qquad (4.11)$$

Now distances of two nearest upper containers are known and time has come to determine the water temperature. Equation (4.12) defines temperature T_{b_j} of water flowing from nearest upper container or gap behind container j to temperature T_{upL_j}. If the distance of container b_j from container j is lower than container diameter d_c, temperature T_{b_j} of water flowing from container b_j on container j is equal temperature $T_{downU_{nb_j}}$ of overflow water from container b_j. If the distance between containers is bigger than d_c or there is no upper container behind container j, the water temperature equals spray water temperature T_{z_k} of container current zone, the same way as is defined in Equation (4.2) for single deck pasteurizer or upper deck.

$$\begin{aligned}&\text{if } s_j(t) - s_{b_j}(t) < d_c \Longrightarrow T_{b_j}(t) = T_{downU_{b_j}}(t),\\ &\text{if } \left(s_j(t) - s_{b_j}(t) \geq d_c \vee s_{b_j}(t) = \emptyset\right) \wedge b_{z_k} \leq s_j(t) \leq e_{z_k} \Longrightarrow T_{b_j}(t) = T_{z_k}(t),\\ &j = 1, \dots, N_L, k = 1, \dots, N_z.\end{aligned} \tag{4.12}$$

The same way as temperature T_{b_j} can be computed temperature T_{f_j} of water flowing from nearest upper container or gap in front of container j, as stated in Equation (4.13)

$$\begin{aligned}&\text{if } s_{f_j}(t) - s_j(t) < d_c \Longrightarrow T_{f_j}(t) = T_{downU_{f_j}}(t),\\ &\text{if } \left(s_{f_j}(t) - s_j(t) \geq d_c \vee s_{f_j}(t) = \emptyset\right) \wedge b_{z_k} \leq s_j(t) \leq e_{z_k} \Longrightarrow T_{f_j}(t) = T_{z_k}(t),\\ &j = 1, \dots, N_L, k = 1, \dots, N_z.\end{aligned} \tag{4.13}$$

Finally, the temperature T_{upL_j} of water flowing from the upper deck on container j is computed as mean value of temperatures T_{b_j} and T_{f_j} in Equation (4.14)

$$T_{upL_j} = \frac{T_{b_j} + T_{f_j}}{2}, \qquad ,j = 1, \dots, N_L. \tag{4.14}$$

4.6 Simulation Scheme of Single Deck Pasteurizer

Simulation scheme in Figure 4.4 corresponds with principal scheme in Figure 4.1. Computation of container distance is realized by S-Function *tp_distances* according to Equation (4.1). The second input *Containers in* of this block defines whether there are containers on the conveyor belt at the pasteurizer input or the belt is empty. The output of block *Container Speed -> Distance* is a vector containing positions of all containers in the pasteurizer and its width is adequate to maximum number of container rows that can be inside pasteurizer at one moment.

Block *Zone Temperature -> Upper Temperature* contains Equation (4.2) implemented in S-Function *tp_temperatures*. For each container in pasteurizer the temperature of water spraying the container is computed. The second output of this block gives information about number of containers in each spray zone, which is not needed anywhere in the model for now, but could be possibly used afterwards. The third output determines whether the rows of signal vector anywhere in the whole model represent a container inside pasteurizer or not. This is used to reset the values in the vectors after container passes out the pasteurizer and reuse the row for new container.

Last block at this model level is called *Container* and contains simulation scheme of the container, which is in Figure 4.5.

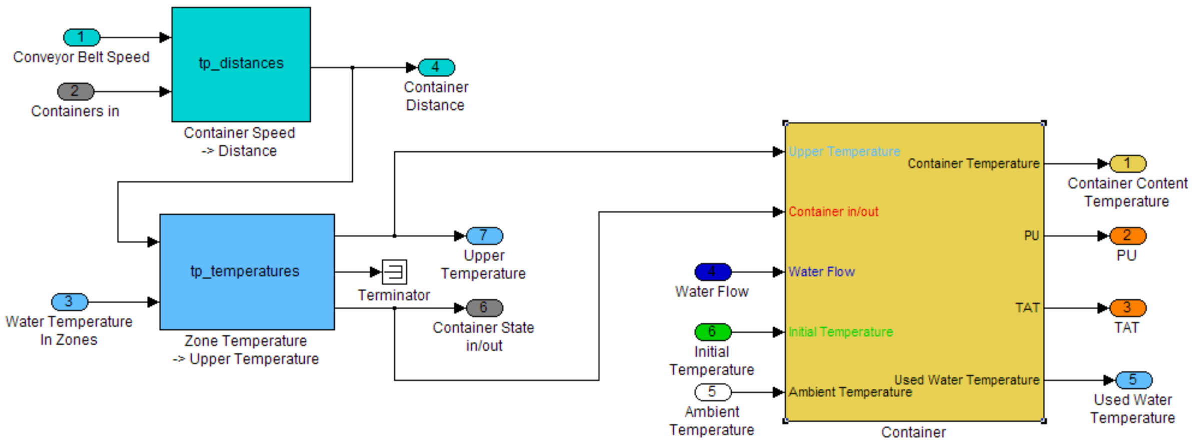

Figure 4.4: Simulation scheme of upper deck of tunnel pasteurizer

The scheme in Figure 4.5 agrees with Figure 4.2. It consists of three *Water Part* blocks that represent spray water flowing down the container, block *Container content* for the beer in the container and blocks for computation *PU* and *TAT*. The scheme of *Water Part* blocks is in Figure 4.6, scheme of *Container content* in Figure 4.9 and schemes of *Pasteurization Units* and *Time Above Temperature* blocks in Figure 4.11 and Figure 4.12.

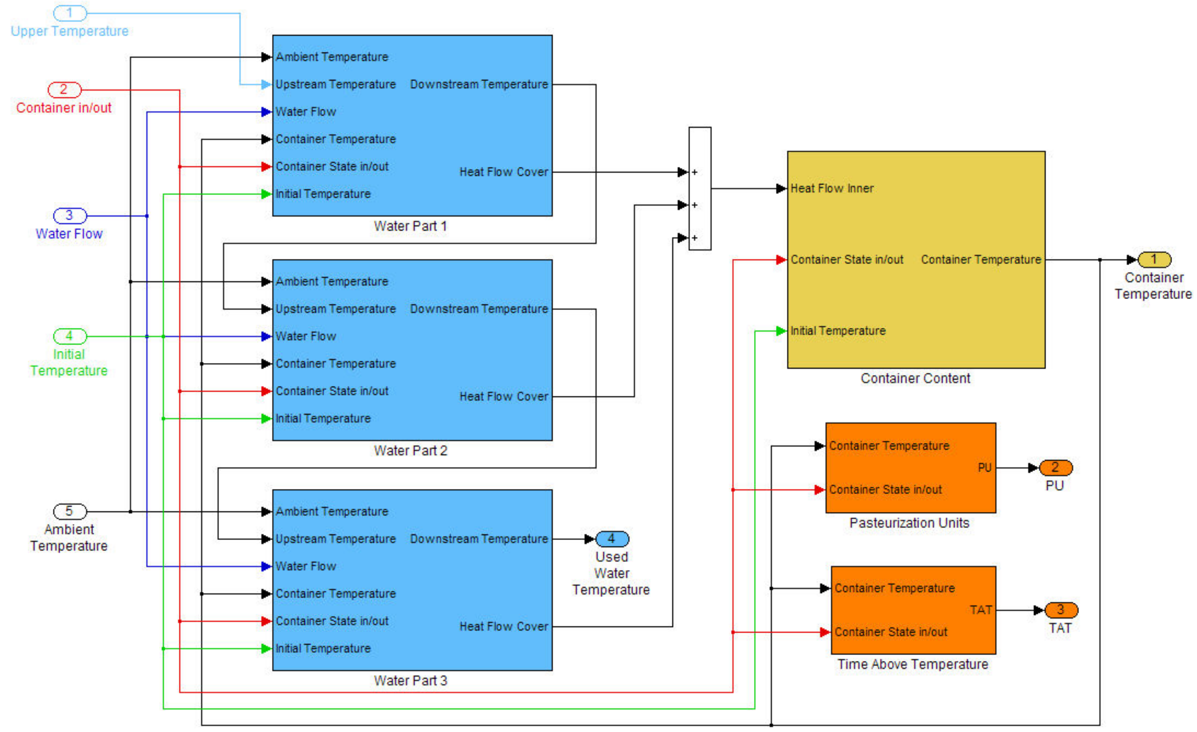

Figure 4.5: Simulation scheme of block *Container* from Figure 4.4

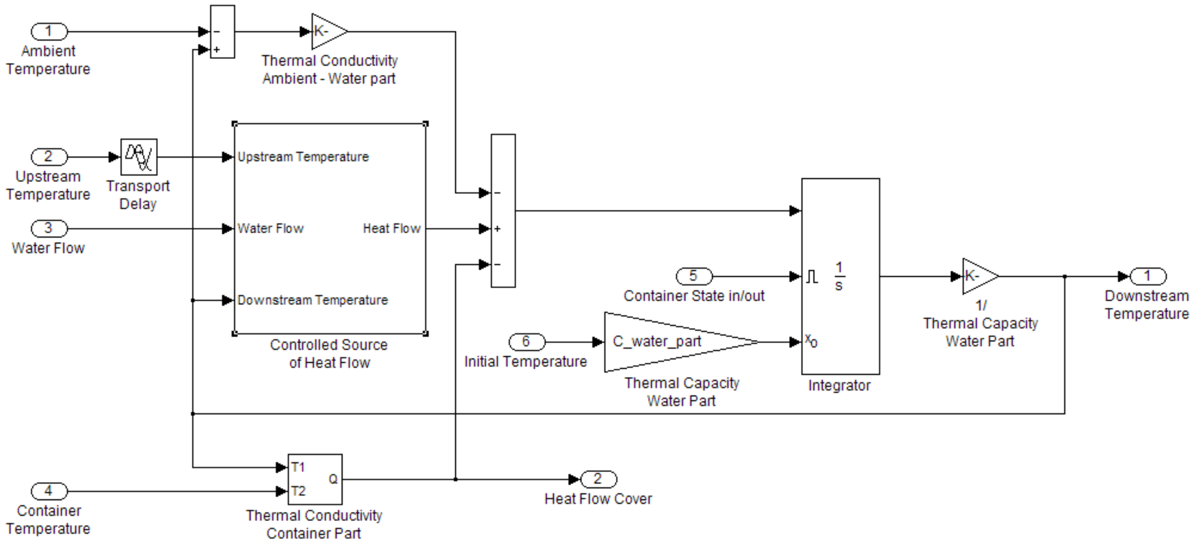

Figure 4.6: Simulation scheme of blocks *Water Part 1*, *Water Part 2*, *Water Part 3* from Figure 4.5

The outputs of *Water Part* block are *Downstream temperature* T_{wp_i} and *Heat Flow Cover* Q_{c_i}. The simulation scheme of *Thermal Conductivity Container Part* for computation of *Heat*

Flow Cover Q_{c_i} is in Figure 4.8. In the block *Controlled Source of Heat Flow* the heat flow between two following water parts is computed. Its simulation scheme is in Figure 4.7. Using inputs *Ambient Temperature* T_{amb} and *Container Temperature* T_{in} the heat flows water part – ambient Q_{amb_i} and water part – container Q_{c_i} are computed by virtue of Sections 4.4.4 and 4.4.2. Having all these heat flows, the *Downstream Temperature* T_{wp_i} calculated according to Section 4.4.5.

The scheme in Figure 4.7 functions as a controlled source of heat flow. The resulting Heat Flow is dependent on difference between *Upstream Temperature* $T_{wp_{i+1}}$ and Downstream *Temperature* T_{wp_i}, which correspond with temperatures in two consecutive water parts. The temperature signal from upper water part is delayed for time T_d in block *Transport Delay* in scheme in Figure 4.6 before entering that stands for the time the water spends in the upper water part.

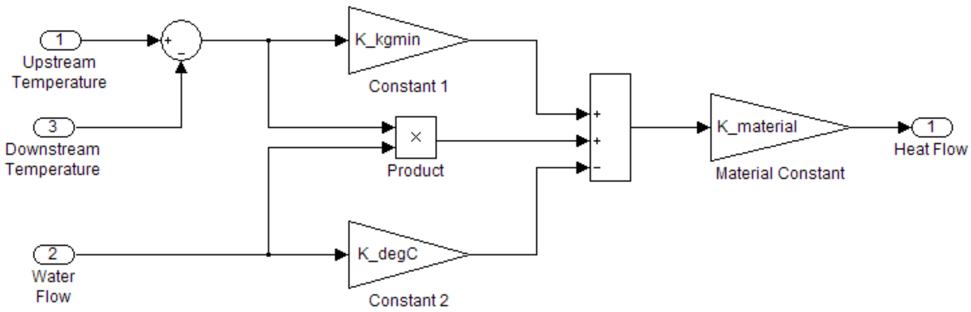

Figure 4.7: Simulation scheme of block *Controlled Source of Heat* Flow from Figure 4.6

Figure 4.8 contains simulation scheme for computation of *Heat Flow Cover* Q_{c_i} from *Container Temperature* T_{in} and *Water Part Temperature* T_{wp_i}. This scheme fully corresponds with Equation (4.5).

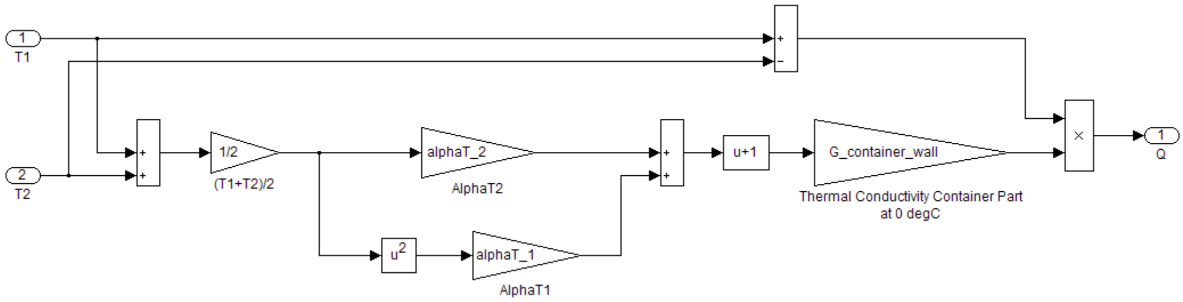

Figure 4.8: Simulation scheme of block *Thermal Conductivity Container Part* from Figure 4.6

In Figure 4.8 is simulation scheme representing beer in a container. From input heat flow the mean temperature of the beer *Container Temperature* is calculated. The thermal capacity of the beer *Container Thermal Capacity* C_c is dependent on *Container Temperature* T_{in} and is computed in block *1/Container Thermal Capacity* Figure 4.10. On the output of this block is reciprocal value of the thermal capacity and multiplies the heat flow incoming to the model. Take note that the reciprocal thermal capacity does not multiply the output of the integrator as usual. This is caused by occurrence of algebraic loop by that model configuration that would slow down the simulation.

The simulation scheme of block *1/Container Thermal Capacity* in Figure 4.10 represents Equation (4.7).

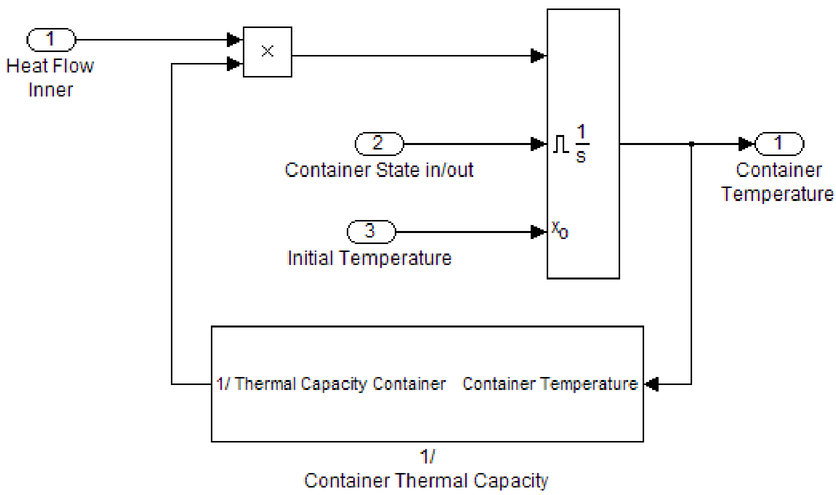

Figure 4.9: Simulation scheme of block *Container Content* from Figure 4.5

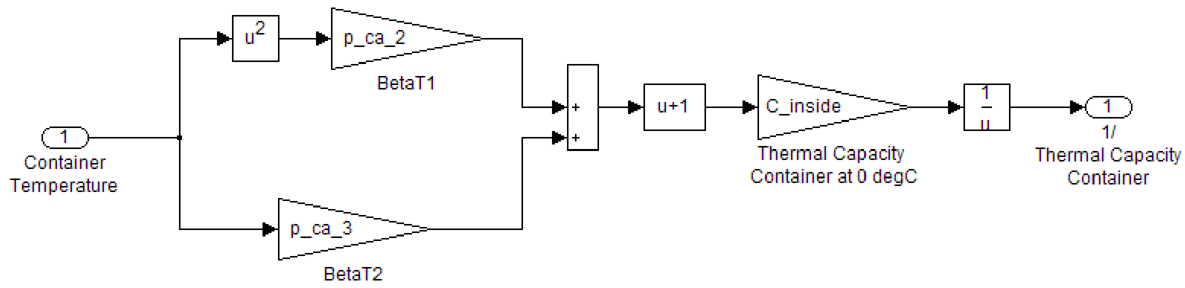

Figure 4.10: Simulation scheme of block *1/Container Thermal Capacity* from Figure 4.9

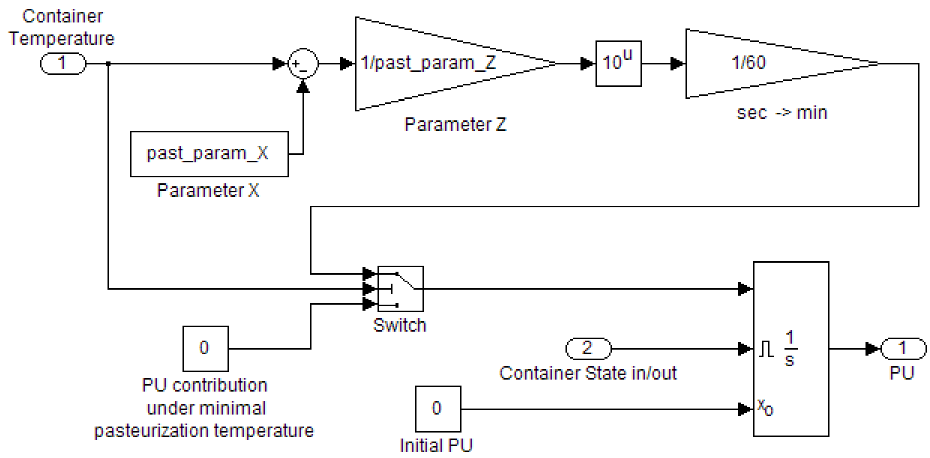

Figure 4.11: Simulation scheme of block *Pasteurization Units* from Figure 4.4

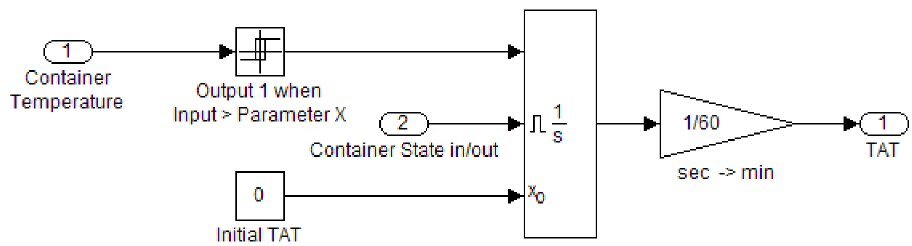

Figure 4.12: Simulation scheme of block *Time Above Temperature* from Figure 4.4

In Figure 4.11 and Figure 4.12 are well known relations for PU and TAT from Equation (2.1) and Equation (2.2) expressed in form of simulation scheme.

4.7 Simulation Scheme of Double Deck Pasteurizer

Simulation scheme of double deck pasteurizer is composed of two blocks containing models of one deck of a pasteurizer. The only difference between them is that the lower deck has additional inputs for information about upper deck, namely temperature of used water from the upper deck, temperature in zones, upper deck container distances and state. The output *Upper Temperature* from block *Zone Temperature -> Upper Temperature* implements equations stated in Section 4.5.1. The simulation schemes are in Figure 4.13 and Figure 4.14.

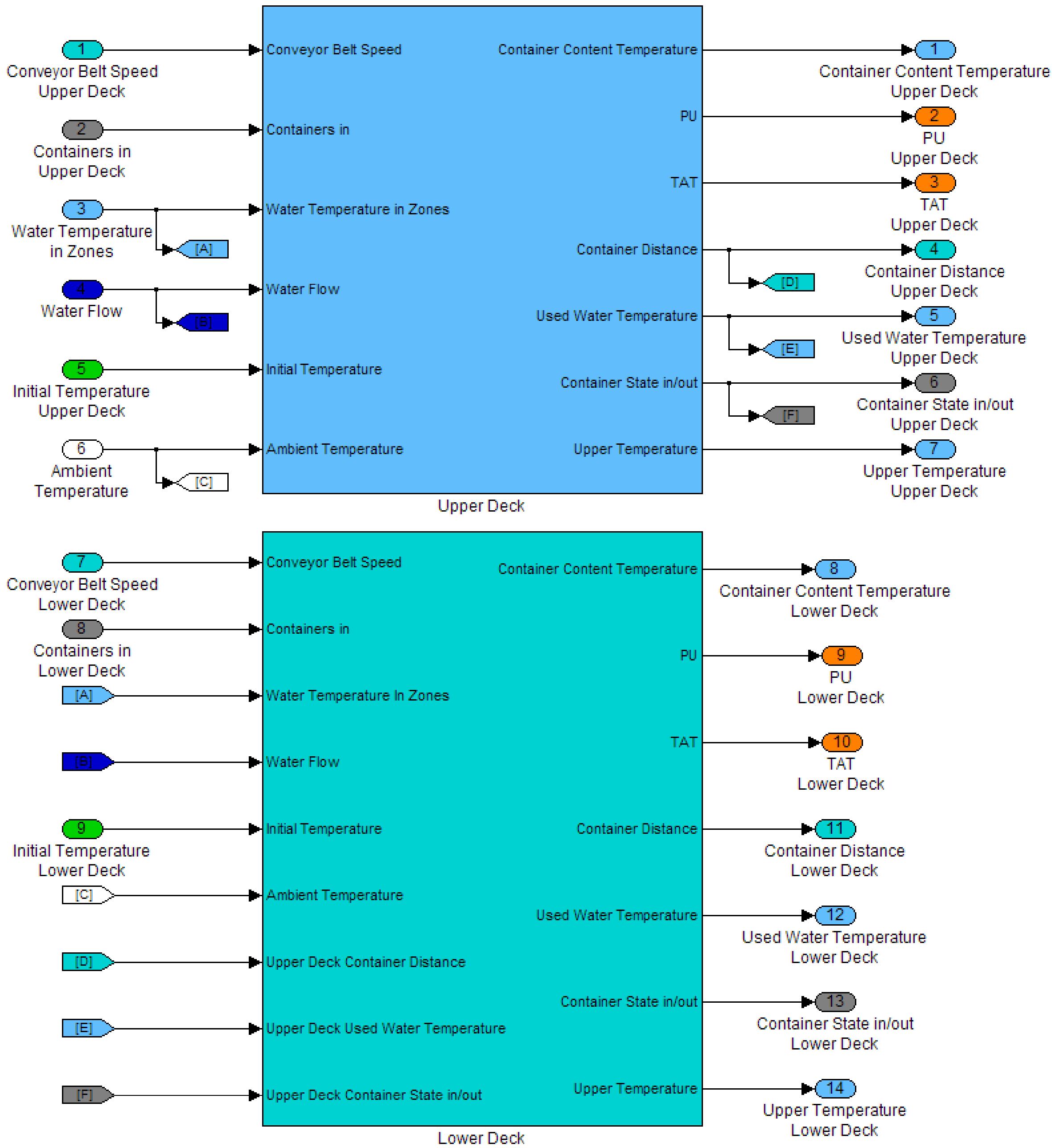

Figure 4.13: Simulation scheme of double deck pasteurizer

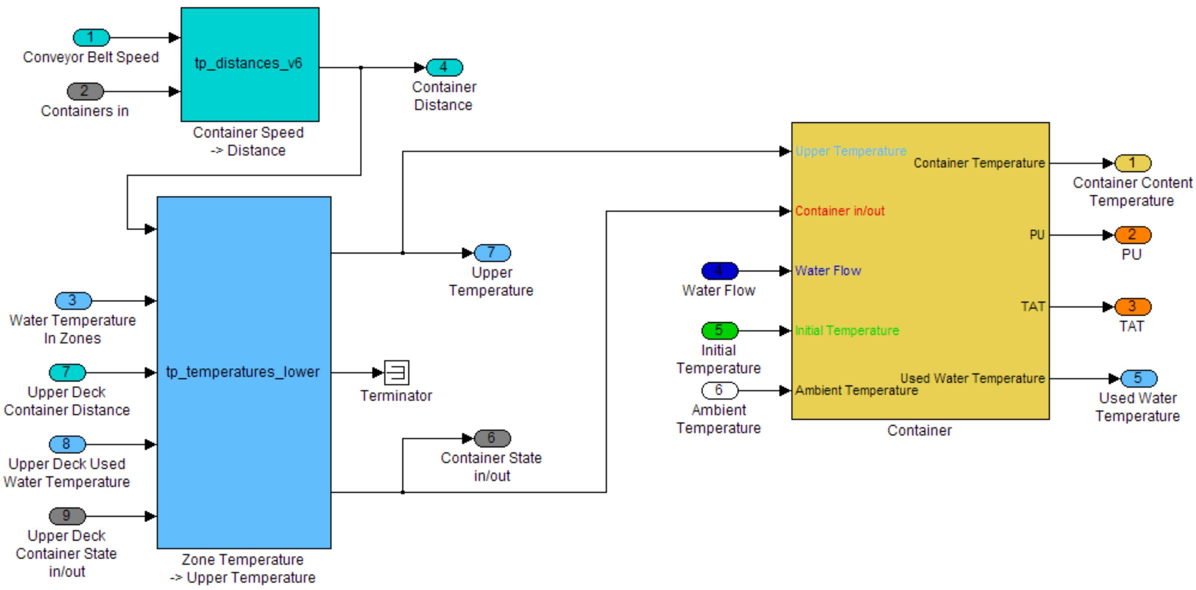

Figure 4.14: Simulation scheme of block *Lower Deck* from Figure 4.13

4.8 Identification of Model Parameters

The identification of model parameters was quite a complicated because of failure in effort to acquire complex measurement data from a real process.

4.8.1 Process Data for Identification

A couple of measurements on small experimental pasteurizer with five spray zones can be found in (19). Unfortunately, there are no tables with precise values, only figures with temperatures measured inside three containers – small can, big can and bottle. Measurements on ten different locations on the container axis were carried out for each container. The approximate mean temperature data was manually exported from these plots and then interpolated by Piecewise Cubic Hermite Interpolating Polynomial method (21) to acquire smooth waveform.

Unfortunately, the necessary input data including spray zone temperatures and conveyor belt speed was completely missing. The input temperatures were estimated from the shape of output temperature curve. In following text, the temperature data and input data acquired the described way will be denoted as “measured”. Although it was not measured in fact, it will play role of real process data.

4.8.2 Pasteurizer Properties

The number and dimensions of spray zones were derived from knowledge of typical pasteurizer properties and are not related to any concrete existing piece of equipment. The same way, the approximate speed of conveyor belt was deduced from known typical time the container spends in pasteurizer. Other values, e. g. water flow from nozzles were determined during parameter estimation. Properties of pasteurizer zones are in Table 4.1.

Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Type	Heat[1]	Heat	Heat	Past[2]	Past	Past	Past	Cool[3]	Cool	Cool
Length [m]	2,5	2	2	2	2	2	2	2	2	2,5
T_{min} [°C]	20	30	40	49	49	49	49	40	30	20
T_{max} [°C]	30	40	50	63	63	63	63	50	40	30

Table 4.1: Pasteurizer zones properties

4.8.3 Container Properties

Physical properties of containers such as diameter and volume are in (19), all thermal properties were estimated.

Table 4.2 contains container parameters and their values and units for two types of containers – small can and big can. The estimation was set to optimize the gap between "measured" and simulated *PU* characteristic in the first place (with weight equal 1000), because this is the main monitored characteristic of pasteurization process. The second objective of the estimation was to narrow down the difference between temperatures (weight 1). The *TAT* characteristic was not included in the estimation as the third output reference, because it is interconnected the two previous characteristics and would be redundant.

Comparisons of the "measured" and simulated characteristics for both small and big can are in Figure 4.15 and Figure 4.16. It is evident that *PU* and *TAT* values are almost identical,

[1] Heating zone
[2] Pasteurization zone
[3] Cooling zone

whereas the temperatures slightly differ in some places. The probable cause is small deviations between real measured input signal and estimated "measured" input signal.

Parameter	Value		Unit
	Small Can	Big Can	
C_c	1346.2	1966.5	J·°C^{-1}
C_{wp}	11.8142	12.2621	J·°C^{-1}
G_{amb}	9.2895·10^{-4}	0.0021	W·m^{-1}·°C^{-1}
G_c	1.6433	1.8439	W·m^{-1}·°C^{-1}
k_2	22.6413	34.1795	kg·s
k_3	0.1850	0.0939	°C
k_1	20.6056	20.1590	W·s·kg^{-1}·°C^{-1}
α_{T1}	-1.6101·10^{-4}	-6.4829·10^{-4}	°C^{-2}
α_{T2}	0.042	0.07	°C^{-1}
d_c	0.064	0.08	m
T_d	2.4401	2.9212	s
β_{T1}	-7.6791·10^{-5}	-2.6952·10^{-4}	°C^{-2}
β_{T2}	0.0057	0.017	°C^{-1}
F_w	0.1358	0.1558	kg· s^{-1}

Table 4.2: Container parameters

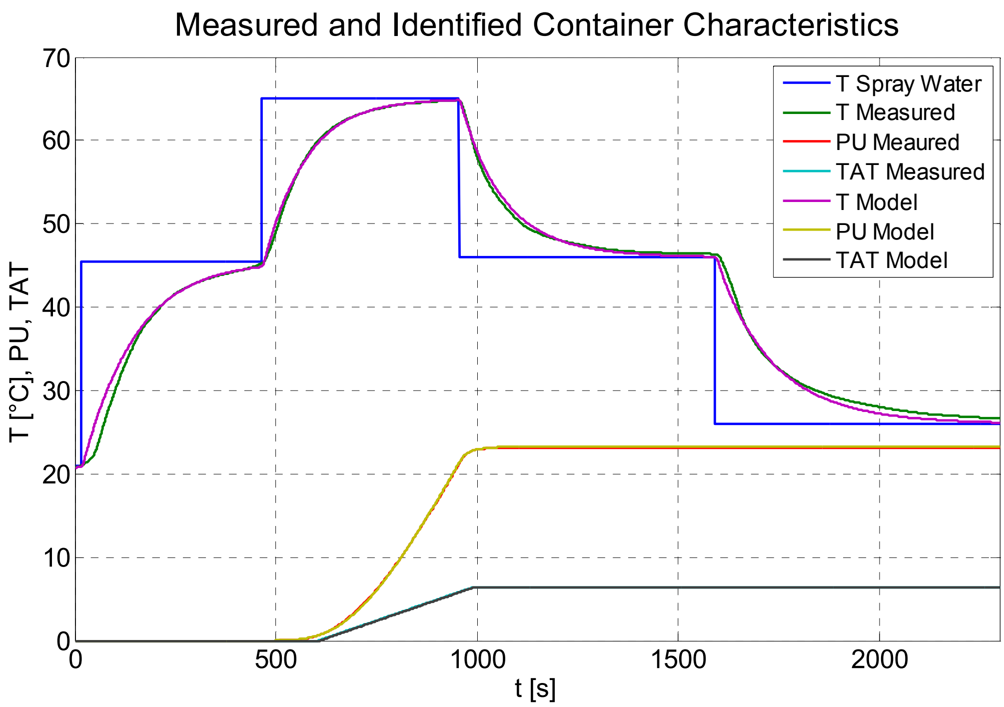

Figure 4.15: Comparison of "measured" and nonlinear model characteristics for small can

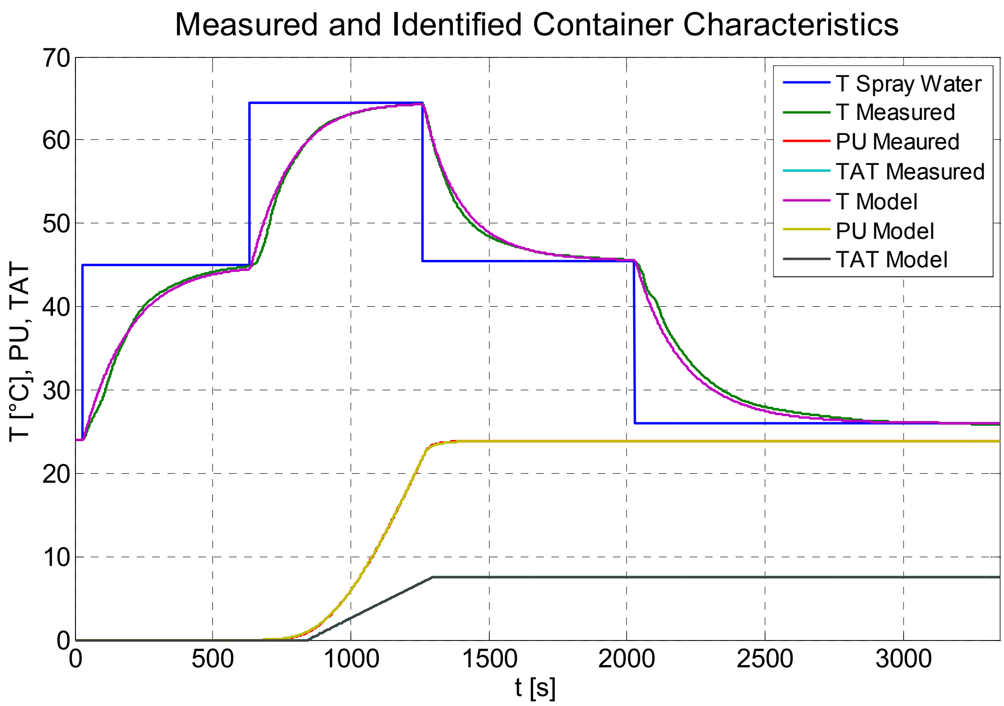

Figure 4.16: Comparison of "measured" and nonlinear model characteristics for big can

4.8.4 Linear model of container

For purposes of design of a controller of the pasteurizer, the linear model of the container must be derived. This was achieved using MATLAB System Identification Tool (21). The emphasis was placed on matching of the characteristics around temperatures higher than minimum temperature needed for PU contribution Equation (2.1), which was set to 50°C. The estimated characteristic was transfer function and the estimation was based on the temperature characteristic obtained by simulation of the nonlinear model using settings similar to typical pasteurizer settings.

In case of good match, the linear system output temperature was used to simulate PU and TAT characteristics. The best fitting system transfer function G_{sc} and G_{bc} for both small and big can has 3 poles and 1 zero. The estimated transfer functions are

$$\begin{aligned} G_{sc}(s) &= \frac{0.003074s + 1.742 \cdot 10^{-5}}{s^3 + 0.3723s^2 + 0.005069s + 1.738 \cdot 10^{-5}}, \\ G_{bc}(s) &= \frac{0.001416s + 5.701 \cdot 10^{-6}}{s^3 + 0.2184s^2 + 0.00243s + 5.605 \cdot 10^{-6}}. \end{aligned} \tag{4.15}$$

Discrete models were obtained from the estimated linear models using Zero Order Hold method with sample time $T_s = 60$ s. These discrete models will be used later in Chapter 5 to predict container state. The discrete transfer functions are

$$\begin{aligned} H_{sc}(z) &= \frac{0.3898z^2 - 0.2626z - 0.01058}{z^3 - 1.315z^2 + 0.4314z - 1.984 \cdot 10^{-10}}, \\ H_{bc}(z) &= \frac{0.3175z^2 - 0.2289z - 0.01768}{z^3 - 1.428z^2 + 0.498z - 2.0389 \cdot 10^{-6}}. \end{aligned} \tag{4.16}$$

Comparison of the nonlinear and linear model is in Figure 4.17 for small can and in Figure 4.18 for big can. Both linear models have in common good approximation of temperature characteristic at higher temperatures, which is not surprising after all, because it was emphasized during model construction. Approximation at lower temperatures is worse, but this fact has no effect on resulting PU and TAT. The last thing worth mentioning is a bit higher deviation of PU characteristic of discrete model of big can, which is caused by the influence of discretization since the sample taken just under 60°C does not make contribution to TAT yet.

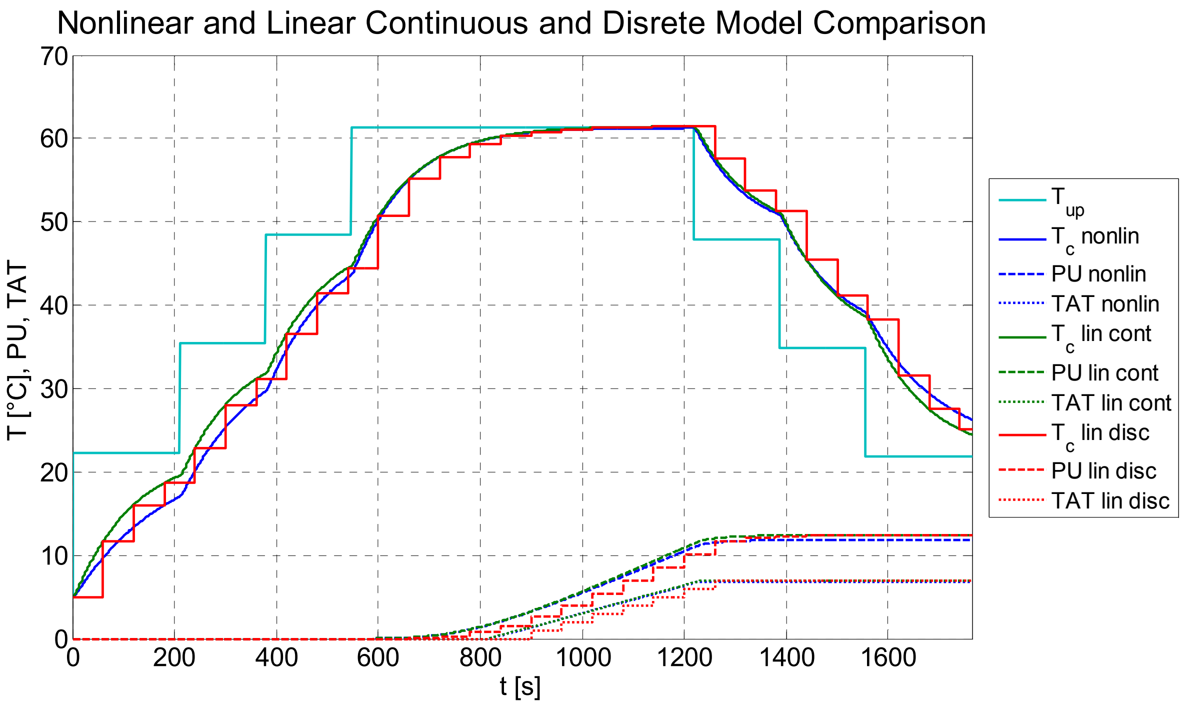

Figure 4.17: Comparison of nonlinear and linear continuous and discrete models of small can

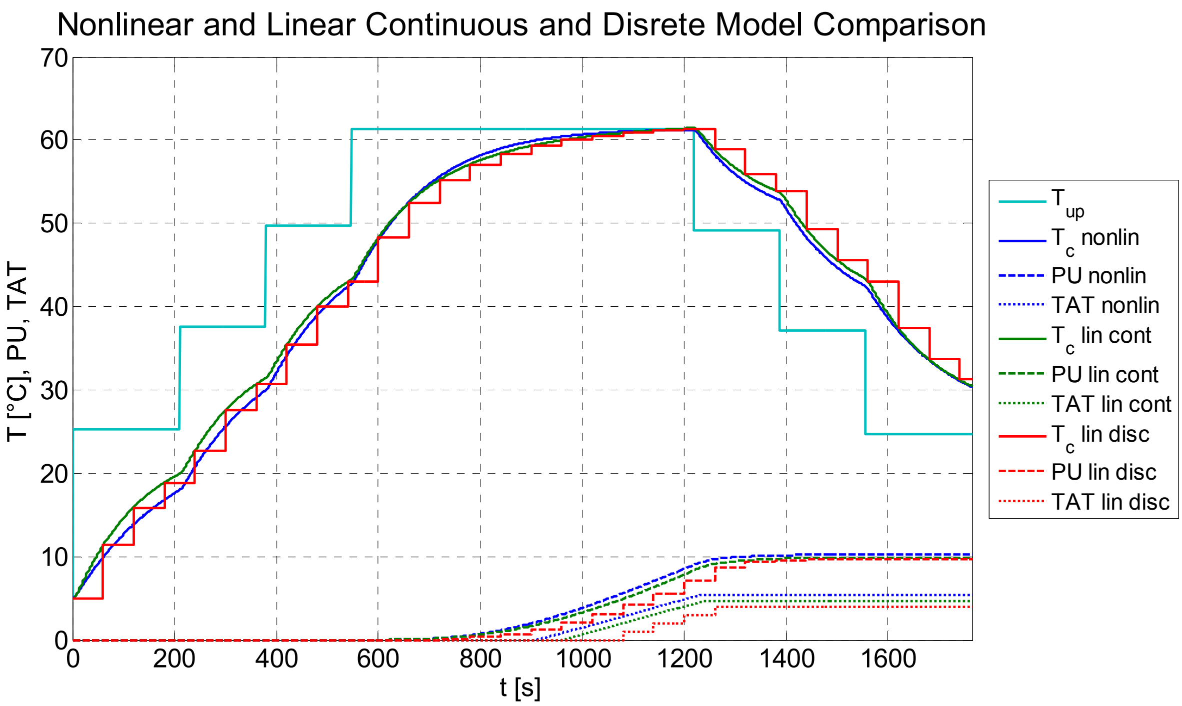

Figure 4.18: Comparison of nonlinear and linear continuous and discrete models of big can

5 Pasteurizer Control

The control algorithm, which will be designed in this chapter, controls the most important part of processes taking place during the tunnel pasteurizer operation – the pasteurization itself. The actuating variables are spray zone temperature and speed of the conveyor belt. The speed of a conveyor belt being an actuating variable is important moment, because in usual control systems, it is set to a constant value.

5.1 Static and dynamic optimization

A tunnel pasteurizer is a system that operates most of the time at the nominal operating point or in its proximity. Each container that passes through the pasteurizer is treated equally. By means of static optimization the steady operating point is found. The results of static optimization are zone temperatures and conveyor belt speed holding one steady value for the whole period the container is inside the pasteurizer.

Dynamic optimization on the other hand is useful to cope with unexpected events and error conditions such as forced conveyor belt stop, when the optimizer works as a MPC controller. The prediction is made in every sampling step and the state of inner model is updated by measured process data. The optimal input computed for this sample time is applied to the system afterwards.

The definitions of static and dynamic optimization problems are not completely different, but have some common passages. These will be described in Section 5.2. The differing parts are separated in their own Sections 5.3 and 5.4.

5.2 Control Algorithm Common Parts

The goals of pasteurizer control system are:

- to minimize the occurrence of unwanted process states such as those listed in Section 3.5, especially over- and under-pasteurization,
- to handle the error states with minimal harmful effect on the pasteurized, which means to ensure equal pasteurization of all products. The basic properties of modern measure and control systems were mentioned in Section 3.4.2.

The control algorithm will be defined in form of linear programming problem. This kind of problem is consists of a linear model of the controlled process, a set of constraints, defining acceptable and inacceptable states of the controlled process, and objective, which represents the goals of the control.

5.2.1 Variables and Constants Definition

Just before the very definition of the LP problem, it is useful to introduce the handlist of variables and constants that figure in it.

Notation	Proportion	Meaning
n_z	1	Number of pasteurizer zones plus two imaginary zones representing space at the input and output of the pasteurizer
b_z	$[1, n_z]$	Beginning of pasteurizer zones
e_z	$[1, n_z]$	End of pasteurizer zones
T_s	1	Sample time
(A_c, B_c, C_c, D_c)		State-space model of container
$(A_{int}, B_{int}, C_{int}, D_{int})$		State-space model of integrator
N	1	Prediction horizon
n_c	1	Number of containers
T_{init}	$[1, n_c]$	Initial value of container temperature
PU_{init}	$[1, n_c]$	Initial value of container Pasteurization Units

Notation	Proportion	Meaning
TAT_{init}	$[1, n_c]$	Initial value of container Time Above Temperature
s_{init}	$[1, n_c]$	Initial value of container position
T_z	$[N, n_z]$	Water temperatures in zones
$T_{z_{init}}$	$[1, n_z]$	Initial water temperature in zones
T_{up}	$[N, n_c]$	Water temperature on container model input
PU_{int}	$[N, n_c]$	Output of the linearized PU equation
TAT_{int}	$[N, n_c]$	Difference of TAT
v_c	1	Speed of conveyor belt
z_c	$[N, n_z, n_c]$	Container zone (binary variable)
T_{in}	$[N, n_c]$	Temperature of container content
PU	$[N, n_c]$	Container PU
s_c	$[N, n_c]$	Container position
p_{end}	$[N, n_c]$	Indicates the sample when container leaves the pasteurizer (binary variable)
PU_{end}	$[n_c, 1]$	Container PU when leaving the pasteurizer
PU_{ref}	1	Demanded value of PU on pasteurizer output
TAT	$[N, n_c]$	Container TAT
TAT_{ref}	1	Demanded value of TAT on pasteurizer output
$T_{z_{min}}, T_{z_{max}}$	$[n_z, 1]$	Minimum and maximum zone water temperature
$\Delta T_{z_{min}}, \Delta T_{z_{max}}$	$[n_z, 1]$	Minimum and maximum zone water temperature change
n_{lin}	1	Number of points where the PU equation is linearized

Notation	Proportion	Meaning
T_{in_0}	$[n_{lin}, 1]$	Points where the PU equation is linearized
a, b	$[n_{lin}, 1]$	PU equation piecewise linear approximation coefficients
$v_{c_{min}}, v_{c_{max}}$	1	Maximal and minimal conveyor belt speed
n_{hc}	1	Number of heating and cooling zones
n_p	1	Number of pasteurization zones
ΔT_{zn}	$[N, 2n_{hc}]$	Temperature differences between spray zones (except the middle pasteurization zones)
$\overline{\Delta T_{zn}}$	1	Average temperature difference between zones
ΔT_{hc}	$[N, n_{hc}]$	Temperature differences between regenerative pairs
ΔT_p	$[N, n_p - 1]$	Temperature differences between pasteurization zones
T_{cool}	1	Approximate drop of temperature in heating zones
T_{ref}	$[n_z, 1]$	Zone temperature reference
v_{ref}	1	Conveyor belt speed reference

5.2.2 Approximation of PU Equation

Because the product PU uptake is part of the LP problem and it is defined as a nonlinear function of temperature T_{in} in Equation (2.1), this relation must be approximated. It will be approximated as a piecewise linear function. The points, where the linearization of the function is computed are

$$T_{in_0} = \{50, 58, 60, 62, 64, 68\}. \tag{5.1}$$

The linearization of Equation (2.1) is

$$\dot{PU} = \frac{10^{\frac{T_{in_0}-60}{6{,}94}}}{6{,}94}\ln 10\,\left(T_{in} - T_{in_0}\right). \tag{5.2}$$

The slope a of a tangent and the intersection with original curve b are defined as

$$a = \frac{10^{\frac{T_{in_0}-60}{6{,}94}}}{6{,}94}\ln 10\,, \qquad b = 10^{\frac{T_{in_0}-60}{6{,}94}}. \tag{5.3}$$

The input of integrator of PU is approximated using coefficients a and b from Equation (5.3). This approximation is possible thanks to fact that the original nonlinear function is convex and therefore the approximated value of PU derivation PU_{int} can be computed as in Equation (5.4)

$$PU_{int} = \max\left(b + a\left(T_{in} - T_{in_0}\right)\right). \tag{5.4}$$

5.2.3 Prediction of model states

The prediction matrices are the same for all containers, therefore it is presumed that the number of containers $n_c = 1$ in the following text to make the notation more easily understandable.

General formula for prediction of output y of a discrete linear system (A, B, C, D) from initial state $x(i)$ and input u is

$$y = Hx + Su,$$

$$y = \begin{bmatrix} y(i) \\ y(i+1) \\ y(i+2) \\ \vdots \\ y(i+N-1) \end{bmatrix}, \quad H = \begin{bmatrix} C \\ CA \\ CA^2 \\ \vdots \\ CA^{N-1} \end{bmatrix}, \quad x = x(i),$$
$$S = \begin{bmatrix} D & & & & \\ CB & D & & & \\ CAB & CB & D & & \\ \vdots & & & \ddots & \\ CA^{N-2}B & & & CB & D \end{bmatrix}, \quad u = \begin{bmatrix} u(i) \\ u(i+1) \\ u(i+2) \\ \vdots \\ u(i+N-1) \end{bmatrix}. \tag{5.5}$$

State variables predictions according to Equation (5.5) are

$$
\begin{aligned}
T_{in} &= H_c x_{init} + S_c T_{up}, \\
PU &= H_{int} PU_{init} + S_{int} PU_{int}, \\
TAT &= H_{int} TAT_{init} + S_{int} TAT_{int}, \\
s_c &= H_{int} s_{init} + S_{int} v_c,
\end{aligned}
\tag{5.6}
$$

where H_c and S_c are computed for system (A_c, B_c, C_c, D_c) representing the container and H_{int}, S_{int} refer to the discrete state-space model of an integrator $(A_{int}, B_{int}, C_{int}, D_{int})$. This integrator is used to compute container PU, position and TAT. The value of TAT_{int} equal to the difference of TAT and is computed according to Equation (2.2). This equation is implemented via command *imply* of YALMIP Toolbox (22).

Since the of system (A_c, B_c, C_c, D_c) has order 3 and is observable, 3 historical inputs and outputs are needed to determine the initial state x_{init}. It is denoted a different way than the other variables to be clear it has no physical significance. In (23) is stated that the initial state can be uniquely determined using the theoretical relation

$$
\begin{gathered}
\tilde{y}(k) = CA^k x_0, \qquad k = 0, 1, \dots, n-1, \\
\tilde{y}(k) = y(k) - \left[\sum_{i=0}^{k-1} CA^{k-(i+1)} Bu(i) + D(k)u(k)\right], \\
\begin{bmatrix} \tilde{y}(0) \\ \tilde{y}(1) \\ \vdots \\ \tilde{y}(n-1) \end{bmatrix} = \begin{bmatrix} C \\ CA \\ \vdots \\ CA^{n-1} \end{bmatrix} x_0,
\end{gathered}
\tag{5.7}
$$

where (A, B, C, D) is substituted by (A_c, B_c, C_c, D_c), $y(k)$ by $T_{in}(k)$, $u(k)$ by $T_{up}(k)$ and $n = 3$. When the last equation of Equation (5.7) is solved, the demanded state x_{init} is not the resulting x_0, but x_{n-1} and is easily computed the common way using prediction matrices.

5.2.4 Constraints

Still holds the premise $n_c = 1$. Following constraints are common for static and dynamic optimization problem.

- Container zone

  To determine the zone where the container is situated, its position is compared with zone beginning and end. In case the container is in the zone, binary variable z_c is set to 1. The container may occur only in 1 zone in one sample; therefore the sum of container positions in one sample is 1.

$$z_c b_z \le s_c \le z_c e_z,$$
$$\sum z_c = 1. \tag{5.8}$$

To avoid containers on border of two neighbouring zones to jump to the previous zone, when it has belonged to the next zone once, the constraint Equation (5.9) is defined. However, it does not give the unique option of choosing particular zone every time the container occurs on the zone border.

$$\text{cumsum } z_c(i) \ge \text{cumsum } z_c(i+1), \qquad i = 1, \dots, N-1. \tag{5.9}$$

- Container model input temperature

Temperature T_{up} depends on the zone, where the container is situated. The constraint is in Equation (5.10). It is not a linear constraint, because it contains multiplication of two variables. The container zone z_c is a binary variable and therefore this constraint can be formulated using mixed logical programming and converted into linear constraints according to Equation (5.11).

$$T_{up}(i) = \sum_{j=1}^{n_z} z_c(i,j) \cdot T_z(i,j)\,, \qquad i = 1, \dots, N. \tag{5.10}$$

In Equation (5.11), z refers to T_u, δ to z_c and x to T_z. M and m are upper and lower bound of variable x and they must be defined for the correct function of this notation. The notation is written generally, because it will be used again for another constraint with binary and continuous variable multiplication.

$$z = \delta \cdot x \Leftrightarrow \begin{array}{l} z \le M\delta \\ z \ge m\delta \\ z \le x - m(1-\delta) \\ z \ge x - M(1-\delta) \end{array}. \tag{5.11}$$

- Limit on zone temperatures

These limits are one of properties of the pasteurizer.

$$T_{z_{min}} \le T_z \le T_{z_{max}}. \tag{5.12}$$

- Limit on conveyor belt speed

The conveyor speed is dependent on speed of the whole beer processing line and during normal operation does not exceed given limits. For purposes of pasteurizer stoppage modelling, there is a possibility to set conveyor speed to 0 for these sample times.

$$v_{c_{min}} \leq v_c \leq v_{c_{max}}, \tag{5.13}$$

5.3 Static optimization problem specific part

5.3.1 Constraints

- Deviation of PU from the reference

The deviation of PU from the demanded value PU_{ref} is measured at the end of the pasteurizer in the last sample the container is inside. Static optimization has capability to bring this deviation always to 0 when the initial condition satisfies $PU \leq PU_{ref}$ and other constraints are loose enough. On the other hand, this is impossible to achieve during dynamic optimization in general, considering use of dynamic optimization especially during error states.

$$\begin{aligned} \left|PU_{ref} - PU_{end}\right| &= 0, \\ PU_{end} &= p_{end}{}^T \cdot PU. \end{aligned} \tag{5.14}$$

The logic relation for p_{end} is converted to mixed integer inequalities

$$p_{end}(i) = z_c(i, n_z - 1) \wedge z_c(i+1, n_z) \Leftrightarrow \begin{aligned} -z_c(i, n_z - 1) + p_{end}(i) &\leq 0 \\ -z_c(i+1, n_z) + p_{end}(i) &\leq 0, \\ z_c(i, n_z - 1) + z_c(i+1, n_z) - p_{end}(i) &\leq 1 \end{aligned} \tag{5.15}$$

$$i = 1, \dots, N-1.$$

The multiplication in Equation (5.15) is realized using Equation (5.11).

5.3.2 Objective

Following two parts of objective belong only to static optimization problem.

- Equal temperature steps between heating and cooling zones

This constraint is applied to improve the fluency of container inner temperature increase and decrease and to avoid unnecessary strain on the container and therefore higher chance of breakage.

$$
\begin{aligned}
J_1 &= \sum_{i,j} |\Delta T_{zn}(i,j) - \overline{\Delta T_{zn}}|, \\
\overline{\Delta T_{zn}} &= \frac{\sum_{i,j} \Delta T_{zn}(i,j)}{2Nn_{hc}}, \\
\Delta T_{zn}(i,j) &= |T_z(i,j+1) - T_z(i,j)|, \\
& i = 1, \dots, N, j = 1, \dots, n_{hc}, n_p + n_{hc}, \dots, n_z - 1.
\end{aligned}
\tag{5.16}
$$

- Similar temperatures in recovery pairs

  Although modern pasteurizers do not have the spray zones organized in recovery pairs as the conventional ones, still it is energetically advantageous when the corresponding heating and cooling zones have similar temperatures. The temperature in cooling zone may be a bit lower, because it is supplied by cooler water. Also demand for similar temperatures in pasteurizing zones is included into this criterion, because one temperature for all means lower expenditures than if the hot water had different temperature in each zone.

$$
\begin{aligned}
J_2 &= \left(\sum_{i,j} \Delta T_{hc}(i,j) + \sum_{i,j} \Delta T_p(i,j) \right), \\
\Delta T_{hc}(i,j) &= |T_z(i,j) - T_z(i, n_z - j + 1) - T_{cool}|, \qquad i = 1, \dots, N, j = 1, \dots, n_{hc}, \\
\Delta T_p(i,j) &= |T_z(i,j) - T_z(i,j+1)|, \qquad i = 1, \dots, N, j = n_{hc} + 1, \dots, n_{hc} + n_p - 1.
\end{aligned}
\tag{5.17}
$$

In result, the whole objective for static optimization is

$$
J_s = W_1 J_1 + W_2 J_2. \tag{5.18}
$$

5.4 Dynamic optimization problem specific part

5.4.1 Constraints

The constraints of dynamic optimization problem vary in dependence on actual operation conditions. It means that in fact different problem is solved when the pasteurizer operates normally and in case of stoppage.

- Limit on zone temperature change

  The constraint defined in Equation (5.19) is included only when the optimization mode is dynamic. While the optimization is static, it is unnecessary to limit the variable change, because the variable is set to a constant value.

  The spray water temperature cannot make large steps in an instant. It is not in the possibilities of the heating. The time behaviour of temperature change is omitted, because it has much lower time constant than the beer inside container.

$$\Delta T_{z_{min}} \leq \Delta T_z \leq \Delta T_{z_{max}},$$
$$\Delta T_z = \begin{bmatrix} 1 & & & \\ -1 & 1 & & \\ & \ddots & \ddots & \\ & & -1 & 1 \end{bmatrix} T_z - \begin{bmatrix} T_{z_{init}} \\ 0 \\ \vdots \\ 0 \end{bmatrix}. \quad (5.19)$$

5.4.2 Objective

Objective for dynamic optimization contains members that stem from optimal values of conveyor belt speed and spray water temperatures obtained in static optimization. As shown in Section 6.1, these values applied on the system give outputs that are slightly deviated from the reference and should be refined. The refined values are used in dynamic optimization.

- Zone temperatures close to refined zone temperatures

  The prediction horizon is shorter than by static optimization. In case the pasteurizer is not fully loaded, some zone temperatures would not take part in the objective and would be practically arbitrary within the constraints. For this reason, refined optimal temperatures from static optimization are introduced in the objective.

$$J_3 = \sum_{i=1}^{N} \sum_{j=1}^{n_z} \left| T_z(i,j) - T_{ref}(i,j) \right|. \tag{5.20}$$

- Conveyor belt speed close to refined speed

  The speed reference in objective is connected with zone temperatures. The demanded PU are obtained only with optimal combination of each.

$$J_4 = \sum_{i=1}^{N} \left| v_c(i) - v_{ref} \right|. \tag{5.21}$$

- Penalization of PU violation

  This objective plays its role when the pasteurizer accidentally stops. This way, violation of PU reference anywhere in the pasteurizer is penalized. A tolerance for small over-pasteurization may be included, because the moderate over-pasteurization is better than under-pasteurization

$$J_5 = \sum_{i=1}^{N} \sum_{k=1}^{n_c} \max\left(0, PU(i,k) - PU_{ref}\right).. \tag{5.22}$$

- Penalization of PU divergence

  This objective forces the containers in last two pasteurization zones to take the amount of PU as closest as possible to the desired PU_{ref}. The reason for formulation of this constraint this way is that the length of prediction horizon is not necessarily sufficient for affecting the value of PU on output at the moment the container is in the pasteurization zone.

$$\begin{aligned} &\text{if } b_z\left(n_{hc} + n_p\right) \le s_{init}(k) \le e_z\left(n_{hc} + n_p\right) \\ &\Rightarrow J_6 = \sum_{i=N-a}^{N} \sum_{k=1}^{n_c} \max\left(0, PU_{ref} - PU(i,k)\right), \qquad k = 1, \ldots, n_c, \end{aligned} \tag{5.23}$$

  where a defines the part of prediction horizon that is affected by the objective.

- Penalization of TAT violation and TAT divergence

  The value of TAT, if included in the objective, is treated the same way as PU in Equations (5.22) and (5.23) and form sub-objectives J_7 and J_8.

- Minimal PU uptake during pasteurizer stop

  Imagine that the pasteurizer had to stop and during the stop would hold sub-objectives defined in Equations (5.23) and (5.24). The containers in all pasteurization zones would gain the demanded values of PU and TAT, but the containers in heating zones cannot achieve any PU uptake. Thus, there would grow a large gap in PU and TAT between the last container in heating zones and the first one in pasteurization zones. This gap would cause unequal pasteurization, resulting in either under- or over-pasteurization. For this reason, minimal PU uptake during the stop is needed to disable generation of large differences between zones

$$J_9 = \sum_{i=1}^{N} K_v \sum_{k=1}^{n_c} PU_{int}\,(i,k), \tag{5.24}$$

where parameter K_v is vector of length N indicating the samples where the conveyor is stopped.

The resulting objective for dynamic optimization is in Equation (5.23)

$$J_D = k_v(W_3J_3 + W_4J_4 + W_6J_6 + W_8J_8) + \left(W_9\bar{k}_v + W_9\right)J_9 + W_5J_5 + W_7J_7, \tag{5.1}$$

where the parameter k_v (negation $\bar{k}_v$) denotes whether the conveyor is moving or not at the present sample time.

5.5 Improvement of Static Optimization Performance

It was decided to use sample time $T_s = 60\ s$ for prediction of model states in the optimization problem. The reasons for this pretty long sample time are high time constants of the model of container and also fast run of the optimization. The drawback is lower precision of obtained results, which is more significant by static optimization, because the predicted values are not updated by data from the process. This will be illustrated in Section 6.1. At this place a method for refinement on results gained by static optimization is going to be proposed.

The resulting value of PU is influenced by temperature in pasteurization zones, where the decisive PU contribution is made. By tiny modification of temperature in these zones, the PU can be changed significantly to be set precisely on the demanded value. This leads to formulation of optimization the problem of retrieval of extreme of function $f(x)$ of single variable x on a given interval. The difference of function $f(x)$ is not known. This type of problem can be solved by Fibonacci Method. The function is unimodular in addition, which means there is only one extreme on the given interval. Detailed description of this method can be found in (23).

The Fibonacci Method applied on this problem will find temperature of spray water in pasteurization zones T_p that corresponds with minimum deviation of PU_{end} from reference value PU_{ref}.

$$T_p \approx \min\left|PU_{end}(T_p) - PU_{ref}\right|.$$

The resulting value of Pasteurization Units $PU_{end}(T_p)$ can be seen as function of temperature T_p.

The initial interval of uncertainty $[a, b]$ is derived from final PU_{end} obtained by static optimization

$$\begin{aligned} &\text{if } PU_{end} > PU_{ref} \Rightarrow a = \max(T_p - 1, T_{ref}), b = T_p, \\ &\text{if } PU_{end} \le PU_{ref} \Rightarrow a = T_p, b = \min(T_p + 1, T_{z_{max}}), \end{aligned} \tag{5.2}$$

where T_{ref} is reference temperature from Equation (2.1) and $T_{z_{max}}$ is maximal temperature in pasteurizing zones. The iterative algorithm proceeds as follows

1. $\alpha_1 = a, \beta_1 = b,$
2. for $i = 1,2, \dots, N - 1,$

$$\begin{aligned} \bar{\alpha}_{i+1} &= \beta_i - \frac{F_{N-i}}{F_{N-i+1}}|\beta_i - \alpha_i|, \\ \bar{\beta}_{i+1} &= \alpha_i + \frac{F_{N-i}}{F_{N-i+1}}|\beta_i - \alpha_i|. \end{aligned} \tag{5.3}$$

3. if $PU_{end}(\bar{\alpha}_{i+1}) \le PU_{end}(\bar{\beta}_{i+1}) \Rightarrow \alpha_{i+1} = \alpha_i, \beta_{i+1} = \bar{\beta}_{i+1},$

   if $PU_{end}(\bar{\alpha}_{i+1}) > PU_{end}(\bar{\beta}_{i+1}) \Rightarrow \alpha_{i+1} = \bar{\alpha}_{i+1}, \beta_{i+1} = \beta_i.$

The parameter F_N in Equation (5.27) is a sequence of Fibonacci numbers of length N, defined as

$$F_i = F_{i-1} + F_{i-2}, \qquad F_0 = F_1 = 1. \tag{5.4}$$

Fibonacci method reduces the original interval of uncertainty by F_N in N steps. The algorithm was used with $N = 20$.

6 Results

6.1 Static Optimization Results

Figure 6.1 and Figure 6.2 contain the resulting characteristics obtained by solving static optimization task formulated in Section 5.2 with objective defined in Equation (5.19). The resulting value of PU after simulation of the nonlinear model with optimal inputs was by coincidence for both containers $PU_{end} = 10.27$, which is very good result. The refinement of the pasteurization zones temperature was nearly unnecessary, but it achieved to lower the deviation of nonlinear model PU to 0 with precision of three decimal numbers. The change of spray water temperature in pasteurizing zones was minimal and that is why the corresponding characteristics overlap.

The temperature characteristics corresponding with predictions during the optimization are following the nonlinear model with moderate accuracy and especially in cooling zones and first pasteurization zone the deviation is clearly visible. There is also a delay compared to the nonlinear model in PU uptake. This is caused just by the temperature deviation in the beginning of first pasteurizing zone. This is compensated at the moment when the product leaves the last pasteurizing zone, since in the discrete model the high temperature value is held for the next sample time and the resulting values of PU at the pasteurizer end from both continuous nonlinear and discrete linear model are close.

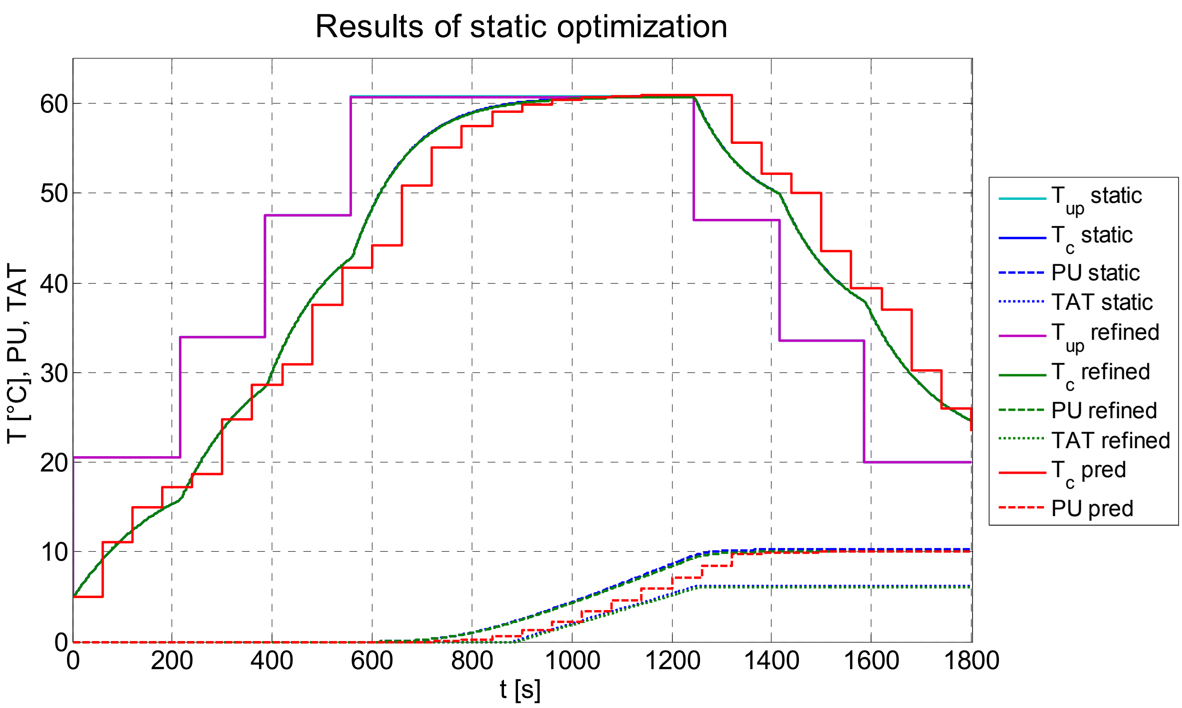

Figure 6.1: Small can static optimization characteristics

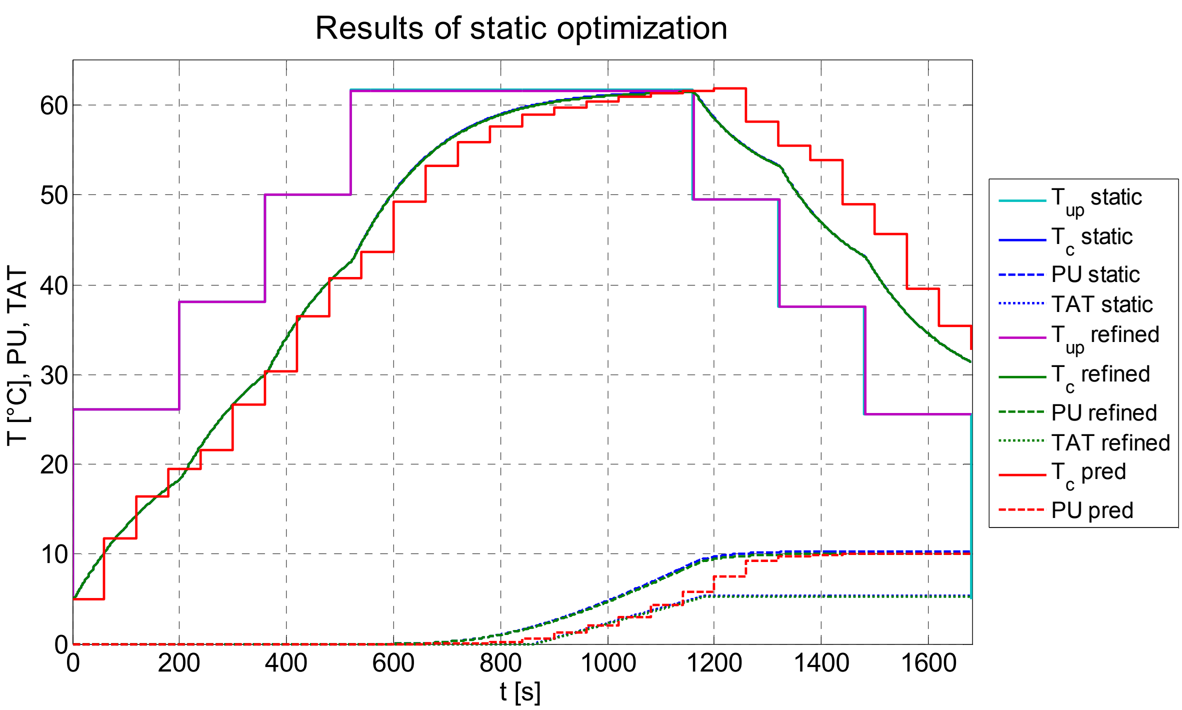

Figure 6.2: Big can static optimization characteristics

6.2 Dynamic Optimization Results

The results are presented as series of plots that display the state of the pasteurizer at discrete times. This way, the distribution of temperatures, PU and TAT along the pasteurizer is clearly visible. The disadvantage of this way of display is that the speed of the belt conveyor is not as evident in most cases.

The length of prediction horizon is set to $N = 5$. With this value, the dynamic optimization algorithm is functioning very quickly (compared to setting $N = 10$ more than 100 times faster) and the results are acceptable.

6.2.1 Reference Containers

It is technically impossible that the optimization problem would involve every container in the pasteurizer. Therefore, suitable containers have to be chosen to represent the states of all the containers in the pasteurizer as best as possible. There is a very large number of ways how this can be carried out and it is not easy to say which method is better unless a number of simulations would be carried out. The currently used method chooses one container from each zone that is closest to the middle of the zone and additional four containers with minimal PU each from another pasteurization zone to avoid under-pasteurization.

6.2.2 Planned 10 minute Stoppage

The first test of MPC controller consists in planned stoppage for 10 minutes. The initial state of the simulation is normal operation state reached with inputs gained in Section 6.1. The container is small can. The summary of optimization settings is in Table 6.1. The scenario is following: optimization starts 5 minutes before stoppage, then the conveyor speed is set to 0 for 10 minutes and then the optimization continues with the restarting period of 15 minutes.

Weight	W_3	W_4	W_5	W_6	W_7	W_8	W_9
Value	2	1	10	100	0	0	10

Table 6.1: Settings of objective weights

The simulated results are in Appendix B Section 1. Graphs with simulation of pasteurizer without control during the stoppage were added as reference characteristics for analysis of effects of the control. The plots have 5 minute time spacing, which is a compromise number between the detail level and number of plots.

The first difference in the characteristics appears just before the stoppage time, as the controller begins to lower down the temperatures. As the stoppage time was approaching, the sub-objective J_9 started to play the decisive role and during the stoppage will be the only applied objective. This way, the PU uptake is forced to 0 by lowering the temperatures of spray water and no significant differences between PU of containers in neighbouring are allowed arising. In $t = 900\,\mathrm{s}$ is the effect of control clear, instead of massive over-pasteurization, the value of PU is still near the reference value and the zone temperatures are being raised again to prepare the pasteurizer restart.

So the controller easily copes with the stoppage, but the critical part is still to come. The main problem lies in fluent restart after the stoppage. There still are differences in container temperatures on the edges of the zones. As the conveyor belt starts to move again, containers with very different temperatures immediately start to share the same spray zone. These containers are from now treated practically equally, which results in differences of PU and TAT characteristics from the reference values. Since the minimal level of PU is the crucial factor here, over-pasteurized containers start to appear. But again should be remarked that the level of over-pasteurization is sufficiently low, because of being reduced by the controller.

6.2.3 Unplanned 10 minute Stoppage

The stoppage length and time is not known by the controller. Therefore, if the stoppage occurs in current sample, it is assumed that the stoppage will last for half the prediction horizon. Again, the pasteurized container type is the small can. The objective has the weights defined in Table 6.1: Settings of objective weights. The results of the simulation are in Appendix B Section 2. They are compared to the results of simulation of planned stoppage.

The characteristics before and during the stop are even smoother than those of informed controller; in this case the information about future inputs influence the PU and TAT characteristic in rather negative way. But still there is a possibility to revise the informed controller and make it ignore the information and act like the uninformed one in this particular case.

The advantage of informed controller takes effect during the restart. While the informed controller raises the temperatures in zones as the end of stoppage approaches, the uninformed controller has to do this even after the stoppage and in combination with pretty high speed of the conveyor around $t = 1200$ s the result are the under-pasteurized containers.

6.2.4 Planned 10 minute Stoppage with TAT

The last test is performed with the values of TAT included into the objective. The used weights are in Table 6.2: Settings of objective weights.

Weight	W_3	W_4	W_5	W_6	W_7	W_8	W_9
Value	2	1	10	100	1	1	10

Table 6.2: Settings of objective weights

The simulated results are in Appendix B Section 3. The performance of this controller setting is compared with controller from Section 6.2.2. The resulting characteristics are almost the same; even the optimized speed was similar in the monitored samples. At the end of the simulation period the controller incorporating TAT into the objective gave better result, less deviated from the reference in both PU and TAT, which was positively affected by the presence of TAT in the objective.

7 Conclusion

This thesis deals with modelling and control of the pasteurization process in tunnel pasteurizers.

In the beginning, the methods of pasteurization used in present were discussed. The batch method is used rather rarely and for special applications, since the modern pasteurization methods offer benefits of continuous processing – time and economic efficiency. Flow pasteurization is widely used especially in dairy industry. In brewing industry this method is mostly used for keg beer. For cans and bottles is usually used tunnel pasteurization. The advantage of this method is filling prior to pasteurization, which means no risk of reintroduction of spoilage organisms to the pasteurized product.

In Chapter 3 are analyzed properties of tunnel pasteurizers, their construction and means of control. Modern pasteurizers are superior to conventional pasteurizers in all areas. The most important innovations include water circulation system with overflow tanks and single heat exchanger and continuous control based on simulation model of the process instead of time demanding measurement with the so called "PU Box".

The simulation model of tunnel pasteurizer was designed in Chapter 4. The simplified model consists of parts representing belt conveyor, spray system and containers. The model is universal and can be used as a subsystem in more complex model of any tunnel pasteurizer. Model of double deck pasteurizer was also developed. Models of the decks correspond with the model of single deck pasteurizer. The only difference is that the input water to the lower deck is overflow water from the upper deck.

Unfortunately, it was impossible to evaluate the accuracy of the models because of impossibility to gain real process data. The attempts to contact certain companies were not successful; therefore the only option left was to take over incomplete measurement data from (19) and use it for identification of the model.

A linear model needed for control design was acquired from simulation data of the nonlinear model. During estimation, the emphasis was placed on the model performance at temperatures around the pasteurization temperature. This way was achieved good accuracy of Pasteurization Unit PU and Time Above Temperature TAT characteristics.

After acquisition of appropriate linear model, the control algorithm was designed in Chapter 5. The pasteurizer operates the most of time around nominal operation point, but from time to may occur time exceptional states. For search for optimal settings of stable state spray water temperatures and conveyor belt speed static optimization was used. Because the linear model is not so precise on longer prediction horizons, the utilization of Fibonacci method was proposed to adjust the pasteurization zones temperatures to get the precise value of PU at the pasteurizer output. Control during exceptional situations is provided by an MPC controller. For example stoppage of conveyor belt or product changeover on the fly belongs to such situations.

In Chapter 6, the results of simulations of the controlled nonlinear model are presented. This model was simulated with inputs equal to zone temperatures and conveyor speed, resulting from the static optimization. The value of PU at the end of the simulation was surprisingly close to the reference value, considering the length of prediction horizon, sample time and nonlinearities of the simulation model. The refinement using the Fibonacci method was applied anyway and the refined operation point was used later in the objective of the dynamic optimization problem.

The performance of MPC controller was tested using test cases containing expected and unexpected stoppage of conveyor belt. The objective of the controller was to follow the reference values of PU and TAT eventually. During the stoppage, the temperatures were lowered down in order to inhibit any PU uptake. The critical point was the restart after end of the stoppage, demanding on coordination of zone temperatures and conveyor speed. More problems to the controller were caused by unexpected stoppage, since the controller could not accommodate the process inputs to the oncoming restart in advance. The expected stoppage did not cause any problems to the controller and was handled without single under-pasteurized container.

Hopefully, the work on pasteurizer modelling and controller design will be continued. The future goals are to design a controller of double deck pasteurizer and to extend the model of pasteurizer by model of water circulation system.

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Appendix A

Contents of the Included CD

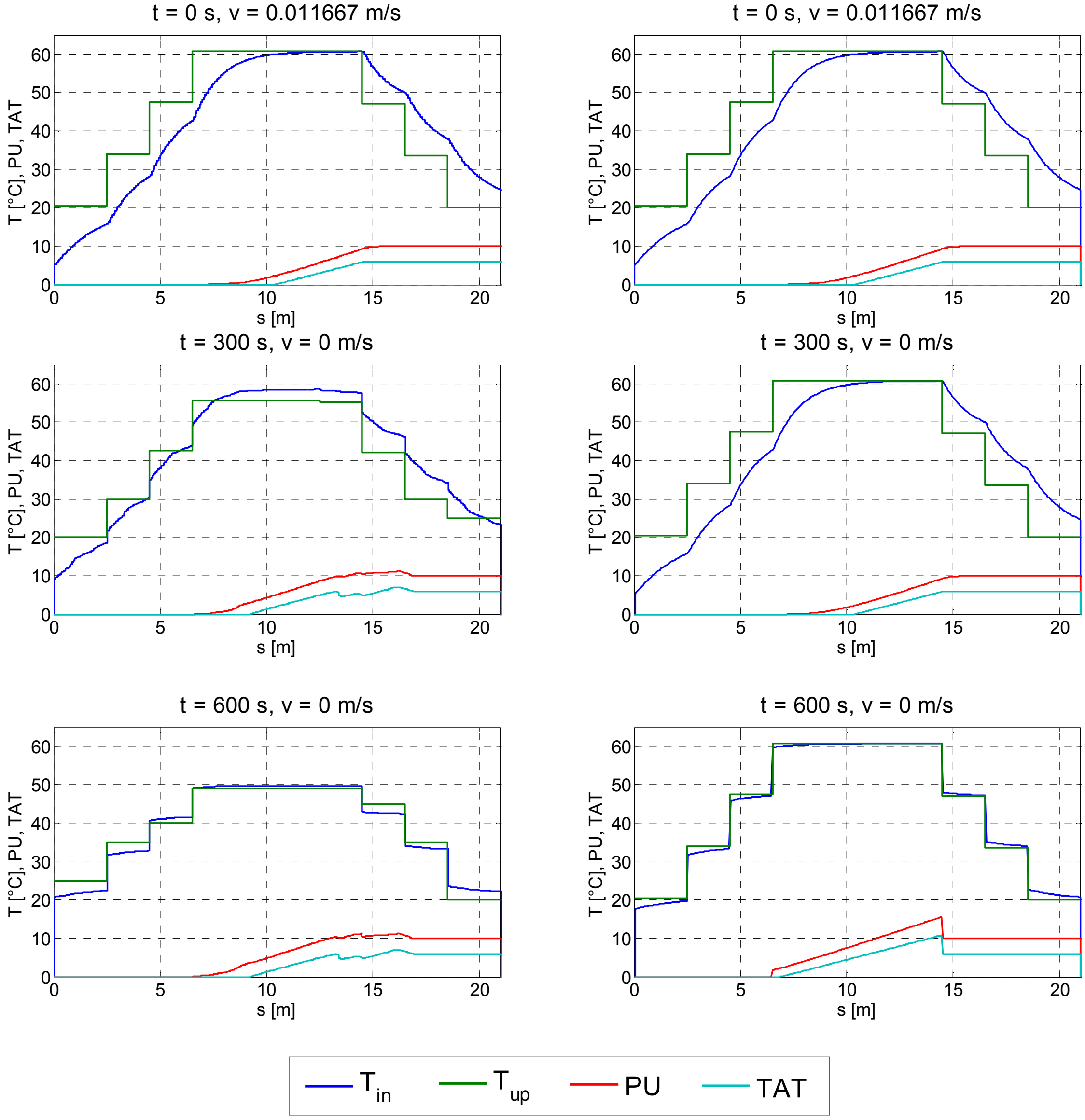
- Electronic version of this diploma thesis.

Appendix B

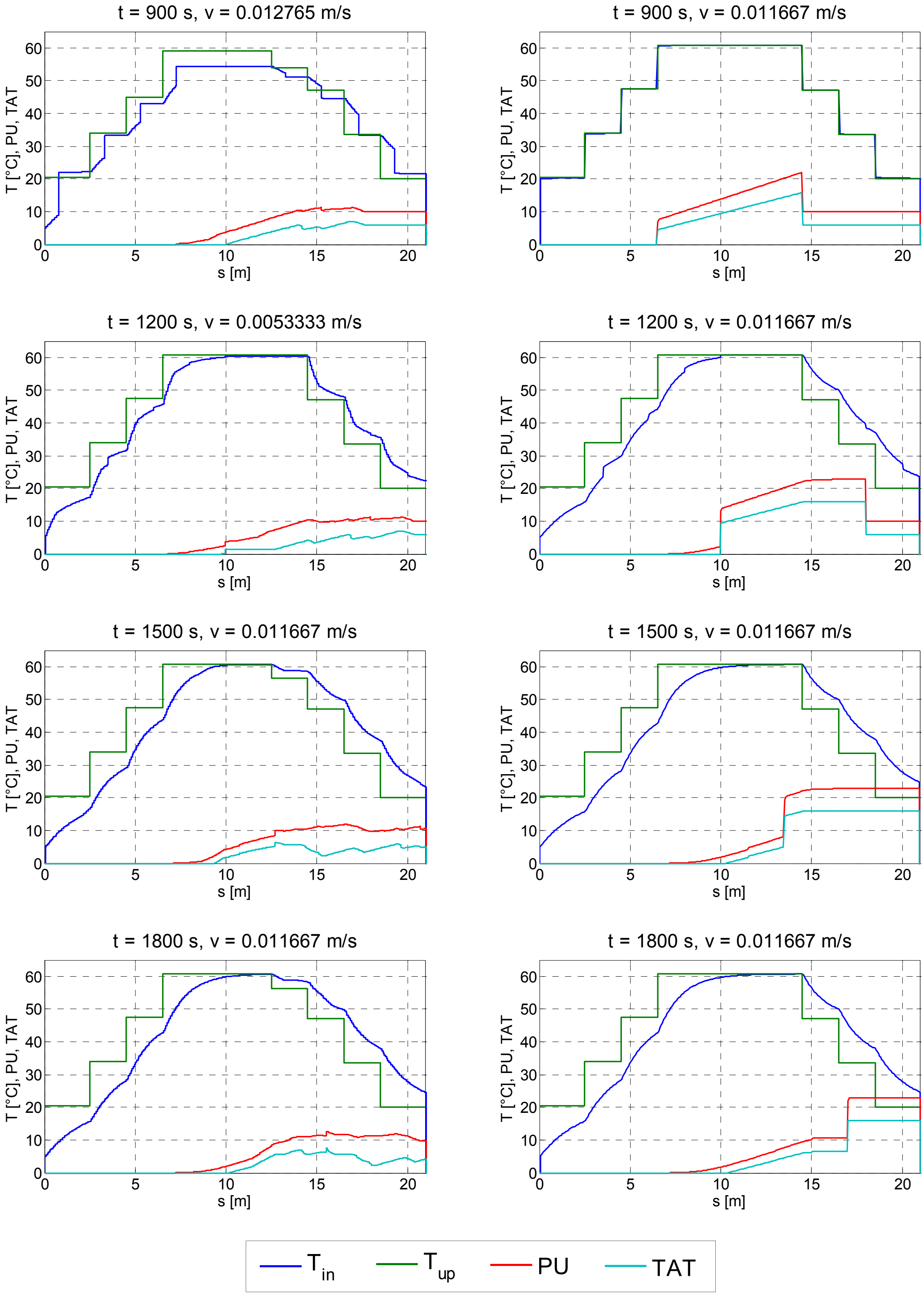
Simulation Characteristics

1. Planned Stoppage Time 10 minutes

Controlled System | Uncontrolled system

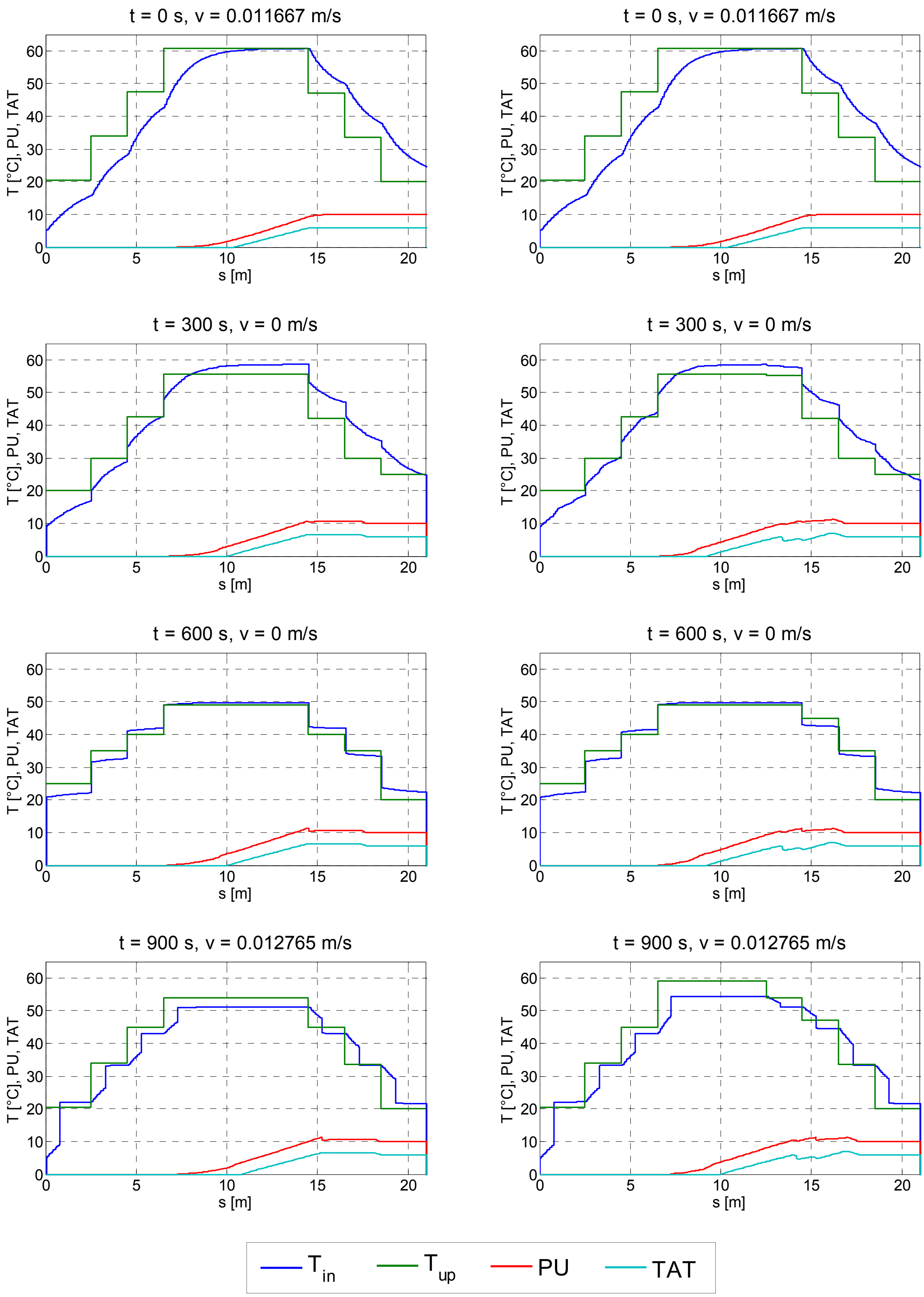


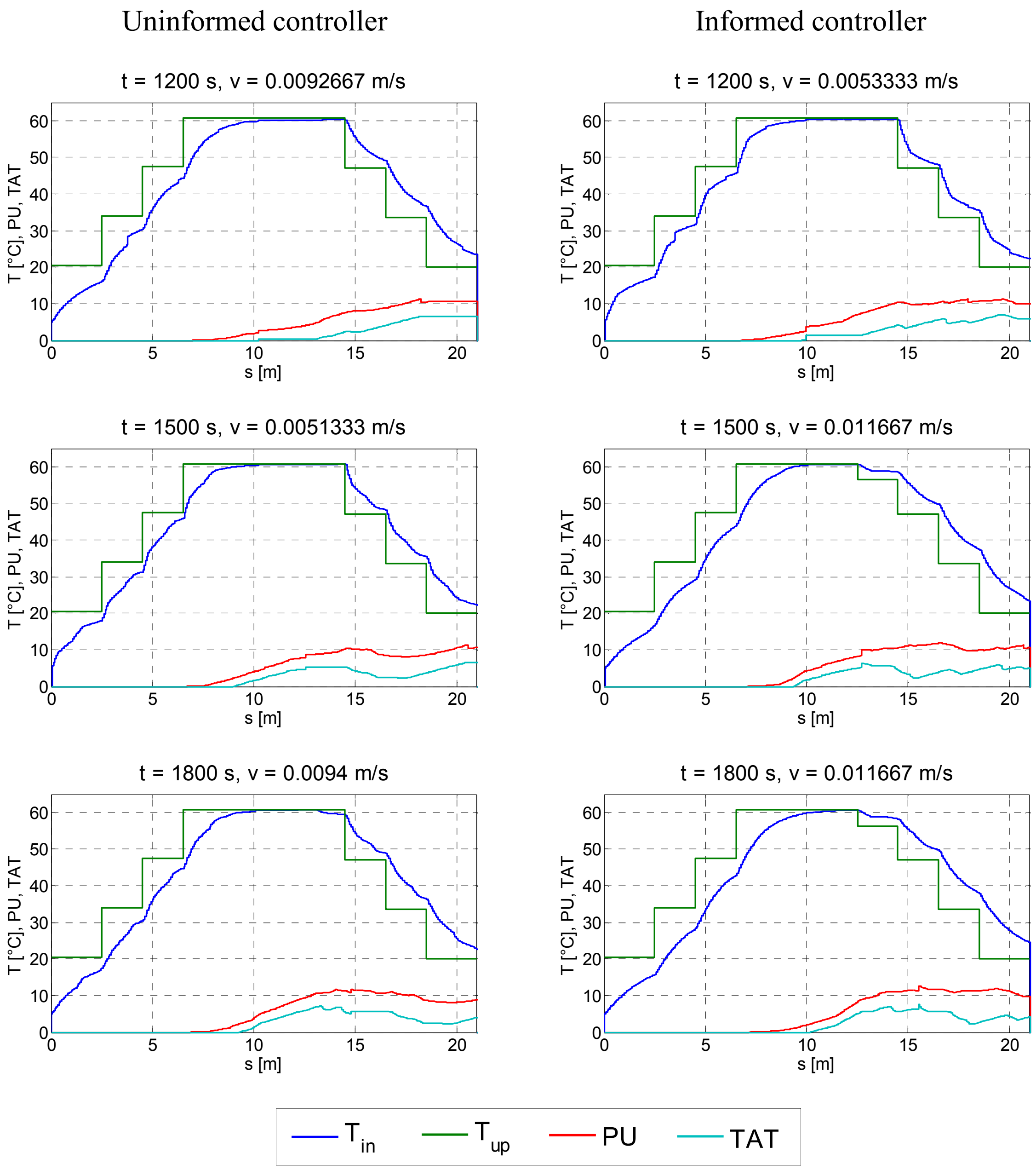
Controlled System | Uncontrolled system



2. Unplanned Stoppage Time 10 minutes

Uninformed controller | Informed controller

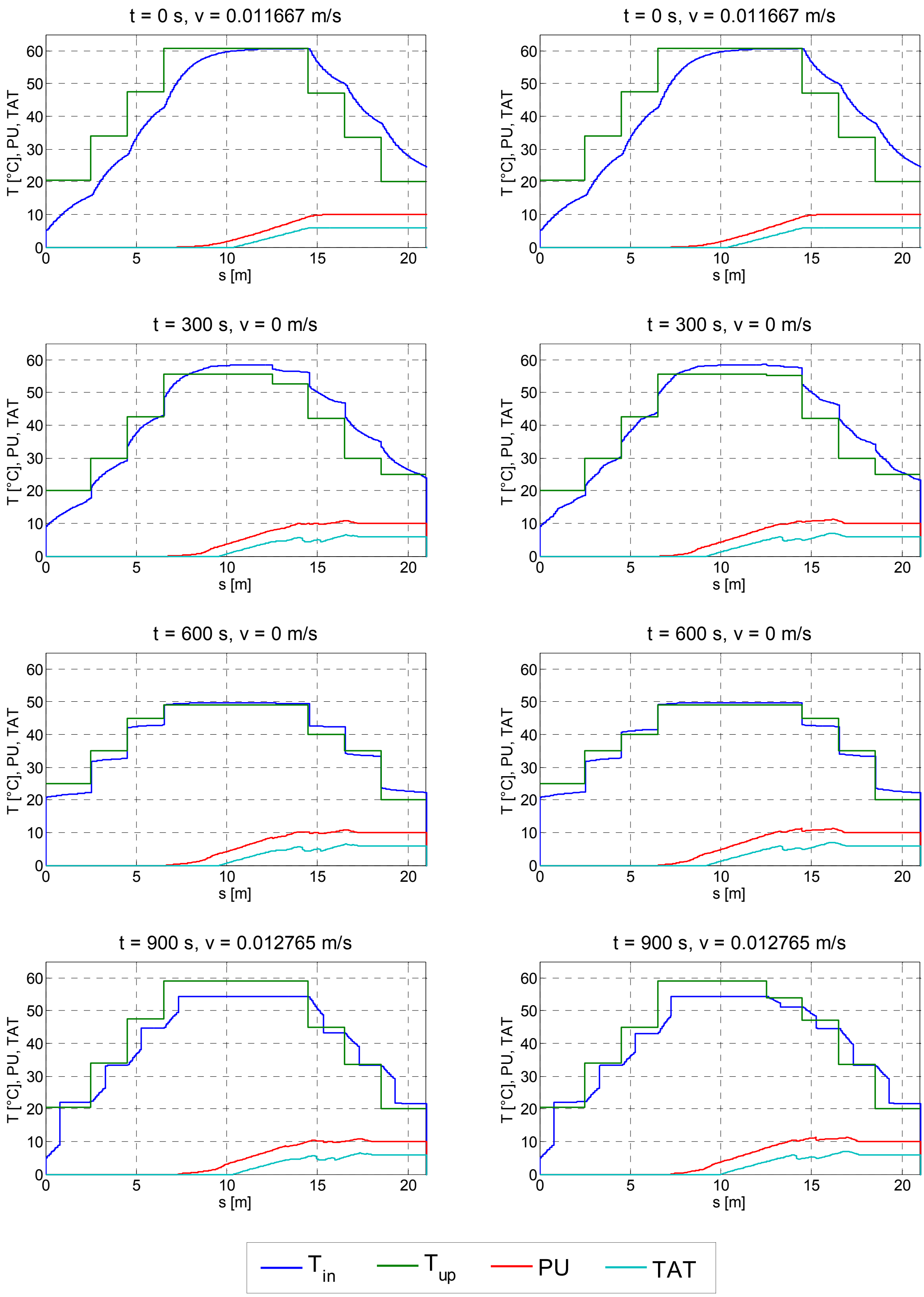



Uninformed controller
Informed controller
t = 1200 s, v = 0.0092667 m/s
t = 1200 s, v = 0.0053333 m/s
t = 1500 s, v = 0.0051333 m/s
t = 1500 s, v = 0.011667 m/s
t = 1800 s, v = 0.0094 m/s
t = 1800 s, v = 0.011667 m/s
T [°C], PU, TAT
s [m]
0
5
10
15
20
0
10
20
30
40
50
60
T_{in}
T_{up}
PU
TAT

3. Planned Stoppage Time 10 minutes TAT Included

Controller with TAT

Controller without TAT



Controller with TAT | Controller without TAT