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Optimal boundary control of a contact thawing process for foodstuff

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Abstract: In this work an approach for thawing blocks of foodstuff, in particular fish, is introduced. The functional principle is based on plate freezer technology, which has been used in industry for decades. The aim of this work is to describe the temperature dynamics of this thawing process by means of partial differential equations (PDEs) and control the boundary conditions in an optimal way. The PDE describing the temperature dynamics is based on the diffusion equation with state-dependent parameter functions.

Keywords: Thawing, Foodstuff, Partial Differential Equations, Optimal Control, MPC

1. INTRODUCTION

Shelf life extension of rapidly spoiling foodstuff is an essential task for the food industry. This holds especially for fish and fish products as they often have to be transported over long distances or stored over long periods in order to deliver them to the consumer or to further processing stages. By lowering the temperature, the rate of spoilage is reduced. As a general rule it holds that, the lower the temperature, the longer the shelf life. Therefore, freezing is the best method for shelf life extension over long periods.

After having been transported over long distances or stored over long periods, the foodstuff might not necessarily be sold in frozen state, but processed further. For example, frozen fillets in block form can be cut more or less directly to fish sticks after a short tempering phase, see Jason (1974). On the other hand, filleting of headed and gutted fish is not possible in frozen state. Therefore, thawing techniques must be used in order to enable further processing. Thus, not only freezing has a large impact on the quality of the final product, but also thawing. Thawing can not enhance the quality of the frozen product, meaning that quality losses and damages caused in earlier stages cannot be reversed by even the most sophisticated way of thawing. Hence it is even more important to understand the process of thawing, come up with new, gentle methods, derive mathematical models and in the end control the process such that an optimal solution is obtained, meaning that quality losses in the thawing process can be minimized.

As quality is influenced by many factors and parameters, a more precise definition for the process of thawing is needed. The most critical quality parameters influenced by the thawing process are water holding capacity, drying of the surface and lipid oxidation. Not only do they lower the overall quality directly, but also the product's yield. Reduced water holding capacity leads to increased drip loss, which results in lower product weight. Drying of the surface also results in lower product weight, whereas lipid oxidation occurs mostly for fatty species and can cause rancid tastes and smells. Both, drying and lipid oxidation are most likely to happen in air-based thawing methods.

There is a whole range of publications in the scientific community introducing different methods for freezing and thawing of foodstuff, see e.g. Johnston et al. (1994) and Jason (1974). Moreover, the modeling of heat and mass transfer phenomena with PDEs has extensively been studied, e.g. in Pham (2006b) and Pham (2006a). In Cleland et al. (1987) experimental data for freezing and thawing of multi-dimensional objects modeled by finite element techniques are presented. As computational power has grown in recent years, complex simulations can provide qualitative and quantitative insights to the system, even in the absence of analytical solutions. An open-loop approach for optimal boundary control of a plate freezing process has been described in Backi and Gravdahl (2013). However, it must be mentioned that thawing is not simply the reversed freezing process, as for example outlined in Olver (2014, Section 4.1). There it is mentioned that the *backwards heat equation*, where future and past are changed by changing from t to $-t$, is an ill-posed problem in the sense that small changes in initial data can lead to randomly large changes in the solution arbitrarily close to initial time.

Applied methods for thawing of fish blocks in industry are mostly based on heat conduction and convection by direct contact with the thawing medium. For this purpose mostly water or air are used. In water-based techniques the fish blocks are put into a water bath. Added air bubbles enhance heat transfer. In addition the water is sometimes heated in order to speed up the process. Another method relies on heat transfer by moving air, known as air-blast thawing. Due to the danger of lipid oxidation and drying of the surface it should be conducted with

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humidified air. The two mentioned methods are only controllable to a small extend as the physical processes underlying heat transfer are complex. The mentioned disadvantages motivate the introduction of another thawing method that is not as widely spread in industry as the two mentioned before. It does not rely on heat transfer by direct contact with the thawing medium, but on principles already known from plate freezer technology. Hereby a refrigerant flows through the plate freezer walls, where it vaporizes and extracts heat from the fish block. The thawing approach investigated here relies on the same principle, but instead of using a refrigerant, a thawing medium with high specific heat capacity can be used to thaw the fish block. The thawing medium, however, does not undergo phase change during the process.

To the authors best knowledge no work has been done so far in modeling the temperature dynamics of a contact thawing process. Also the important matter of (optimal) control of such a process has not been covered. Therefore this work presents a novelty with respect to the field of application.

The rest of the paper is organized as follows. Section 2 introduces the model and addresses some issues regarding the application of this model to both, freezing and thawing processes. Section 3 describes the problem setting for Model Predictive Control, whereas Section 4 shows numerical simulation examples that highlight the results in the previous section. Finally, Section 5 provides some concluding remarks.

2. PROBLEM FORMULATION

The process of thawing foodstuff is often performed based on thermodynamic steady state calculations (prior to execution), meaning that the temperature dynamics are neglected. In order to obtain better monitoring and in the end control the quality during thawing, the temperature dynamics play a vital role. However, these temperature dynamics and the temperature distribution throughout the foodstuff are hard to model in standard ways of thawing, such as immersion or air-blast processes. Thus we propose a contact thawing process in order to monitor and control the foodstuff's interior temperature field, which directly influences the quality. The choice of contact thawing is justified by the fact that the related process of freezing in plate freezers is well-understood and its results in modeling can be directly applied to the contact thawing process. Existing monitoring-algorithms to estimate the temperature field inside the foodstuff can be adapted to the contact thawing application, see e.g. Backi et al. (2015).

The overall aim of this work is to provide an optimal boundary control formulation for a contact thawing process such that determined temperature margins can be satisfied during the whole operation. This is beneficial for the final product quality.

It must be mentioned here that the time it takes to thaw foodstuff is significantly larger than to freeze it. The reason for this is that ice is a better conductor of heat compared to water. This means that for freezing the heat flow from the inner domain towards the boundary layer is accelerated over time due to ice layer formation at the boundary propagating towards the interior. For thawing, however, an initial liquid layer builds up at the boundary and propagates towards the interior causing a decrease in heat flow from the boundary to the inside of the food over time.

2.1 System structure

In Figure 1 we propose a control structure for the thawing process consisting of a cold water feed, a hot water buffer tank, two pumps and three (controlled) valves. The idea is to use an algorithm based upon Model Predictive Control (MPC) controlling the unit consisting of the two pumps and the valve mixing the hot and the cold water such that the desired boundary temperature in the thawer can be adjusted. The return water from the thawer can be split up to be either fed back to the hot water buffer tank or be disposed via the outlet (parts of it could also be fed back to the cold water feed, for example).

In the present work only the temperature dynamics of the thawer will be considered. In addition, we assume that the required temperature of the thawing medium can be exactly provided by the valve combining the hot and cold water feed. It is explicitly not intended to provide an underlying control structure for the unit providing the desired water (and thus boundary) temperature to the thawer. This is a task for future work and can result in energy-efficient operation.

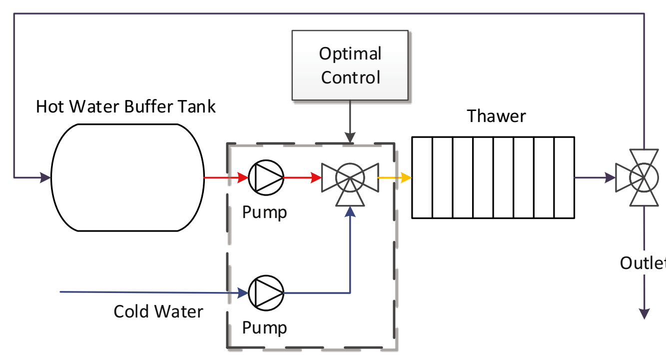

Fig. 1. Functional principle of the contact thawing process

2.2 Temperature dynamics model in the thawer

To model the temperature dynamics of the food in the thawer we use the diffusion equation with state-dependent parameters in the variable $T = T(t,x)$, which can be expressed in the following standard form:

$$\rho(T)\,c(T)\,T_t = [\lambda(T)\,T_x]_x \tag{1}$$

subject to (controlled) Dirichlet boundary conditions

$$T(t,0) = T(t,L) = u, \tag{2}$$

where $\rho(T) > 0$ denotes the density, $c(T) > 0$ indicates the specific heat capacity and $\lambda(T) > 0$ describes the thermal conductivity of the good inside the thawer. Note that $\rho(T)$, $c(T)$ and $\lambda(T)$ all depend on the temperature T. For completeness we point out that u is the control variable (input), whereas its derivative $\dot{u} = v$ is the optimization variable, see Section 3.2.

The diffusion equation (1) can be rewritten as

$$\rho(T)\,c(T)\,T_t = \lambda_T(T)\,T_x^2 + \lambda(T)\,T_{xx}. \tag{3}$$

due to

$$\lambda_x(T) = \lambda_T(T)T_x.$$

To keep notation simple, two new parameters can be introduced as