Modelling of the Heating Process in a Thermal Screw

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Abstract. The procedure of separating efficiently dry-stuff (proteins), fat, and water is an important process in the handling of waste products from industrial and commercial meat manufactures. One of the sub-processes in a separation facility is a thermal screw where the raw material (after proper mincing) is heated in order to melt fat, coagulate protein, and free water. This process is very energy consuming and the efficiency of the product is highly dependent on accurate temperature control of the process. A key quality parameter is the time that the product is maintained at temperatures within a certain threshold. A detailed mathematical model for the heating process in the thermal screw is developed and analysed. The model is formulated as a set of partial differential equations including the latent heat for the melting process of the fat and the boiling of water, respectively. The product is modelled by three components; water, fat and dry-stuff (bones and proteins). The melting of the fat component is captured as a plateau in the product temperature. The model effectively captures the product outlet temperature and the energy consumed. Depending on raw material composition, “soft” or “dry”, the model outlines the heat injection and screw speeds necessary to obtain optimal output quality.

1. Introduction
The procedure of separating efficiently dry-stuff (proteins), fat and water is an important process in the handling of waste products from industrial and commercial consumption meat manufactures. For the particular process presented in this paper, which includes coagulation of protein, melting of fat and separation of components, the total plant raw material (meat waste, intestates and carcasses) intake is about 150,000 ton/year. With an energy consumption of about 700 kWh/ton raw material the total plant is prone to very high potential savings in terms of energy if one or more of the unit processes can be optimized by even a small amount. Also the efficiency in terms of separation into different components is an important parameter. If, for example, the unit process described here can be increased in efficiency by 1 % more separation of fat from the protein it will yield an increase of 300 ton fat pr. year.

With the dual aim of reducing energy consumption and increasing the final separation ratio, the present project seeks to implement a model based control scheme. This article presents the mathematical modeling effort directed towards one of the unit operations in the plant, namely the melting of fat. This process takes place in a thermal screw where raw meat is heated. Heat transfer is analyzed, taking into account phase transition of fat (melting) and water (boiling).

Phase transitions, for example melting, freezing, evaporation and condensation, results in multiphase flow and it can be described as a moving boundary problem. Due to phase transitions,
properties of materials at different phases may vary a lot. Front-tracking method [1] and fixed-domain method [2] are two commonly used approaches for handling moving boundary problems [3]. [4, 5] applies the moving boundary method to evaporation process, taking into account mass change during evaporation. All these methods require inclusion of enthalpy. In our work, we apply phase identifier functions to distinguish the solid and liquid or liquid and gas phases, similar with the study about rock properties during melting [6]. In this way, we avoid enthalpy in our set of equations which is important since we do not have, a priori, an equation of state for the material. Instead, temperatures are the independent unknown variables, since they are important for the control of the thermal screw.

2. Thermal Screw
The heating process, which coagulates protein and melts fat, is done in the thermal screw. Figure 1 is a cross-sectional representation along the central axis of the thermal screw. The screw is fed by a bulk mixture of fat, protein, crushed bone and water. The inlet temperature of the bulk is 10-20°C. The purpose of the thermal screw is to heat the meat bulk by hot water (flowing inside the screw) and super-heated steam (flowing inside the lower part of the chamber) to a temperature between 80 and 95°C. In this process the fat melts and the protein coagulates, facilitating subsequent separation of liquids (fat and some of the water) and solid material (bones, proteins and water).

The thermal screw has length $L$ and diameter $D$. The screw rotates at a frequency $f$ thereby transporting meat through the thermal screw. The thermal screw is in essence a counter flowing heat exchanger where meat enters at one end and hot water and steam enter at the other end, see Figure 1. In the thermal screw under consideration, two screws are set parallel to each other inside the chamber as shown in Figure 2 and 3.

3. Components of the Process Material
In this article, we assume that the meat bulk consists of three components, fat (A), water (B) and dry material (C, bone and protein). Their volume fractions are $\gamma_i, i = A, B, C$. The volume fractions obey the equation $\sum \gamma_i = 1$. We assume thermal equilibrium between the three components in the meat and the thermal conductivity of each component (fat, water and dry stuff) to be a constant. We lump the three components together and use averaged properties based on their volume fraction to describe the meat as one material.

There are two types of phase transitions in the heating process: melting of fat and evaporation of water. In the process we aim at melting all the fat and evaporation of water happens when the temperature of meat bulk reaches the water boiling point. However, to avoid disintegration of the proteins, boiling of the water is to be avoided. In our work, we define a phase identifier function $\phi_i, i = A, B$, which is equal to 0 or 1 if component $i$ is in solid or liquid phase (or liquid or vapour...
phase). In practice, we approximate $\phi_i$ by a smoothed Heaviside step function in the similar way with
\[ \phi_i(T_i) = \frac{1}{\pi} \arctan[\delta(T_i - T_{C,i})] + \frac{1}{2} \]  
(1)
where $T_{C,i}$ is the temperature at which component $i$ changes phase. The value of $\delta$ determines the steepness of the transition. The derivative of $\phi_i$ with respect to $T_i$ is a smoothed delta function
\[ \phi'_i = \frac{\partial \phi_i}{\partial T_i} = \frac{1}{\pi/\delta + \pi\delta(T_i - T_{C,i})} \]  
(2)
The properties of the meat components, for example heat capacity, density, and thermal conductivity, which depend on the phase, can be expressed using the phase identifier function $\phi_i$. This is similar with the way of expressing permeability and viscosity of rock during melting [6, 9, 10]. For heat capacity, the latent heat $dh_i$ should be included, since it has an additional contribution to energy transfer during phase transition. According to the definition of latent heat, the effective heat capacity of component $i$ is
\[ cp_i = cp_{i,0}(1 - \phi_i) + cp_{i,1}\phi_i + dh_i \phi'_i \]  
(3)
where $cp_{i,0}$ and $cp_{i,1}$ represent the heat capacity of component $i$ at phase 0 and phase 1, respectively.

As temperature $T_i$ increases, component $i$ changes from phase 0 to phase 1.

If the density and thermal conductivity also change significantly during the phase transition, they can be expressed in a similar way as equation (3). However, in our work, we assume they are constant during the phase transition except for the density of water.

4. One-Dimensional Model of the Process
We assume that the heating process can be lumped across the radial and azimuthal direction, reducing the problem to one dimension, namely in the axial direction, $z$, as presented in Figure 1. Figure 2 shows a cross-sectional representation of the thermal screw orthogonal to the central axis including notations of geometric parameters. Figure 3 shows the filling of meat inside the thermal screw and notations of temperatures in the system.

Both meat and air are inside the thermal screw. We define the filling factor, $r_V$, as the volume fraction of meat relative to the volume of the chamber. Thus $1 - r_V$ is the volume fraction of air. Similarly $r_A$ is defined to be the cross-sectional area fraction of meat relative to the cross-sectional area of thermal screw. In our 1D model we assume that $r_A$ is constant and due to this $r_A = r_V$. Another filling factor, $r_P$, is defined as the perimeter fraction of meat relative to the perimeter of the upper part of the process chamber. Thus $1 - r_P$ is the perimeter fraction of air.
We assume that the super-heated steam condensates in the separation process without changing the temperature. Furthermore, it is considered that the meat flow fully covers the screws and the lower part of the process chamber. But it may cover only part of the chamber.

The governing equations for the temperature of the components shown in figure 3 are the energy balance equations:

\[
(\epsilon \rho \rho) \frac{\partial T_n}{\partial t} - k_n \frac{\partial^2 T_n}{\partial z^2} + (\epsilon \rho \rho) U_n \frac{\partial T_n}{\partial z} = \sum_{m} q'_{nm}
\]

where \(U_n\) is the velocity of component \(n\), and \(q'_{nm}\) is the heat transfer rate from component \(m\) to component \(n\) due to temperature differences:

\[
q'_{nm} = h_{nm} (T_m - T_n) p_{nm} / A_n
\]

where \(h_{nm}\) is the heat transfer coefficient between components \(n\) and \(m\), \(p_{nm}\) is the contact perimeter between components \(n\) and \(m\), and \(A_n\) is the cross-sectional area of component \(n\). In figure 3, for example the area marked with /// is the cross-sectional area of component 1, i.e. meat, and the length of the red line is the contact perimeter of component 1 and 5, i.e. meat and lower part of the thermal screw chamber. Experiments on deep frying [7] provide us appropriate estimates for heat transfer coefficients between meat and metal.

For hot water and meat bulk, we set their inlet temperatures to be fixed values. We assume the heat flux at the outlet is zero. This is implemented by setting the first order derivatives of the temperatures in space to be zero. For other components, we assume zero heat flux at both inlet and outlet.
5. Results

In this article, cases of soft, mixed and hard meat are studied. The differences between soft, mixed and hard meats differ due to different fractions of fat, water and dry stuff. Hard meat contains more protein, but less fat and water than soft and mixed meat. Generally, soft meat contains about 24% fat, 62% water and 14% protein. Hard meat contains about 13% fat, 49% water and 38% protein [11]. Mixed meat can be viewed as the mixture of soft and hard meat. In our work, we used 60% soft meat and 40% hard meat for the composition of the mixed meat. This corresponds to 19.6% fat, 56.4% water and 24% protein. Parameters regarding the geometry, thermal properties of material and inlet temperatures of heat source are listed in Table 1. All the thermal parameters of meat, for example specific heat of fat and protein, are obtained from [12] by ignoring the temperature-dependent terms.

| Geometric parameters (in units of m) |
|-------------------------------------|
| Length $L$                         | 8.02 |
| Pitch interval $P$                 | 0.34 |
| Height of chamber $D$              | 0.92 |
| Width of chamber $W$               | 0.72 |
| Thickness of chamber $t$           | 0.016|

| Thermal parameters                |
|-----------------------------------|
| **Meat**                          |
| Specific heat of solid fat $c_{p_{A,1}}$ (J/kg/K) | 2800 |
| Specific heat of liquid fat $c_{p_{A,0}}$ (J/kg/K) | 3000 |
| Melting temperature of solid fat $T_{C,A}$ (K)     | 373.15|
| Latent heat of fat $d\eta_{A}$ (J/kg)              | $2.09 \times 10^5$ |
| Specific heat of water $c_{p_B}$ (J/kg/K)          | 4200 |
| Specific heat of protein $c_{p_C}$ (J/kg/K)        | 2000 |
| **Metal**                                      |
| Specific heat of metal $c_{p_4}$, $c_{p_5}$, $c_{p_6}$ (J/kg/K) | 450 |
| Density of metal $\rho_4$, $\rho_5$, $\rho_6$ (kg/m$^3$) | 7874 |
| Thermal conductivity of metal $k_4$, $k_5$, $k_6$ (W/K/m) | 55 |
| Heat transfer coefficient between meat and metal $h_{14}$, $h_{15}$, $h_{16}$ (W/m$^2$/K) | 2000 |
| **Air**                                     |
| Density of fat $\rho_A$ (kg/m$^3$)           | 1000 |
| Specific heat of air $c_{p_7}$ (J/kg/K)        | 1005 |
| Density of water $\rho_B$ (kg/m$^3$)          | 1000 |
| Density of air $\rho_7$, $\rho_8$ (kg/m$^3$)   | 1.2 |
| Thermal conductivity of air $k_7$ (W/K/m)      | 0.025|
| **Steam**                                     |
| Heat transfer coefficient of steam under forced convection $h_{35}$ (W/m$^2$/K) | 100 |
| **Water**                                    |
| Thermal conductivity of water $k_2$ (W/K/m)     | 0.6 |
Temperatures (in units of K)

|                         |                   |                  |
|-------------------------|-------------------|------------------|
| Inlet temperature of meat flow $T_{1,\text{inlet}}$ | 285.15            |                  |
| Temperature of super-heated steam $T_3$               | 406.65            |                  |
| Inlet temperature of water $T_{2,\text{inlet}}$     | 385.15            |                  |

Figure 4 presents the temperature profiles of soft, mixed, and hard material at steady state. The three cases are all based on a screw frequency of 1.03 rpm and a volume fraction of meat of 0.4. The phase transition of fat appears as a plateau in the temperature profiles at 60°C. The large amount of fat in the meat (soft material) leads to large phase transition plateau. This also requires more energy compared to hard and mixed material, so temperature change between the inlet and exit is smaller for soft material.

The cooking time is defined as the time meat stays above 85°C before going out of the thermal screw at steady state. This is one of the key parameters for the heating process. In practice, cooking time cannot be measured and instead the exit temperature of meat flow is used for control. From figure 5 we see the correspondence between cooking time and exit meat temperature. The result is obtained at a meat volume fraction 0.4. The curves are obtained by varying the screw frequency. In figure 5, the three curves all approach to 100°C asymptotically. That is because of the boiling of water. After all water evaporates, temperature goes above 100°C. However, boiling water is not the interest of our work.

**Figure 4.** Steady state temperature along length axis of thermal screw for soft, mixed and hard meat material.

**Figure 5.** Exit meat temperature as function of cooking time, obtained at meat volume fraction 0.4 and various screw frequencies.

In this article, we investigate the steady state energy consumed by per unit mass of meat at a fixed exit meat temperature equal to 91°C for different volume fractions. We calculate the “perfect” screw frequency for different volume fractions, which produces the desired exit meat temperature, 91. This is shown in figure 6. Due to the mechanical limit of the screw frequency which is between 0.65 to 2.35 rpm in the equipment presented in this article, there also exists a limit to the meat volume fraction. The
mass flow rate of meat (figure 7) and energy consumption (figure 8) are obtained based on the screw frequencies in figure 6.

From Figure 7 we see that when the outlet temperature is fixed the rate of mass flow of meat does not change much as a function of volume fraction, but it depends on the type of material (soft/mixed/hard). Figure 8 show that soft meat uses more energy than mixed and hard meat. This is due to the latent heat of fat and the large heat capacity of water.

Since the meat processed in the thermal screw is not homogeneous, it is hard to compare precisely the numerical results and the industrial data. However, the industrial observation tells that when there is more hard meat inside the thermal screw, the “perfect” screw frequency is higher on average than the situation that there is more soft meat. Our numerical results are in agreement with this observation (figure 7).

![Figure 6. Screw frequency as function of meat volume fraction, at fixed exit meat temperature 91°C.](image)

![Figure 7. Mass flow rate of meat as function of meat volume fraction, at fixed exit meat temperature 91°C.](image)

![Figure 8. Energy consumed by per kilo meat as function of mass flow rate of meat, at fixed exit meat temperature 91°C.](image)
6. Conclusion
A model for the heating process of meat in a thermal screw is developed and analysed. The model is formulated as a set of general partial differential equations including the latent heat for the melting of fat and the boiling of water, respectively. The meat is modelled as a mixture of three components: water, fat and dry-stuff (bones and proteins).

Steady state temperature profiles for different kinds of meat (soft, mixed, hard) are shown. The melting of the fat component is captured as a plateau in the meat temperature. Cooking time, as an important factor for control of this process, is analysed and related to the exit meat temperature, which is measurable in reality.

The model effectively captures the product outlet temperature and the energy consumption. Soft meat material consumes more energy to reach the same temperature as hard meat material, because of the latent heat of fat and large heat capacity of water.

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References
[1] Lewis R W and Ravindran K 2000 Finite element simulation of metal casting Int. J. Numer. Meth. Engng. 47 29-59
[2] Yang H T and He Y Q 2010 Solving heat transfer problems with phase change via smoothed effective heat capacity and element free Galerkin methods Int. Commu. Heat Mass Transf. 37 385-392
[3] Lewis R W, Morgan K, Thomas H R and Seetharamu 1996 The Finite Element Method in Heat Transfer Analysis (West Sussex, England: John wiley&Sons)
[4] Willatzen M, Pettit N B O L and Ploug-Sørensen L 1997 A general dynamic simulation model for evaporators and condensers in refrigeration Part 1: moving-boundary formulation of two-phase flows with heat exchange Int. J. Refrig 21(5) 398-403
[5] Veje C T, Madsen S and Willatzen M 2010 Efficient numerical solution of one-dimensional governing equations for evaporating flow in tube 7th International Conference on Multiphase Flow, Tampa, FL May 30-June 4
[6] Barboza S A and Bergantz G W 1997 Melt productivity and rheology: complementary influences on the progress of melting Numer Heat Transf Part A. 31 375-392
[7] Cheevasathianchaiporn W and Tangduangdee C 2009 Heat transfer coefficient of a deep fat fryer As. J. Food Ag-Ind. 2(04) 240-248
[8] Oldenburg C M and Spera F J Hybrid model for solidification and convection 1992 Numer Heat Transf Part B. 21 217-229
[9] Beckermann C and Viskanta R 1988 Double-diffusive convection during dendritic solidification of a binary mixture Physicochem. Hydrodyn 10 195-213
[10] Shaw H R 1972 Viscosities of magmatic liquids: an empirical method of prediction Am. J. Sci. 272 870-893
[11] Composition of raw material 2011 DAKA Factory Report
[12] Kar S, Chen X D, Adhikari B P and Lin S X Q 2009 The impact of various drying kinetics models on the prediction of sample temperature-time and moisture content-time profiles during moisture removal from stratum corneum Chem. Engng. Research and Design 87 739-755