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Heat transfer analysis of cheese cooling incorporating uncertainty in temperature measurement locations: Application to the industrial process

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ABSTRACT

A cylindrical cheese product with an irregular cross sectional geometry is cooled by partial immersion in brine. It is essential to calculate the temperature–time history of the product during this cooling phase to ensure its microbiological safety. The heat transfer analysis is complicated by both the non-standard product geometry and the non-uniform surface heat transfer coefficients that prevail. The flotation behaviour of the cheese at the air/brine interface is analysed to determine the heat transfer areas exposed to each cooling fluid. A finite element model is developed to predict temperature histories at various points in the product and to determine the slowest cooling region in the product. The cooling performance of the cheese is also studied experimentally. Comparison of the theoretical and experimental temperature histories is complicated by uncertainty in the location of the thermocouples in the product. By statistically quantifying the imprecision in thermocouple position, the expected temperatures in each region of interest can be found from the thermal model by Monte Carlo sampling. With the model, the top region of the cheese stick has been shown to determine cooling time because the existence of the non-uniform boundary condition is significant in determining the evolution of temperature.

1. Introduction

A cheese product is manufactured in an extrusion process and exits from the circular die of the extruder in the form of a continuous rope at a temperature of about 40 °C. The rope has an approximately circular cross section. At an adjacent cutting station, it is immediately chopped into individual sections that are known as sticks (in the order of 15 mm diameter and 125 mm long). As no preservatives are added to the ingredient mix, the cheese sticks are a microbiologically sensitive product and must be cooled down prior to vacuum packing. The cooling is necessary to prevent moulds forming in the pack.

Hydraulic transport is used to transfer the sticks from the cutting station to the packaging station. The conveying system consists of an open trough channel which contains a flowing brine (water and salt) solution. The cut sticks are dropped into the brine and carried along to the packing station. The brine is at a temperature of 0 °C and moves with a velocity of 0.5 m/s. The cutting, transport and packaging equipment are all located in a single room that is at a temperature of 18 °C. Hence the sticks are cooled while simultaneously being conveyed. As the cheese density is lower than that of the brine, the sticks float in the liquid. Hence the lower part of the stick is immersed in the brine solution while the upper part is exposed to room air. There will be two quite different temperatures and heat transfer coefficients over the lower (contact with a liquid) and upper (contact with a gas) parts of the cheese product. It is essential to calculate the temperature history of the product during this cooling phase to ensure its microbiological safety; specifically the time required to cool all of the product below some threshold temperature value. Stopping the cooling process too early is microbiologically dangerous and letting it run too long can damage product quality. For most food product cooling applications, the central region of the product interior determines the cooling time; for this application this may not be the case and it is necessary to ascertain which region of the cheese is slowest to cool.

For the analysis of this paper, a number of simplifications to the actual industrial cooling process are made. The surface of the brine is assumed to remain quiescent with no splashing and stick angular orientation is assumed to remain invariant with no rotation to interchange the exposed and immersed surfaces. The variable time that the sticks spend in the brine at the cutting station while they await being marshaled for packaging is ignored. These three effects (splashing, rotation, waiting) enhance the cooling process by increasing the effective heat transfer coefficient and lengthening

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Nomenclature

C	chord length (m)
d	protrusion distance (m)
R	radius (m)
r_T	radial location of centre/bottom thermocouple (m)
r_{TM}	mean radial position of bottom thermocouple (m)
r_{TR}	range in centre thermocouple position (m)
x_T	horizontal location of top thermocouple (m)
x_{TS}	standard Deviation of horizontal position of top thermocouple (m)
y	distance from cross section geometric centre to centroid (m)
y_T	vertical location of top thermocouple (m)
y_{TM}	mean vertical position of top thermocouple (m)
Greek letters	
θ_F	flotation angle (rad)
θ_C	chord angle (rad)
θ_T	angular location of centre/bottom thermocouple (rad)
θ_{TR}	range in angular position of centre thermocouple (rad)
θ_{TS}	standard Deviation in angular position of bottom thermocouple (rad)
ρ	density (kg/m^3)

the cooling time. However they are difficult to quantify and the manufacturer was unable to supply accurate data concerning them. It was decided to examine the most conservative case with respect to cooling and err on the side of microbiological caution, by ignoring them. So in reality, the sticks should cool more rapidly than predicted here though the analysis of this paper will provide the limiting analysis for acceptable cheese cooling.

Previous work into the investigation of heat transfer in cheese processing includes the work of Luna and Bressan (1985) who examined the thermal behaviour of cheese during immersion in brine. Temperature evolution was shown to be controlled by the thermal diffusivity of the product. Zhong et al. (2004) developed a thermal model of a regular shaped, rectangular slab of cheese using the Fourier field equation in three spatial Cartesian coordinates which permitted analytical solutions to be obtained. Concerning the modelling of cheese processing incorporating uncertainty, Baudrit et al. (2009) proposed a methodology to simulate heat and mass transfer for cheese ripening that takes into account imprecision or incompleteness in the required model input data set. In a related paper to this one, the thermal properties of the product and the separate heat transfer coefficients of the product in air and brine were measured, (Cronin et al., 2010). An analytical heat transfer model was built and its accuracy assessed by comparing theoretical predictions of temperature to experimentally measured temperatures. It was demonstrated that for a soft and very deformable material, such as this cheese product, a precise and known positioning of thermocouples is not possible and this phenomenon must be included in any model validation studies. Hence when comparing theoretical predictions of temperature to experimental values, a probabilistic approach is required, (Cronin and Caro-Corrales, 2008). Where the product was treated as having a regular cylindrical geometry and a uniform boundary condition, a theoretical probabilistic analysis could be employed. This had the advantage of providing a definite benchmark for validation; it also demonstrated that because the cheese is soft, thermocouple location imprecision is important and significantly affects the results. For this work, the analytical approach is not possible and the Monte Carlo method (that was validated in the first paper) is used to generate temperature histories where spatial location of measurement position in a zone is the random variable. The statistics of these realizations are then used to check for agreement between theory and experiment.

2. Theory

2.1. Product geometry and buoyancy model

For the work described in the previous paper, (Cronin et al., 2010), the cheese was treated as having the cross section of a full circle and for immersion in a single fluid, the error associated with this approximation was shown to be negligible. However in the case of partial immersion, to accurately determine the fractional surface areas exposed to air and brine respectively, the correct geometry must be used. The cross section of the stick can be defined by a radius, R (or diameter, D) and chord of length, C and is shown in Fig. 1. The chord angle, θ_C (angle subtended by two radial lines through each extremity of the chord) can be calculated from

$$\theta_C = 2\sin^{-1}\left(\frac{C}{2R}\right) \quad (1)$$

The surface area and volume of the stick can be calculated accordingly. To analyse the flotation behaviour of the stick, the location of the centroid of the cross section must be known. The centroid will lie below the centre of the describing circle by an amount, y where

$$y = R\frac{-2/3\sin^3\frac{\theta_C}{2}}{[\pi - \frac{1}{2}(\theta_C - \sin\theta_C)]} \quad (2)$$

The centre of gravity of the cheese product lies at the centroid of the cross section and the centre of buoyancy lies at the centroid of the submerged portion of the cross section. The orientation of the cheese stick is in equilibrium when the centre of mass and centre of buoyancy are aligned in the vertical position, (Massey and Ward-Smith, 2006). The product has two equilibrium positions; the first when the chord is horizontal and forms part of the top surface of the product and the second position is a 180° inversion of this. The first position is least favourable from a cooling perspective and temperature analysis and experiments were conducted with this orientation. Fig. 1 also illustrates the flotation geometry. The degree of immersion of the stick in the liquid can be quantified by calculating the flotation angle, θ_F. This can be defined as the angle subtended by two radial lines that pass through the intersec-

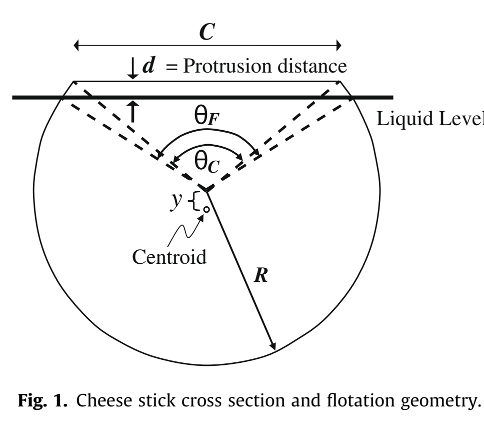

Fig. 1. Cheese stick cross section and flotation geometry.