PH.D. THESIS

Numerical analysis of conjugate heat and mass transfer phenomena in food freezing using hydrofluidisation impingement method

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Abstract

Nowadays, freezing and chilling are the most common methods for achieving the long shelf life of food products. It is also the first element of the whole food cold chain. However, according to the latest data, while 46% of global food production should be refrigerated, less than half of that number is subjected to this process. It results in enormous food waste, which is estimated to account for approximately 13% of global production. Novel food freezing methods should be developed to be energy efficient, economically attractive, and to guarantee a high quality of frozen food products. A method that guarantees such conditions is hydrofluidisation (HF), which was proposed for the rapid chilling and freezing of small food products. It is based on freezing in a liquid medium that is additionally agitated by the flow through a group of orifices located at the bottom of the HF tank. As a result, very high heat transfer coefficients (HTC) of over 2 000 $W{\cdot}m^{-2}{\cdot}K^{-1}$ can be reached. Moreover, food products behave as a fluidised bed which allows them to freeze individually and achieve a uniform freezing process for all the products in the whole group.

This work focuses on different aspects of the numerical investigation of the HF process. First, the jet flow over the food sample having a spherical shape was modelled. In this stage, the fluid flow model was formulated with the appropriate turbulence modelling approach, which is K-ω SST model. Several aspects of the numerical domain formulation were also examined. The numerical model of the fluid flow was validated by comparing the velocity fields obtained numerically with the experimental measurements of the velocity fields. The accuracy of the fluid velocity field prediction was approximately 11.5%, which is very satisfactory considering very high velocity gradients in the region that was analysed. In further steps, the geometrical domain of the HF tank included a full array of orifices and several food products, in a static configuration and with realistic movement. The static configuration allowed for the examination of several geometric parameters such as the ratio of the position of food products above the orifice and the orifice diameter (H/d) or the effect of the spacing between the orifices (S) or between food samples (z) on HTC. The parameters H/d and S were shown to significantly affect HTC, but the freezing time is no longer reduced when HTC is higher than 2 500 $W{\cdot}m^{-2}{\cdot}K^{-1}$. In the second scenario, the realistic HF process was investigated for a group of spherical samples having a diameter of 20 mm using the macroscopic particle model (MPM) approach for Lagrangian modelling of individual particle movement. In this case, different refrigerating medium mass flow rates were tested in the range of 0.1 $kg{\cdot}s^{-1}$ to 2.0 $kg{\cdot}s^{-1}$. Furthermore, three different water-based

solutions were compared, i.e., the aqueous solution of ethanol (mass concentration 30%), the aqueous solution of glycerol (40%) and the aqueous solution of ethanol and glucose mixture (15%/25%). In the case of the solution of ethanol, the behaviour of food products in the HF tank was dependent on the flow rate, because of the lower density of this solution compared to the density of the food product (potato). For other fluids that are denser than the food, the samples formed a static bed at the top of the tank. For such conditions, HTC was in the range of 1 000 $W \cdot m^{-2} \cdot K^{-1}$ up to 4 000 $W \cdot m^{-2} \cdot K^{-1}$ for a very high fluid mass flow rate of 2.0 $kg \cdot s^{-1}$.

The second aspect that was investigated in this study is the phenomenon of heat and mass transfer within the food product during the freezing process. First, the heat transfer model based on the apparent heat capacity approach was developed to characterise the temperature distribution within the food product during the freezing process. The developed model was validated using the temperature measurements of the potato sample. The agreement with the measurements was very high. The model was used to determine the freezing time for different conditions. In the water-ethanol solution with a temperature of -15°C, the freezing time of the 20 mm potato sphere was 6 min. For smaller products, it was even lower, e.g., 1.5 min for a 10 mm sample. The freezing times were compared with the immersion freezing (IF) method, which is similar, but the fluid flow is not forced. The comparison proved that the freezing process can be significantly faster when HF is used instead of IF. The freezing time was reduced by approximately 40% for spherical food samples having a diameter of 30 mm and by up to 60% for smaller foods having a diameter of 10 mm. In a further step of the investigation, the food product model was complemented by the mass transfer analysis. It allowed quantifying the unwanted side effect of HF, which is the absorption of the solution components by the food product. The model was based on several assumptions and compared with data from the literature for similar conditions to confirm its reliability. It turned out that depending on HTC and the size of the food product (5-30 mm), the uptake of the solution components is in the range of 15-26 $g \cdot kg^{-1}$ of food for the ethanol solution (30%) and 20-35 $g \cdot kg^{-1}$ of food for the glycerol solution (40%). Using the solution of ethanol and sugar mixture (15%/25%) allowed to preserve the ethanol concentration in the food product in the range of 9-15 $g \cdot kg^{-1}$ and the glucose concentration in the range of 16-24 $g \cdot kg^{-1}$ for the same cases. Furthermore, the results confirmed that the reduction in the temperature of the refrigerating medium from -10°C to -20°C allows one to reduce the mass absorption by approximately 40%. It is worth noting that HF allowed for a significant reduction of the mass uptake with respect to the IF method.