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Experimental analysis and modeling of ultrasound assisted freezing of potato spheres

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ABSTRACT

In recent years, innovative methods such as ultrasound assisted freezing have been developed in order to improve the freezing process. During freezing of foods, accurate prediction of the temperature distribution, phase ratios, and process time is very important. In the present study, ultrasound assisted immersion freezing process (in 1:1 ethylene glycol–water solution at 253.15 K) of potato spheres (0.02 m diameter) was evaluated using experimental, numerical and analytical approaches. Ultrasound (25 kHz, 890 W m^{-2}) was irradiated for different duty cycles (DCs = 0–100%). A finite volume based enthalpy method was used in the numerical model, based on which temperature and liquid fraction profiles were simulated by a program developed using OpenFOAM® CFD software. An analytical technique was also employed to calculate freezing times. The results showed that ultrasound irradiation could decrease the characteristic freezing time of potatoes. Since ultrasound irradiation increased the heat transfer coefficient but simultaneously generated heat at the surface of the samples, an optimum DC was needed for the shortest freezing time which occurred in the range of 30–70% DC. DCs higher than 70% increased the freezing time. DCs lower than 30% did not provide significant effects on the freezing time compared to the control sample. The numerical model predicted the characteristic freezing time in accordance with the experimental results. In addition, analytical calculation of characteristic freezing time exhibited qualitative agreement with the experimental results. As the numerical simulations provided profiles of temperature and water fraction within potatoes frozen with or without ultrasound, the models can be used to study and control different operation situations, and to improve the understanding of the freezing process.

1. Introduction

Like drying [1–4], refrigeration [5–10] is one of the most preferred methods for the preservation of food and biological materials. However, refrigeration process is energy consuming and costly, and the cost is increased significantly by increasing the cooling capacity of the equipment. Especially for freezing, the quality of the product is directly related to the freezing rate. Therefore, the improvement of freezing process and investigation through experimental and numerical analysis has been a center of research for a long time.

In recent years, innovative methods have been developed in order to improve heat transfer during freezing and increase the process efficiency [11–22]. Ultrasound irradiation (frequency of 16–100 kHz) has been newly addressed as a novel method to boost the rate of heat transfer in convective heat transfer [23–30], phase change heat transfer [31–33] and heat exchangers [34–36]. Ultrasound irradiation can also improve the crystallization process [37–40]. It has been shown that, the heat transfer process can be considerably improved at the presence of an acoustic field due to physical effects (i.e. streaming and cavitation) induced by the propagation of ultrasonic waves in the liquid. Freezing and cooling are among the processes assisted by the aid of ultrasound [29,37,41–45]. These studies have been performed in an experimental scale and further investigations are still needed to understand the process, which can be completed by numerical simulation of the process.

During freezing of foods, accurate prediction of temperature distribution, enthalpy changes, phase ratios, process time and total energy requirement is very important [46]. The thermo-physical properties of foods including specific heat, thermal conductivity, and density experience abrupt changes during freezing [47–51]. Therefore, a highly non-linear mathematical problem which is very challenging to model is established. Although good analytical tools

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Nomenclature

A	surface area (m^2)
c_p	specific heat ($J\ kg^{-1}\ K^{-1}$)
c_{pf}	specific heat of frozen product ($J\ kg^{-1}\ K^{-1}$)
c_{pice}	ice specific heat capacity ($J\ kg^{-1}\ K^{-1}$)
c_{pu}	specific heat of unfrozen product ($J\ kg^{-1}\ K^{-1}$)
c_{pw}	water specific heat capacity ($J\ kg^{-1}\ K^{-1}$)
c_{pvol}	volumetric specific heat ($J\ m^{-3}\ K^{-1}$)
h	convective heat transfer coefficient ($W\ m^{-2}\ k^{-1}$)
H	enthalpy ($J\ kg^{-1}$)
k	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
k_{ash}	thermal conductivity of ash ($W\ m^{-1}\ K^{-1}$)
k_{carb}	thermal conductivity of carbohydrate ($W\ m^{-1}\ K^{-1}$)
k_f	thermal conductivity of frozen product ($W\ m^{-1}\ K^{-1}$)
k_{fat}	thermal conductivity of fat ($W\ m^{-1}\ K^{-1}$)
k_{pr}	thermal conductivity of protein ($W\ m^{-1}\ K^{-1}$)
L	latent heat of freezing of water ($J\ kg^{-1}$)
L_p	product latent heat of freezing ($J\ kg^{-1}$)
R	radius (m)
S_p	source term caused by phase change ($J\ m^{-3}\ s^{-1}$)
S_{US}	source term caused by ultrasound irradiation ($J\ m^{-3}\ s^{-1}$)
Q_{US}	heat generation rate caused by ultrasound irradiation ($W\ kg^{-1}$)
T	temperature (K)
T_∞	cooling medium temperature (K)
T_c	final desired temperature (K)
t_f	freezing time (s)

T_f	potato freezing point (K)
T_{f0}	initial freezing temperature of potato (K)
T_{fm}	potato freezing temperature (K)
T_{fw}	freezing temperature of water (K)
T_i	initial product temperature (K)
V	volume (m^3)
x_{ash}	ash mass fraction
x_{carb}	carbohydrate mass fraction
x_{pr}	protein mass fraction
x_{fat}	fat mass fraction
x_{ice}	ice mass fraction
x_w	water mass fraction
x_{wb}	bound water mass fraction
x_{wtot}	total water mass fraction
ΔH	Enthalpy change ($J\ kg^{-1}$)
δH	enthalpy change caused by phase change ($J\ kg^{-1}$)
ΔT	temperature change (K)
ρ	density ($kg\ m^{-3}$)
ρ_0	density of unfrozen potato ($kg\ m^{-3}$)
ρ_{ash}	density of ash ($kg\ m^{-3}$)
ρ_{carb}	density of carbohydrate ($kg\ m^{-3}$)
ρ_{fat}	density of fat ($kg\ m^{-3}$)
ρ_{ice}	density of ice ($kg\ m^{-3}$)
ρ_{pr}	density of protein ($kg\ m^{-3}$)
ρ_w	density of water ($kg\ m^{-3}$)
ε_V	relative expansion of ice

exist for the prediction of freezing time, only numerical methods can give an accurate solution to the parameters involved in phase change problems [52]. The main difficulty in the numerical solution to heat equation during phase change is in dealing with the release of latent heat occurring over a very small temperature range [53]. A range of approaches have been proposed for the numerical solution of phase change problem or the so called "Stefan problem". These methods include the apparent specific heat method where the sensible heat is combined with the latent heat to produce a specific heat curve with a large peak around the freezing point, the source method, in which the latent heat is treated as a separate heat source, and the total enthalpy method [52–55].

Another challenging parameter when dealing with the prediction and modelling of heat transfer during freezing is the convective heat transfer coefficient (*h*) estimation. Accurate prediction of this coefficient is difficult while it affects the process strongly. A lot of research has been performed for the estimation of *h*, which has led to the introduction of experimental equations for different situations [28,41,20]. However, these equations can have errors up to 20% [28,41]. Copper sphere has been used widely for evaluating the convective heat transfer studies [28,56]. A lumped system is likely to happen when using copper in the experiments. However, when food is used, both internal resistance (1/thermal conductivity) and external resistance (1/convective heat transfer coefficient) play an important role during the process of heat transfer. This will make the system more complicated, thus estimation of the values of convective heat transfer coefficient (*h*) will be difficult. For evaluation of the effect of ultrasound irradiation on the convective heat transfer, it was desired to eliminate or diminish the effect of thermal conductivity. This could be achieved by choosing copper spheres for the experiments, which has a high thermal conductivity and allows the application of lumped system analysis, leading to more accurate results on convective heat transfer. Then the estimated h values can be used for heat transfer modelling of food in a similar situation.

Plant tissues such as potatoes are water-rich materials and possess a semi-rigid structure and therefore are prone to freezing damages [57–60]. Freezing damages affect the quality and freshness and should be minimized by different means including rate of freezing increase. Ultrasound assisted freezing has been addressed as a tool to reduce freezing time and thus can be used to improve the quality of potatoes [29,36].

However, to the best of our knowledge, the modelling of ultrasound assisted freezing process of food products has not been studied yet, therefore the aim of this research is to experimentally evaluate the ultrasound assisted freezing process of potato spheres and to compare the results with the analytical and numerical solution of the heat transfer phenomenon within samples.

2. Theory

2.1. Freezing time calculation method and modeling theory

2.1.1. Analytical freezing time calculation

A range of analytical methods have been introduced for the prediction of freezing time, most of them are based on the well-known Plank's equation. Pham [61] derived a simple equation for freezing time estimation with some modifications to the Plank's equation, in which sensible heat is also considered. Furthermore, Pham [61] suggested the use of an experimental correlation to calculate the mean freezing point, to account for freezing that occurs over a range of temperatures. The equation proposed by Pham [61] for the calculation of freezing time was used in this study.

2.1.2. Numerical model using the latent heat source term

One of the widely used approaches for the numerical solution of phase change problems is the latent heat source term method [62]. In this method, a non-linear source term in the governing equation is developed. The water fraction can be updated numerically or analytically based on the temperature of the numerical cell [62].