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Study of the dynamic characteristics of the food freezing process using a cryogenic immersion freezing tank

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Abstract

In this work, an immersion freezing system was proposed to shorten the total freezing time and improve the quality of frozen food. The thermal performance of the refrigerant liquid prepared for using in the immersion freezing system was evaluated. A three-dimensional model (3D) was developed to investigate the dynamic characteristics of food freezing process. The effects of the refrigerant liquid inlet flow rate, inlet temperature, total freezing time and freezing rate of chicken breast, velocity and temperature distribution in the immersion freezing system were investigated. In addition, the freezing rates of food using traditional air-blast freezing and the proposed immersion freezing were evaluated. The results showed that the freezing rate of food in immersion freezing was approximately 12.85 times higher than that of the traditional air-blast freezing. When the flow rate increased from 0.11 $kg \cdot s^{-1}$ to 0.63 $kg \cdot s^{-1}$, the total freezing time shortened by 36.9%. When the temperature decreased from -25 °C to -40 °C, the total freezing time shortened by 35.5%. However, the temperature of the refrigerant liquid should not be too low, which will lead to high viscosity of the liquid, thus resulting in increasing in the overall power consumption of the proposed system.

Keywords: immersion freezing; refrigerant liquid; freezing rate; numerical simulation; experiment.

Practical Application: A novel refrigerant liquid for use in an immersion freezing system was prepared. The freezing rates for air –blast freezing and immersion freezing were compared. Possibility to shorten the total freezing time of food of IF system was explored. An experimental immersion freezing system was designed and built. Effects of inlet flow rate and temperature on the freezing process were clarified.

1 Introduction

Freezing is a highly effective method for extending the shelf-life of foods, especially those that are perishable, such as fish and meat (Alizadeh et al., 2007; Li & Chen, 2016; Chauhan et al., 2019). However, traditional freezing methods, such as traditional air-blast freezing (AF) and indirect contact freezing, have long freezing times that lead to the formation of large and irregular ice crystals in the cells of food, high energy consumption, and compromised quality of the frozen products (Delgado et al., 2009; Zhu et al., 2004). In general, the heat transfer coefficient in liquid medium is up to 20 times higher than that in air (Lucas & Raoult-Wack, 1998). Immersion freezing (IF) is one of the rapid freezing methods, and provides an excellent way to address the challenges mentioned above. In this method, the food is placed in the refrigerant liquid, and both the food and refrigerant liquid directly exchange heat, thus achieving a rapid freezing of the food (Liang et al., 2015). The ice crystals formed by rapid freezing are large in number, small in size and evenly distributed in the cells, which can minimize the damage to the cellular structure and improve the quality of frozen foods (Cheng et al., 2017; Xu et al., 2019). Therefore, IF technology has attracted great interest in recent years and its application in food-freezing has shown a substantial promise.

Freezing rate is recognized as a critical factor controlling the quality of frozen products. Qian et al. (2018) investigated the effect of IF on the quality characteristics of big-head carp and compared the results with those of AF. The results showed that the freezing rate of fillets treated with IF was approximately 4.5 times higher than that of AF treated samples. Moreover, IF had higher retention (60%) of texture and better integrity of the muscle's microstructure. Hou et al. (2020) compared the effects of AF and IF on the changes in quality of pork. The study found that smaller-sized and more uniform distribution of ice crystals was observed in IF group due to higher freezing rate. Besides, IF played a better role in improving the water-holding capacity and slowing down the oxidation of lipids. Yang et al. (2020) compared AF with IF by freezing pufferfish fillets, and found that IF could retard the deterioration of physical properties of frozen fish in a better way than AF. Some new freezing techniques, such as ultrasound-assisted freezing and electric field-assisted freezing have been introduced in the food industry to increase the freezing rate and alter the crystal and nucleation rates during the freezing of foods. Zhang et al. (2019) investigated the effects of ultrasound-assisted immersion freezing and immersion freezing on the structure and gel properties of myofibrillar protein of chicken breast. They reported that ultrasound-assisted immersion freezing improved the rate of freezing of samples, and an appropriate ultrasonic power could reduce the changes in protein's structure and improve

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the gel properties of myofibrillar protein. Wiktor et al. (2015) investigated the effect of pulsed electric field on the kinetics of IF. The results showed that the pulsed electric field reduced the total freezing time by 3.5-17.2%, and the apples treated using 10 pulses at 3 kV/cm were characterized by lower mass loss compared to IF treated apples.

However, most of the investigations have focused on the effect of freezing rate on the quality of food. Several studies have reported the effects of different operating parameters, such as refrigerant liquid inlet flow rate and inlet temperature. A good selection of freezing conditions, such as the refrigerant liquid inlet flow rate and inlet temperature are very important in optimizing the efficiency of freezing equipment and process and simultaneously retain the nutritional and structural quality of food. Moraga et al. (2012) developed a 2-dimensional (2D) numerical model to predict total freezing time for the freezing of three different ground meat cylinders. The study found that the diameter of cylinder affected total freezing time of foods. According to some previous studies, the 2D model may have some limitations for IF problem when compared to 3D analysis, whereas the 3D case can be considered as a higher fidelity simulation. However, only a handful of studies have focused on a 3D analysis of the dynamic characteristics of IF system. In addition, the viscosity of the refrigerant liquid increases at low temperatures, thus affecting the pump power required for circulating the refrigerant. Therefore, the present investigation was undertaken.

In this article, a multiple refrigerant liquid with low freezing point and low viscosity is studied, and its thermo-physical properties are investigated. ANSYS FLUENT is used to develop a 3D model for the freezing process of IF system. The proposed model is verified using experiments. The freezing rates of AF and IF are evaluated. Moreover, in IF system, the effect of refrigerant liquid inlet flow rate and temperature on the velocity distribution, temperature distribution, freezing time and freezing rate of chicken breasts are numerically investigated. The results provide guidelines for the design and optimization of IF system.

2 Materials and methods

2.1 Materials

In this work, a novel quaternary refrigerant liquid (RL-1) is developed for IF system. The thermal performance of the proposed quaternary refrigerant is investigated. The freezing point of RL-1 was found to be -49.48 °C using the cooling curve method.

2.2 Methods

The freezing point of material was found using step cooling curve analysis method. The temperature change with time in the solidification process of the experimental sample was plotted as the temperature change curve with time, find out the steep sections (cooling curve) and flat sections (crystallization curve) on the step cooling curve, both in the projection point on the vertical axis of the intersection point is the freezing temperature of the sample.

The specific heat capacity of refrigerant liquid (RL-1) was measured using a differential scanning calorimeter (DSC). Before the DSC measurement, the temperature and sensitivity calibration of the system was required. When the measurement was carried out, the baseline heat flow curve of the empty crucible was acquired. Then, the sapphire and sample were tested. After subtracting the baseline curve, two DSC signals were obtained. By analyzing the DSC signals, the specific heat capacity of the refrigerant liquid was calculated. In addition, a digital rotary viscometer was used to measure the viscosity of refrigerant liquid (RL-1). We used Hot Disk Thermal Constants Analyser to measure the thermal conductivity, which adopting transient plane source method. In addition, Density Balance Precisa/XB220A was used for the density measurement of refrigerant liquid (RL-1).

2.3 Thermal performance of a novel refrigerant liquid

The thermal performance of a novel refrigerant liquid were obtained by the above methods, as shown in Table 1. Table 1 lists the thermo-physical properties of RL-1 at different temperatures.

3 Physical and mathematical models

3.1 Physical model

Experiments were carried out in an IF tank with quaternary refrigerant liquid (RL-1). Twelve vacuum-packed chicken breasts were fully immersed and frozen in the freezing tank. Each food had the dimensions of 350 mm (length) × 150 mm (width) × 60 mm (height), and the food was coated with 0.025 mm-thick polyethylene (PE) material. The inlet and outlet (with the radius of 12.5 mm) were located at the side of the tank, and their distances from the upper and lower surfaces were 50 mm each.

The refrigeration system controlled the refrigerant liquid temperature and the inlet fluid flow into the freezing tank. The refrigerant liquid exchanged heat with the chicken breasts, and was discharged out of the tank. During the freezing process, the temperature of the chicken breasts gradually dropped. When the temperature at the center of the chicken breast reached -18 °C, the freezing process was considered to have completed (Zhang et al., 2020a, b).

Table 1. Thermophysical properties of RL-1 at different temperatures.

Parameter	Temperature		
	-25 °C	-35 °C	-40 °C
Freezing point		-49.48	
Viscosity (mPa.s)	35.5	75.56	90.62
Thermal conductivity (W m^{-1} k^{-1})	0.35	0.33	0.30
Specific heat capacity (kJ kg^{-1} k^{-1})	2.698	2.595	2.528
Density (kg m^{-3})	1046	1073	1084
Specific Heat Capacity (J g-1 K-1)	2698	2595	2528

3.2 Mathematical model

In this study, a 3D model was established to simulate the freezing process of the chicken breast in the freezing tank. The heat transfer was calculated using the energy conservation. Furthermore, turbulent flow was described using the standard k-ε model. The governing equations of the proposed model are based on the following assumptions.

(1) In the initial stage, the temperature distributions of the refrigerant liquid and the chicken breast in the freezing tank were uniform.

(2) The heat loss from the freezing tank was negligible.

(3) The flow rate of the refrigerant liquid was stable, incompressible, and fully developed.

(4) The chicken breast had no obvious volume change during the freezing process.

(5) Heat was transferred through the conduction process within the chicken breast.

3.3 Governing equations

This section describes the mass, momentum and energy equations used in the proposed model.

1) Mass conservation equation

The mass conservation equation is also known as the continuity equation, and is given by (Equation 1).

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho_l \vec{v}_i\right) = 0 \tag{1}$$

where $\vec{v}$ is the velocity, ρ_l is the density of the liquid, and t is the time. For an incompressible fluid, (Equation 1) can be rewritten as (Equation 2).

$$\nabla \cdot \vec{v} = 0 \tag{2}$$

where $\vec{v}$ consists of the components of $\vec{v}_i$.

2) Momentum conservation equation (Equation 3)

$$\frac{\partial \rho v}{\partial t} + \nabla \cdot (\rho \vec{v}\vec{v}) = -\nabla P + \nabla \cdot [\mu(\nabla \vec{v}\vec{v})] + \frac{\left(\rho_f - \rho_l\right)}{\rho_l} g + \vec{F} \tag{3}$$

where P is the pressure, μ is the dynamic viscosity, ρ_f is the density of chicken breast, g is the gravity acceleration vector, and $\vec{F}$ is the term representing the momentum force, which is considering equal to zero.

3) Energy conservation equation (Equation 4)

$$\rho_l c_p \frac{\partial \vec{v}_i}{\partial t} + \vec{v} \cdot \nabla T = \nabla(\lambda \nabla T) + q_r \tag{4}$$

where C_p is the specific heat, T is the temperature, λ is the thermal conductivity, and q_r is the source, which is set to zero.

4) Turbulence equations. The turbulence energy equation and the turbulent dissipation rate equation can be expressed as follows, respectively (Equations 5-6):

$$\frac{\partial(\rho_l k)}{\partial t} + \nabla(\rho_l \vec{v} k) = \nabla\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\nabla k\right] + G_k + G_b - \rho_l \varepsilon \tag{5}$$

$$\frac{\partial(\rho_l \varepsilon)}{\partial t} + \nabla(\rho_l \vec{v} \varepsilon) = \nabla\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\nabla \varepsilon\right] + \frac{\varepsilon}{\lambda}(C_{1\varepsilon} G_k - C_{2\varepsilon} \rho \varepsilon) \tag{6}$$

where k is turbulence kinetic energy, ε is turbulent fluctuation energy dissipation rate, G_k represents the generation of turbulence kinetic energy due to the mean velocity gradients and G_b is the generation of turbulence kinetic energy due to buoyancy. $C_{\varepsilon 1}$ and $C_{\varepsilon 2}$ are constants. σ_k and σ_ε are the turbulent Prandtl number for k and ε, respectively. ($C_{\varepsilon 1} = 1.44$, $C_{\varepsilon 2} = 1.92$, $\sigma_k = 1$, $\sigma_\varepsilon = 1.2$)

3.4 Boundary and initial conditions

In order to solve the governing equations, initial and boundary conditions must be considered. The walls of the freezing tank were considered to be adiabatic. The surface of the vacuum-packed chicken breast was set as a coupling surface. The refrigerant liquid inlet was defined as the velocity-inlet, whose flow rate and temperature were set. The outlet was defined as the pressure-outlet. In addition, the initial temperature of the refrigerant liquid in the tank was consistent with the inlet temperature. The temperature of the chicken breast was set to be 20 °C. Through grid independence verification, it can be obtained that the mesh size of 890782 cells was accurate enough.

In order to evaluate the influence of refrigerant liquid inlet flow rate and temperature on the freezing process of chicken breast, several cases were simulated. Five different inlet flow rates of 0.11 $kg \cdot s^{-1}$, 0.21 $kg \cdot s^{-1}$, 0.32 $kg \cdot s^{-1}$, 0.47 $kg \cdot s^{-1}$ and 0.63 $kg \cdot s^{-1}$ were simulated at the initial temperature of -35 °C. Furthermore, the inlet temperature was varied with values of -25 °C, -35 °C and -40 °C for the inlet flow rate of the refrigerant of 0.32 $kg \cdot s^{-1}$.

4 Experiments

An immersion system was established to verify theoretical analyses. Figure 1 shows the schematic of the experimental setup. The experimental setup consisted of a refrigeration cycle system, a measurement system, a freezing tank and a controller.

The measurement system consisted of the thermocouples and a Keithley 2700 data acquisition setup. The temperature variations at the geometric center of food were monitored using the thermocouples connected to a data acquisition system. During the freezing process, a refrigerant liquid at a certain flow rate entered the tank, exchanged heat with the chicken breasts, and then, flowed out of the tank. When the center of the food reached -18 °C, the freezing process was considered to have completed. The target temperature was set by the controller. The refrigerant liquid flow rate was measured using an ultrasonic

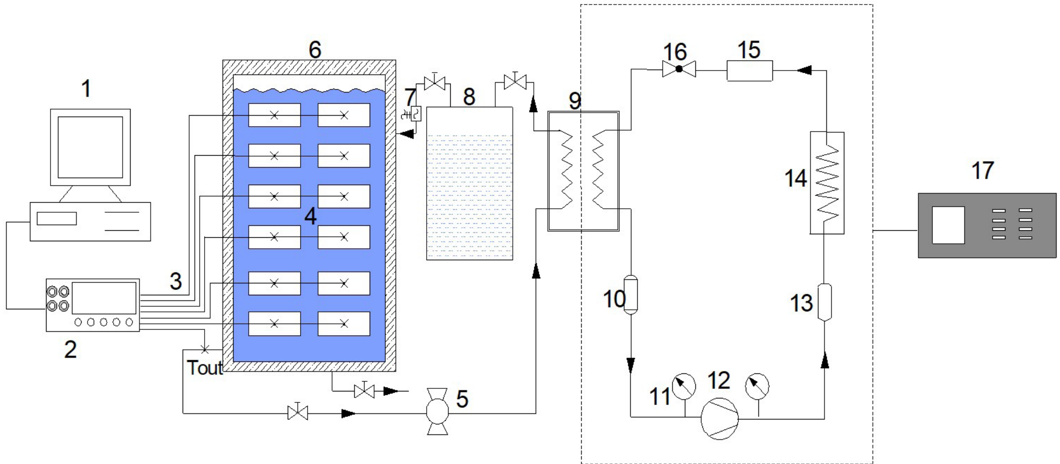

Figure 1. Schematic of the experimental setup. 1. Computer; 2. Data acquisition system; 3. Thermocouple extension wire; 4. Samples; 5. Circulation pump; 6. Freezing tank; 7. Ultrasonic flow-meter; 8. Refrigerant liquid storage tank; 9. Evaporator; 10. Gas-liquid separator; 11. Pressure gauge; 12. Compressor; 13. Oil separator; 14. Condenser; 15. Dry filter; 16. Evaporator; 17. Control panel.

flow meter. Multiple tests showed that the deviation in the results was marginal, and well within the range of measurement error of various devices.

5 Results and discussion

5.1 Comparison of the traditional air-blast freezing, and immersion freezing

The temperature variation curves in the center of the chicken breast under different freezing treatments (traditional air-blast freezing and immersion freezing). Initially, the fluid temperature for the two processes was maintained at -35 °C.

It can be seen that different treatments had different effects on the total freezing times. The total freezing time was defined as the time required for the temperatures of the center of chicken breasts to reach -18 °C. The total freezing times for IF and AF were 113 min and 1323 min, respectively. The results also show that the freezing rate of food in IF was approximately 12.85 times higher than that of AF method. In addition, the time for food to pass the maximum ice crystal formation zone was found in the ascending order of: AF (709 min) > IF (45 min). The time required to pass through the zone is an important indicator of the quality of the frozen food (Li et al., 2018). In theory, the time for food to pass the zone of maximum crystallization of ice was shorter, the formed ice crystals were smaller and distributed more evenly, which led to great improvements in food quality (Liu et al., 2015; Zhang et al., 2018). Therefore, applying IF method can shorten the total freezing time of food, and improve the quality of frozen food.

5.2 Effect of refrigerant liquid inlet flow rate on the velocity distribution in the freezing tank

Figure 2 shows the velocity streamlines of refrigerant liquid in the freezing tank with different flow rates on the X-Z plane. The blue streamline represents the refrigerant liquid.

The refrigerant liquid inlet temperature was set to be -35 °C, whereas the flow rates were 0.11 $kg{\cdot}s^{-1}$, 0.21 $kg{\cdot}s^{-1}$, 0.32 $kg{\cdot}s^{-1}$, and 0.47 $kg{\cdot}s^{-1}$. Figure 2 shows that the greater the flow rate of the refrigerant liquid, the denser the streamline between the chicken breast and the wall surface was, and the greater the extent of contact between the streamline and the food was. These results implied that freezing effect on the food will get better. On the other hand, the liquid flow rate could not be too high, which could results in dead zones where the heat transfer would be very inefficient.

5.3 Effect of refrigerant liquid inlet flow rate on the freezing process

Figure 3 and Figures 4B-4C show the effects of refrigerant liquid flow rates on the freezing process, while the refrigerant liquid inlet temperature was -35 °C. Figure 3 shows the temperature distribution of X-Z (Y = 225 mm) plane at the freezing times of 1000 s, 3500 s and 6000 s. At a certain time, greater the refrigerant liquid flow rate, more uniform was the distribution of the refrigerant liquid temperature fields in the freezing tank, faster was the temperature drop for the food, and shorter was the total freezing time.

The temperature variation curves for the center of the chicken breasts under different flow rates (0.11, 0.21, 0.32, 0.47, and 0.63 $kg{\cdot}s^{-1}$) are shown in Figure 4B. When the temperature reached the value of -2.8 °C, the food entered the phase change stage, and the temperature began to drop slowly because of the transition of water into ice. It can be seen that the phase change time was the longest for the refrigerant liquid flow rate of 0.11 $kg{\cdot}s^{-1}$. From Figure 4B, it can also be seen that different flow rates had different effects on the total freezing time. When the refrigerant liquid flow rates were 0.11 $kg{\cdot}s^{-1}$, 0.21 $kg{\cdot}s^{-1}$, 0.32 $kg{\cdot}s^{-1}$, 0.47 $kg{\cdot}s^{-1}$, and 0.63 $kg{\cdot}s^{-1}$, the corresponding total freezing times were 9774 s, 7542 s, 6748 s, 6347 s, and 6172 s, respectively. Compared to the refrigerant liquid flow rate of 0.11 $kg{\cdot}s^{-1}$, the total freezing times for the flow rates of 0.21 $kg{\cdot}s^{-1}$, 0.32 $kg{\cdot}s^{-1}$, 0.47 $kg{\cdot}s^{-1}$, and 0.63 $kg{\cdot}s^{-1}$ were shortened by approximately 22.8%, 30.9%, 35.1%, and 36.9%, respectively. It was found that increasing the refrigerant liquid flow rate can

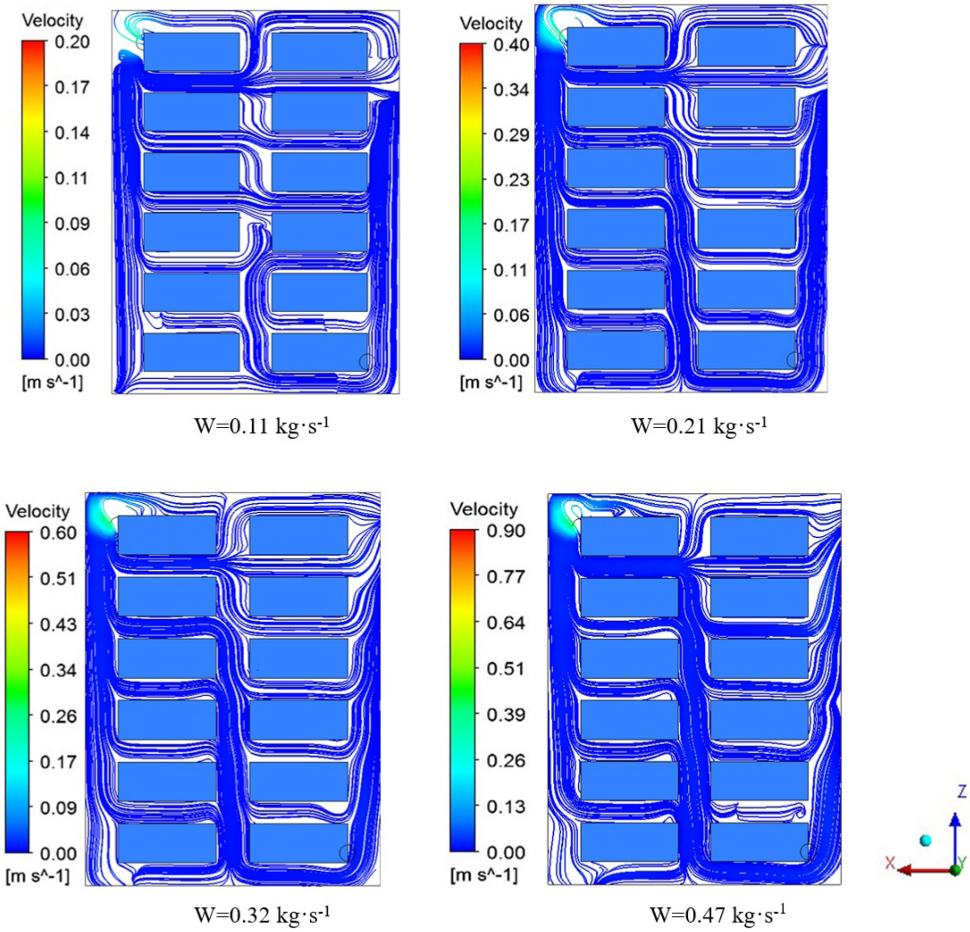

Figure 2. Velocity streamline distributions (X-Z plane, Y = 225 mm).

shorten the total freezing time of the food. However, excessive liquid flow rate has little influence on the total freezing time, and would increase the flow resistance, leading to unnecessary energy waste.

Figure 4C shows the temperature variations of T_1, T_2, T_3 and T_{out} at different refrigerant liquid inlet flow rates. Furthermore, the values of T_1, T_2, and T_3 were 2.35 m, 0.47 m, and 0.17 m far from the center of the tank. Additionally, T_{out} was located at the refrigerant liquid outlet. During the initial period, the temperatures of T_1, T_2, T_3 and T_{out} gradually increased, and the refrigerant liquid with a greater flow rate was the first one to reach the peak value. It indicates that the heat transfer between the refrigerant liquid and the food was the fastest. As time went by, the temperatures of T_1, T_2, T_3 and T_{out} gradually decreased. The decrease was slow for the flow rates of 0.32 kg·s^{-1} and 0.63 kg·s^{-1} until the freezing process was completed. It can be found that, greater the refrigerant liquid inlet flow rate, smaller was the liquid temperature fluctuation in the tank.

5.4 Effect of inlet flow rate on the freezing rate of food

Freezing rate is the most important factor affecting the quality of frozen food. The food at different positions in the freezing tank have different freezing rates. Figure 4D shows the effect of different flow rates of refrigerant liquid at -35 °C on the freezing rates. When the flow rates of the refrigerant liquid were 0.11 kg·s^{-1}, 0.21 kg·s^{-1}, 0.32 kg·s^{-1}, 0.47 kg·s^{-1}, and 0.63 kg·s^{-1}, the slowest freezing rates of food were 2.15 cm·h^{-1}, 2.94 cm·h^{-1}, 3.33 cm·h^{-1}, 3.61 cm·h^{-1}, and 3.75 cm·h^{-1}, respectively. For flow rates of 0.21 kg·s^{-1}, 0.32 kg·s^{-1}, 0.47 kg·s^{-1}, and 0.63 kg·s^{-1}, the freezing rates of food improved by around 1.37, 1.54, 1.67 and 1.74 times, respectively than that for the case of refrigerant liquid flow rate of 0.11 kg·s^{-1}. Therefore, the freezing rate of food can be effectively improved by increasing the refrigerant liquid flow rate and strengthening the heat transfer.

Meanwhile, Figure 4D shows that the difference between the fastest and slowest freezing rates narrowed with the increase in the refrigerant liquid flow rate. This indicates that, by increasing the refrigerant liquid flow rate, the freezing effect of food was enhanced.

5.5 Effect of refrigerant liquid inlet temperature on the velocity distribution in the freezing tank

The quality of frozen food is closed associated with crystallization size and location, which strongly depends on freezing time or freezing rate. Therefore, consciously shortening the freezing time

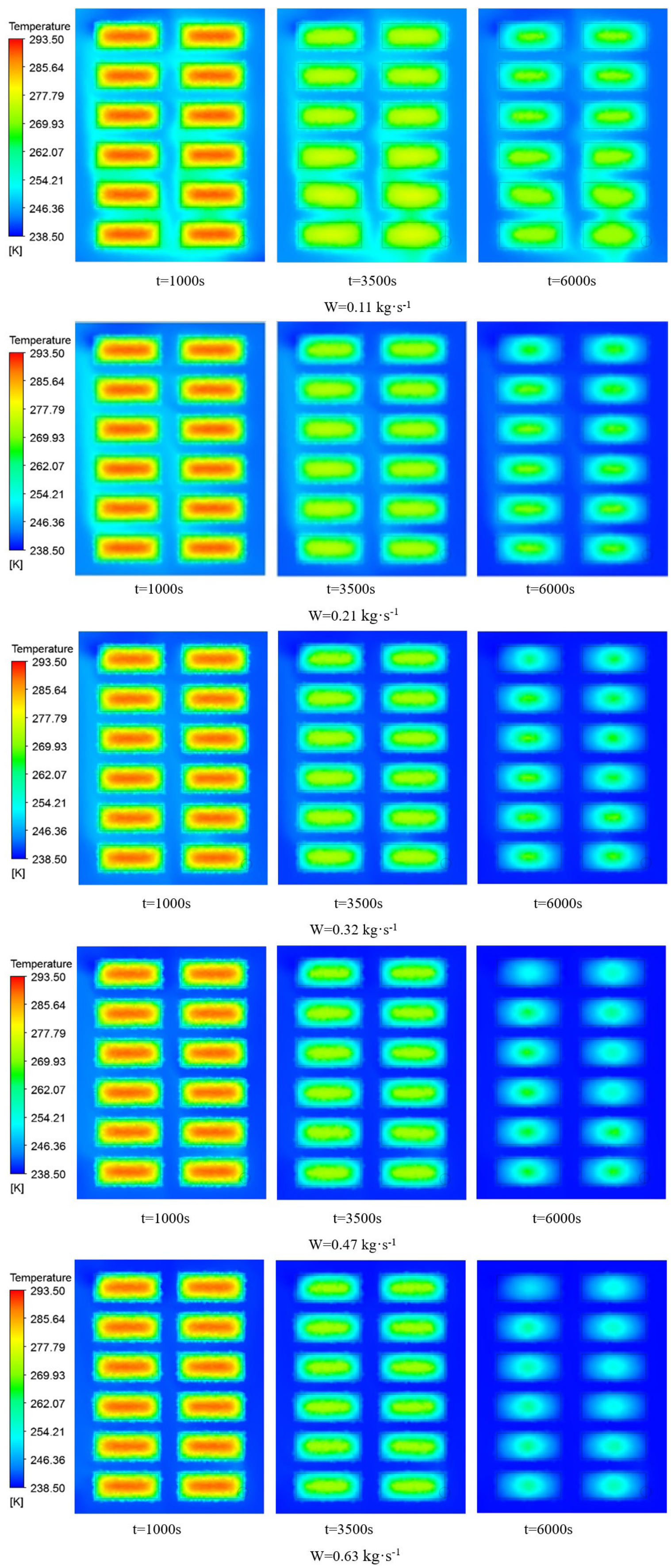

Figure 3. Temperature profiles of the freezing tank at different liquid inlet flow rates.

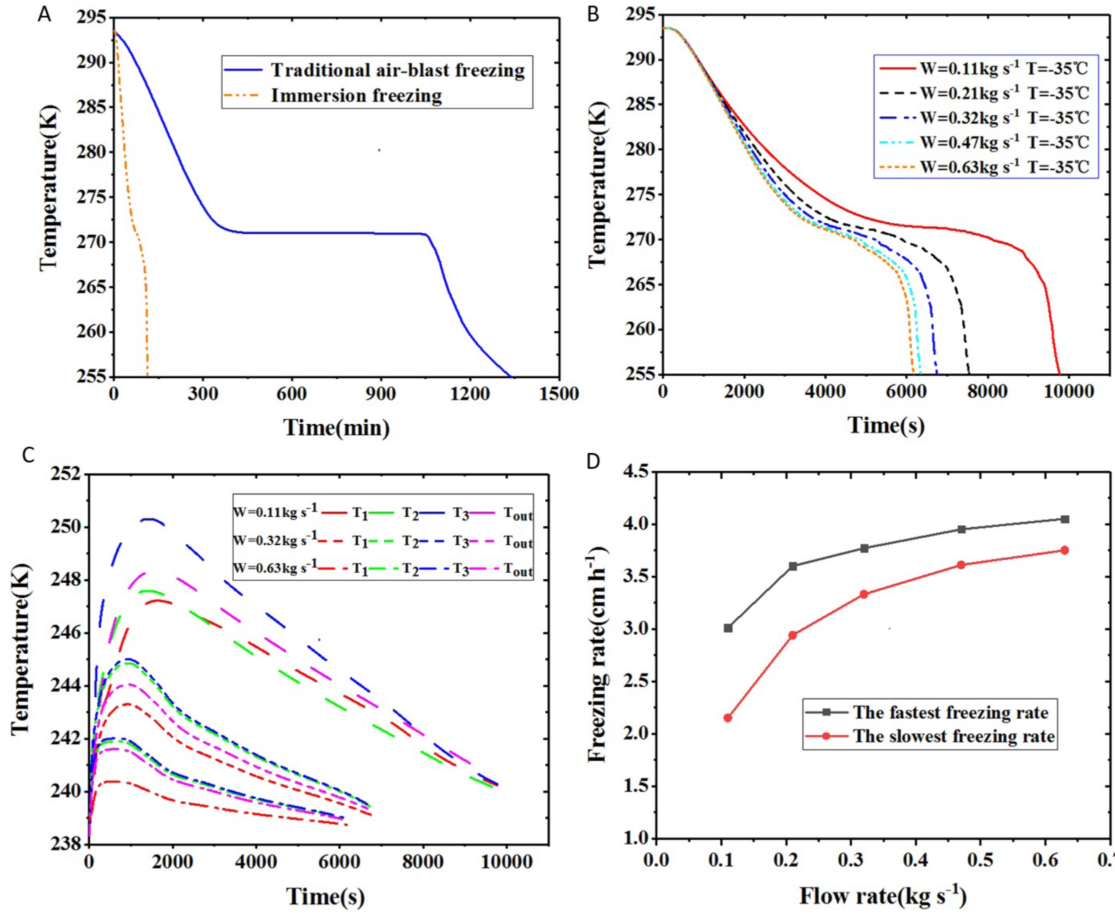

Figure 4. Variations in temperature of food at different freezing treatments (A), variation in the temperature of food at different liquid flow rates (B), temperature variations of the refrigerant liquid at different liquid flow rates (C), freezing rate of food at different liquid flow rates (D).

and improving the freezing rate is beneficial for reducing the size of ice crystals and improving the quality of frozen products (Xu et al., 2019). Figure 5 shows the velocity streamlines of the refrigerant liquid in the tank at different inlet temperatures. The refrigerant liquid inlet flow rate was 0.32 $kg{\cdot}s^{-1}$ whereas the refrigerant inlet temperatures were consecutively varied through values of -25 °C, -35 °C, and -40 °C.

From Figure 5, it can be seen that, lower the refrigerant liquid inlet temperature, denser was the streamline between the chicken breast and the wall surface, and greater was the extent of contact between the streamline and the food, implying that the freezing effect on the food will become better. However, the temperature of the refrigerant liquid should not be too low, which will lead to high viscosity of the liquid. Pumping of more viscous liquids consumes more power, thus reducing the overall efficiency of the process.

5.6 Effects of the refrigerant liquid inlet temperatures on total freezing time

Figure 6A shows the effect of inlet temperature on the total freezing time for a flow rate of 0.32 $kg{\cdot}s^{-1}$. A freezing temperature plateau occurred at -2.8 °C. Furthermore, higher the inlet temperature, longer was the phase change time. It took approximately 3700 s to complete the phase change stage for the inlet temperature of -25 °C. When the inlet temperature of the refrigerant liquid was changed to values of -25 °C, -35 °C, and -40 °C, the total freezing times were found to be 9408 s, 6748 s, and 6071 s, respectively. Compared to the refrigerant liquid inlet temperature of -25 °C, the total freezing times for inlet temperatures of -35 °C and -40 °C decreased by 28.3% and 35.5%, respectively, whereas the freezing rates of the chicken breast increased by 1.53 and 1.82 times, respectively. This indicates that the inlet temperature of the refrigerant liquid has a great influence on the total freezing time and the freezing rate of the food.

5.7 Comparison between the experimental and numerical results

Figure 6B shows the experimental and numerical temperature curves of the chicken breast during the freezing process when the refrigerant liquid inlet flow rate and temperature were 0.32 $kg{\cdot}s^{-1}$ and -35 °C, respectively. The numerical results show the same variation trend as the experimental data. However, due to the unsteady inlet flow rate and the heat loss from the freezing

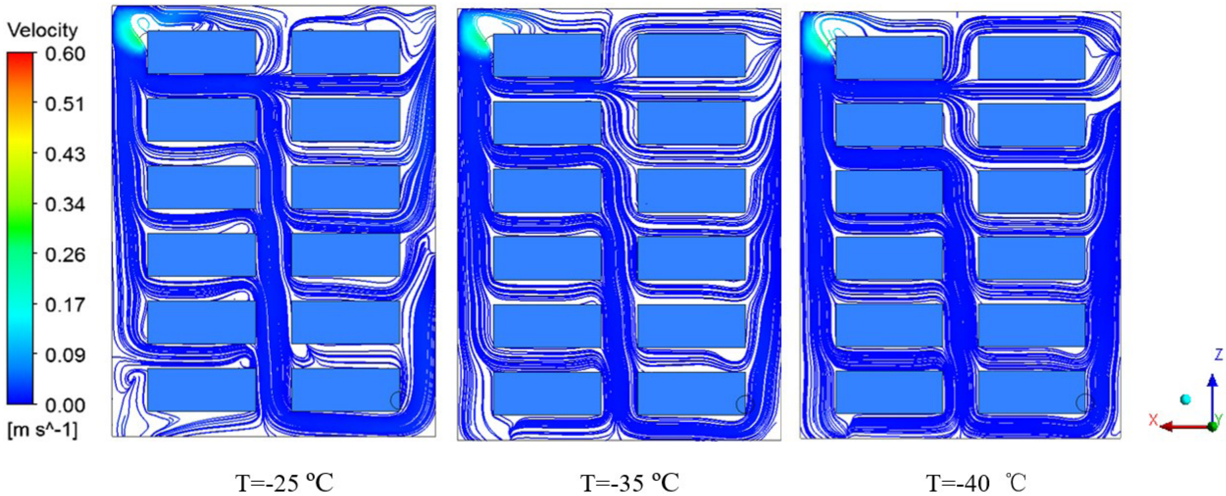

Figure 5. Velocity streamlines in the freezing tank at different liquid temperatures.

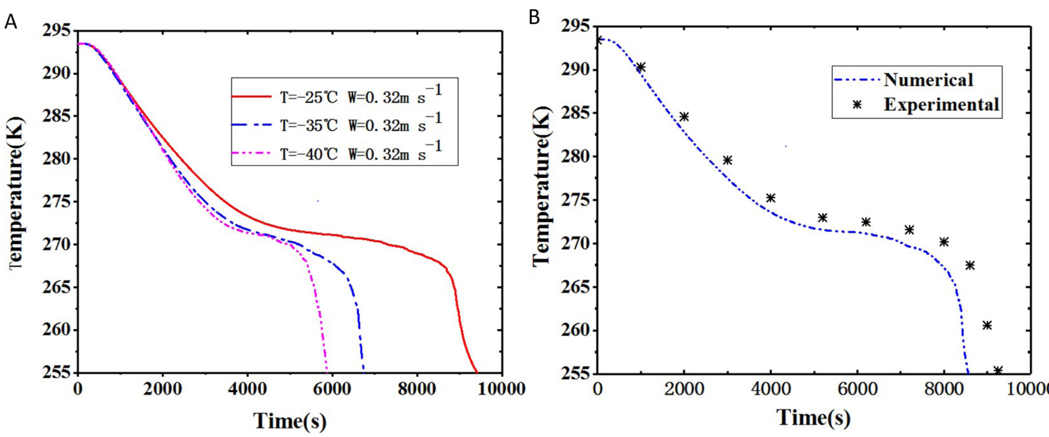

Figure 6. Variations in the temperature of food at different liquid temperature (A), temperature curves of food during the freezing process (B).

tank's walls, there were some deviations in the experimental data. The total freezing times for the experiments and simulations were 6748 s and 7368 s, respectively, and deviated from each other by around 8%. However, the comparison between the numerical and experimental freezing curves shows a relatively good agreement and confirms the validity of the numerical model.

6 Conclusions

In this work, a novel quaternary refrigerant liquid was proposed for use in immersion freezing system. Dynamic simulations and experimental investigations of the freezing process were used to study the heat transfer performance of the immersion freezing system. The effect of the refrigerant liquid inlet flow rate, and inlet temperature on the performance of the system during freezing were investigated. Based upon the results, following conclusions are drawn.

(1) A novel quaternary refrigerant liquid RL-1 for immersion freezing system is prepared, which the freezing point was -49.48 °C and had a low viscosity. Thus, it is suitable for immersion freezing system purposes.

(2) A comparison of the freezing process for air-blast freezing and immersion freezing was performed. The simulation shows that the freezing rate of food in immersion freezing was approximately 12.85 times higher than that for the traditional air–blast freezing food. Immersion freezing is proved to be a greatly superior freezing method in terms of shortening the total freezing time and improving the quality of the frozen food.

(3) The simulation results show that a faster flow rate of the refrigerant liquid reduced the total freezing time. For the flow rates of 0.21 $kg{\cdot}s^{-1}$, 0.32 $kg{\cdot}s^{-1}$, 0.47 $kg{\cdot}s^{-1}$ and 0.63 $kg{\cdot}s^{-1}$, the time required to complete the freezing process were about 22.8%, 30.9%, 35.1%, and 36.9% shorter compared to the flow rate of 0.11 $kg{\cdot}s^{-1}$. However, a too high flow rate will increase the flow resistance and lead to unnecessary energy consumption during the freezing process. Therefore, the flow rate must be controlled within a certain range.

(4) A lower refrigerant liquid inlet temperature tends to produce a shorter total freezing time. Compared with the inlet temperature of -25 °C, the inlet temperatures of -35 °C and -40 °C shortened the freezing times by 28.3% and 35.5%, respectively. However, the temperature of the refrigerant liquid should not be too low, which will lead to high viscosity of refrigerant liquid, and increase the energy consumed by the pump.

(5) The simulation results show the same variation trend as the experimental data and the corresponding deviation is found to be within 8%. The deviations arose from unsteady inlet flow rate and the heat losses from the freezing tank's walls that have a certain influence on the freezing process during the experiments.

Abbreviations

AF: traditional air-blast freezing. IF: immersion freezing. DSC: differential scanning calorimeter. T: temperature (°C). c_P: constant-pressure specific heat (kJ kg^{-1} k^{-1}). t: time (s). v: velocity (m s^{-1}). W: flow rate (kg s^{-1}). P: pressure (N m^{-2}). G_b: generation of tubbulence kinetic energy. G_k: generation of tubbulence kinetic energy. F: momentum force. q_r: source term. g: gravity acceleration vector (m s^{-2}). k: turbulence kinetic energy. ρ: density (kg m^{-3}). μ: dynamic viscosity coefficient (N m^{-2} s^{-1}). λ: thermal conductivity (W m^{-1}k^{-1}). ε: turbulent fluctuation energy dissipation rate. $c_{\varepsilon 1}$: constant. $c_{\varepsilon 2}$: constant. σ_k: constant. σ_ε: constant. f: food. l: liquid.

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