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Research Note

On the Applicability of a Plug Flow Immersion Freezer: Theoretical Considerations

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The most promising means of fast-freezing is the immersion of the product in a liquid of appropriately low temperature. The direct contact of a product with low temperature freezing mediums can, however, cause several problems, the most usual being the burning of its surface or even its rupture, due to the thermal shock it undergoes. It is possible to overcome these problems with the application of a plug flow immersion freezer. The aim of this paper is to investigate the applicability of a plug flow immersion freezer on a theoretical basis. For this purpose, a theoretical model was developed and tested for the freezing of squid. The results of this model indicate that the use of the proposed freezer is quite attractive for products of small thicknesses, up to 1 cm. A rather high value of the heat transfer coefficient can be achieved, while it is possible to set the temperature range of the freezing medium between − 10 and − 30 °C, significantly higher than the ones found in most commercial freezers.

Keywords: freezer; immersion freezing; plug flow; model system

Introduction

Several freezing mediums have been applied in the past for the immersion freezing of foodstuffs. These include NaCl (1) and $CaCl_2$ (2–4) brines, liquid dichlorodifluoromethane (5–7), aqueous solutions of propylene glycol (8,9), ethanol (10) and a solution of ethanol with water and sodium chloride (11). They find use in continuous or batch freezers which operate at a constant temperature. In these freezers, the flow of the freezing medium can be safely regarded as completely stirred. In practice it has been demonstrated that they can be used successfully for freezing a variety of foodstuffs with low cost and little maintenance. The only disadvantage they present is the fact that the use of low enough operating temperatures, lower than − 25 to − 30 °C, can cause burning of the product's surface or even its rupture due to the thermal shock it undergoes. In this case, an increase in the processing cost of the product is experienced and this can become restrictive for products of high-end value. In practice, it is possible to overcome this drawback by precooling the product to a temperature a little lower than its freezing temperature in a separate freezer, operating either with cold air or a liquid freezing medium (12). Such a solution is not very satisfactory, however, because it is accompanied by an increased fixed cost and, most important of all, by an excessive complexity of operation.

A promising solution to the above mentioned problem would be the application of a plug flow immersion freezer, where the freezing medium flows countercurrently to the product. In this way it is possible to accomplish relatively high heat transfer rates, simultaneously avoiding the application of large temperature differences between the product and the freezing medium and, therefore, the thermal stress the former is subjected to. Thus, the objective of a plug flow immersion freezer is the highest possible thermal performance, meaning the highest possible value of the heat transfer coefficient with the minimum thermal stress to the product.

A survey of the literature showed that, until today, a plug flow immersion freezer has not been applied at an industrial level or even proposed as a potential alternative for the freezing of foodstuffs. The aim of this paper is to examine the advantages and/or the restrictions that the usage of this kind of freezer presents. For this purpose, a theoretical design model was developed, based on a model proposed by Lovatt *et al.* (13) for the prediction of the product heat load during freezing. The developed model allows the complete determination of all the design variables of the freezer using a minimum of necessary information.

Theoretical Development of the Model

A plug flow freezer can be considered as a countercurrent heat exchanger. The total heat balance for a plug flow freezer, taking into account only the heat removal from

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the product and the heat loss through the freezer wallls, can be expressed by the equation:

$$Q_\alpha = W_\alpha C_\alpha \Delta T_\alpha - (Q_p + Q_w) \qquad \text{Eqn [1]}$$

where Q_α is the freezing heat load (Jh^{-1}); W_α is the freezing medium mass flow rate (kgh^{-1}); C_α is the heat capacity of the freezing medium ($Jkg^{-1}K^{-1}$); T_α is the freezing medium temperature (K); Q_p is the product heat load (Jh^{-1}) and Q_w is the heat loss to the environment (Jh^{-1}).

The distribution of Q_w along the freezer can be estimated without significant loss in accuracy by the following equation (14):

$$\Delta Q_w = \frac{Q_w}{N_{Points}} = \frac{U_w A_w \dfrac{(T_{air} - T_{\alpha 1}) - (T_{air} - T_{\alpha 2})}{\ln \dfrac{T_{air} - T_{\alpha 1}}{T_{air} - T_{\alpha 2}}}}{N_{Points}} \qquad \text{Eqn [2]}$$

where N_{Points} is the number of points taken along the freezer; U_w is the total heat transfer coefficient due to heat losses ($W_m^{-2}K^{-1}$); A_w is the total external surface of the freezer (m^2); T_{air} is the environmental temperature (K).

The amount of heat removed from the product between two successive positions inside the freezer and the corresponding amount of heat for the whole freezer can be computed from equations [3] and [7], respectively:

$$\Delta Q_p = \int_{(i-1)t_{fr}/N_{Points}}^{i \cdot t_{fr}/N_{Points}} Q_{p,i-1}\, dt \qquad \text{Eqn [3]}$$

$$Q_{p,total} = W_{fr} H (T_{p2} - T_{p1}) \qquad \text{Eqn [4]}$$

where T_p is the product mass average temperature.

In equation [4], W_{fr} represents the freezer capacity (kgh^{-1}), which can be estimated (15) by equation [5]. In the latter, m_{fr} stands for the mass of product (kg) that can be accommodated by the conveyor belt of the freezer and is a function of both the product and freezer geometry.

$$W_{fr} = \frac{3600 m_{fr}}{t_{fr}} \qquad \text{Eqn [5]}$$

The distribution of the product heat load along the freezer can be computed using the model proposed by Lovatt *et al.* (13). Details of this model, which was proved accurate within ± 10% against experimental data, can be found in the relative reference. Here, only a brief description of its basic equations will be attempted. In this model, in accordance with most other empirical relationships used in freezing time prediction, the freezing procedure is divided into three stages, discrete only for computational reasons, chilling, freezing and subcooling. The equation for the calculation of the product heat load during the chilling stage is the following:

$$Q_{Chill} = V_p C_u \frac{dT_p}{dt} = \frac{E}{3} \frac{V_p \beta_1 k_u}{R^2} (T_\alpha - T_p) \qquad \text{Eqn [6]}$$

where Q_{Chill} is the product heat load during the chilling stage; V_p is the product volumetric flow based on its unfrozen density (m^3h^{-1}); C_u is the unfrozen product volumetric heat capacity ($Jm^{-1}K^{-1}$); E is Equivalent Heat Transfer Dimensionality (EHTD); β_1 is the first root of the equation $\beta_1 = 1 - N_{Bi}$, where N_{Bi} is the Biot number; k_u is the unfrozen product thermal conductivity ($Wm^{-1}K^{-1}$); R is the product characteristic length (m).

Equation (6) is also used during the subcooling stage. The only difference in this case is that the thermal properties of the frozen product are used. For the freezing stage, the following equation is valid:

$$Q_{freeze} = N \left(\frac{x_f}{R}\right)^{N-1} \frac{V_p R}{x_f} \frac{T_\alpha - T_p}{x_f^n \left[\dfrac{1}{hR^n} - \dfrac{x_f^{n-1} - R^{1-n}}{k_s(1-n)}\right]} \qquad \text{Eqn [7]}$$

where Q_{freeze} is the product heat load during the freezing stage (Jh^{-1}); N is the heat release geometry factor; X_f is the distance of freezing front from thermal centre (m); k_s is the frozen product thermal conductivity ($Wm^{-1}K^{-1}$).

In order to solve the system of the above mentioned equations, knowledge of the overall heat transfer coefficient, the distribution of the freezing medium temperature and the average mass temperature of the product are necessary. The heat transfer coefficient can be estimated from the well known Nu-Re correlations for unobstructed flow in closed ducts. Undoubtedly, such an approach is not particularly accurate (16), but it can be used as a first approximation. The distribution of the freezing medium temperature can be calculated by the following equation, which is a differential expression of the total heat balance between two successive points along the freezer:

$$T_{\alpha,i} = T_{\alpha,i-1} + \frac{\Delta Q_p + \Delta Q_w}{W_\alpha C_\alpha} \qquad \text{Eqn [8]}$$

The average mass temperature of the product can be estimated from its enthalpy function with the use of a numerical method, such as the Newton–Raphson method. The enthalpy function follows Schwartzberg's model and has two branches, which are given by the following equations:

$$H = a + bT_p + \frac{c}{T_p} \quad T \le T_f \qquad \text{Eqn [9]}$$

$$H = H_f + C_u(T_p - T_f) \quad T > T_f \qquad \text{Eqn [10]}$$

where H is the product volumetric enlthalpy (Jm^{-3}); T_f is the product freezing temperature (K); H_f is the product volumetric enthalpy at T_f, Jm^{-3}.

Model Implementation

A plug flow immersion freezer differs from the freezers already in use by the fact that the temperature of the freezing medium varies along the freezer. This results in direct dependence of the heat transfer coefficient from the total heat amount that must be removed by the freezing medium. From the Nu-Re correlation, it can be easily deduced that the heat transfer coefficient is proportional to the mass flow of the freezing W_α, which in turn is a function of the total heat load. This can be seen in the following equation derived for specified W_α and ΔT_α, which is a combination of equations [2] and [4]:

$$W_\alpha = \frac{W_{fr}(H(T_{p2}) - H(T_{p1})) + Q_w}{C_\alpha \Delta T_\alpha} \quad \text{Eqn [11]}$$

Defining the geometry of the freezer, its capacity (and consequently the freezing time), and the entrance and exit temperatures of both the product and the freezing medium, the mass flow of the freezing medium is fixed and can be calculated by equation [11]. Using its value in the Nu-Re correlations, it is possible to calculate a value of the heat transfer coefficient. If the latter is substituted to the equation for the prediction of the product heat load, the value of the exit temperature T_{p2} that is computed is not necessarily the same as the corresponding value used earlier in the equation. In this sense, the value of h that is calculated in this way is not correct because it does not simultaneously satisfy the total heat balance. Given the discussion above, the following algorithm was used for the design of a plug flow immersion freezer:

a) The geometry of the freezer, its capacity and the entrance and exit temperatures of the product and the freezing medium are defined;
b) Using equations [5], [4] and [2], the freezing time, the total product heat load and the heat loss from the freezer walls are calculated respectively;
c) The mass flow of the freezing medium is computed by equation [11] and its value is used for the estimation of the heat transfer coefficient. The latter is utilized in equations [6] and [7] for the calculation of the product heat load. In this way, the distribution of the product and freezing medium temperature along the freezer are obtained;
d) The calculations are repeated for various values of ΔT_α until the computed value of T_{p2} is equal to the one specified initially.

Results and Discussion

The proposed model will be used for the design of a plug flow immersion freezer for the freezing of squid. The freezing medium being considered in this paper is an aqueous solution 600 g/kg in ethanol. It must be emphasized, however, that the selection of the freezing medium does not affect the accuracy of the model. The data input to the model as well as the geometric characteristics of the product are given below:

L_{fr} : 5–15 m T_{p1} : 20 °C
B_{fr} : 1 m T_{p2}: − 20 °C
W_{fr} : 1 tn/h $T_{\alpha 1}$: − 30 °C, − 40 °C
L_p : 16–19.6 cm w_p: 7–9 cm
R : 0.3–0.5 cm m_p : 0.2 kg

where L_{fr} is the length of freezer (m); B_{fr} is the width freezer (m); L_p is the product length (m); w_p is the product width (m); m_p is the product weight (kg).

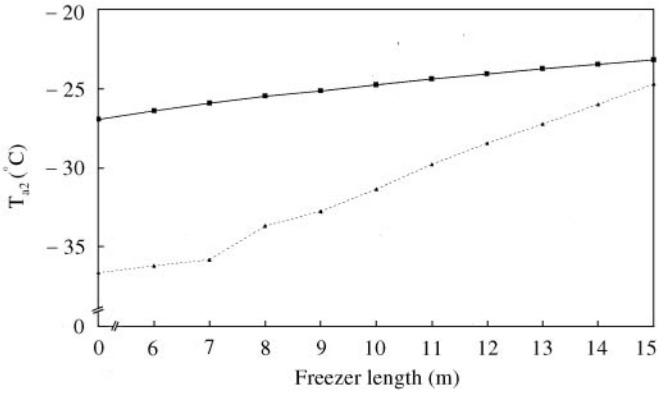

Fig. 1 Variation of freezing medium exit temperature T_{a1} with the freezer's length; -■-, $T_{a1} = -30$°C; - - -▲- - -, $T_{a1} = -40$°C

Figure 1 illustrates the dependence of the freezing medium outlet temperature T_{a2} from the length of the freezer for two different inlet temperatures, − 30 °C and − 40 °C. These results as well as the ones that will be presented are accurate to within 5% based on the total heat balance for the product. **Figure 1** shows that for $T_{a1} = -40$ °C greater temperature differences are achieved for the freezing medium. The outlet temperature T_{a2} is greater in all cases for an entrance temperature of − 30 °C and it hardly reaches − 23°C. Also, the outlet temperature of the freez medium increases with the freezer length. From these results it seems that the main advantage of a plug flow immersion freezer, that is the mild thermal treating of the product, is not valid, at least for the case examined here. The achievement of outlet temperatures near − 20 °C, however, is a clear improvement on the air and stirred flow immersion freezers, where the operating temperature ranges typically between − 30 and − 40 °C (4, 10, 17). It should be noticed that the Nu-Re correlations used for the computation of h are valid only for totally unobstructed flow of fluids in closed ducts. In this sense, for fixed inlet–outlet temperatures and mass flow of the fluid, their outcome is the lowest possible value of the heat transfer coefficient. The flow inside the freezer will be far from totally unobstructed since the movement of the conveyor belt is sufficient for the creation of significant turbulence. In practice, the value of the heat transfer coefficient can be increased with the employment of heat transfer enhancement devices. This can be accomplished relatively easily, the results with increased values of h by 50 and 100% respectively, are given in **Table 1.** These values were calculated utilizing the values of the freezing medium mass flow used with the Nu-Re correlations. For comparison, the results obtained using the Nu-Re correlations are also given.

From **Table 1** it can be seen that the increase of the heat transfer coefficient is accompanied by a similar increase in the freezing medium outlet temperature T_{a2}. The latter is accompanied by a reduction of the freezing time of the product, however, which is inversely proportional to the heat transfer coefficient. The reduction in freezing time is smaller in magnitude than the corresponding increase in the heat transfer coefficient. This fact reveals the lower

Table 1 Results for increased heat transfer coefficient; t_{fr} is the freezing time(s); h is the heat transfer coefficient (w/m^2 °C)

	Nu-Re Correlations			50% increase of h			100% increase of h		
L_{fr} (m)	$T_{\alpha 2}$ (°C)	h (W/m^2 °C)	t_{fr} (s)	$T_{\alpha 2}$ (°C)	h (W/m^2 °C)	t_{fr} (s)	$T_{\alpha 2}$ (°C)	h(W/m^2 °C)	t_{fr} (s)
5	− 26.93	138.9	241.9	− 25.77	208.4	172.4	− 24.78	277.8	137.8
6	− 26.38	113.1	292.3	− 25.02	169.6	208.4	− 23.78	226.2	165.2
7	− 25.90	95.8	342.7	− 24.38	143.7	242.2	− 23.03	191.6	194.0
8	− 25.46	83.1	393.1	− 23.75	124.6	278.8	− 22.29	166.1	220.9
9	− 25.13	75.0	433.4	− 23.36	112.5	308.5	− 21.71	150.0	244.2
10	− 24.76	67.3	483.8	− 22.78	100.9	342.7	− 21.11	134.5	272.6
11	− 24.39	60.5	534.2	− 22.34	90.7	379.7	− 20.61	121.0	302.7
12	− 24.07	55.4	584.6	− 21.95	83.2	416.1	− 20.14	110.9	331.8
13	− 23.76	50.9	635.0	− 21.58	76.4	452.0	− 19.63	101.8	358.8
14	− 23.48	47.3	685.4	− 21.24	71.0	489.6	− 19.18	94.6	387.9
15	− 23.20	44.0	735.8	− 20.84	66.0	524.9	− 18.80	88.0	417.6

$T_{\alpha 1} = -30$ °C

thermal output of a plug flow freezer in comparison to a freezer operating at a temperature equal to the inlet temperature of the plug flow freezer and under completely stirred conditions. The reduction of the product freezing time results in the increase of the freezer capacity, as stated in equation [5]. The freezer's capacity varied between 1400 and 1415 kg/h and 1755–1775 kg/h for an increase of 50 and 100%, respectively, of the heat transfer coefficient. The observed slight fluctuation in the values of the freezer capacity can be attributed to fluctuation in the accuracy of the calculations.

As stated before, the above results are valid for a 600 g/kg aqueous solution of ethanol. The application of a different freezing medium will lead to a different thermal output of the freezer clearly demonstrates the dependence on the heat transfer coefficient by the thermal properties of the freezing medium. According to existing experimental data for completely stirred immersion freezers (18), the use of a $CaCl_2$ brine would give the highest heat transfer coefficient, approximately 30–40% higher than an ethanol solution. Hence, the results for unobstructed flow for $CaCl_2$ brine would be almost the same as the corresponding in **Table 1** for a 50% increase of the heat transfer coefficient. This fact clearly states the potential use of $CaCl_2$ brine in a plug flow freezer. The only drawback of such a solution is the fact that the extended contact of the product with the brine can affect its quality (2). This may not be the case for the plug flow freezer since a low residence time for the product must be used.

Finally, the applicability of a plug flow immersion freezer for chilling applications was examined. In this case, the plug flow freezer can be used in conjunction with an already existing air freezer, in order to reduce the total freezing time and, as a result, to increase the total output of the whole process. In addition, the implementation of such an arrangement offers, via the selection of the chilling apparatus of a suitable product exit temperature, the extra advantage of reducing the weight losses of the product due to dehydration to negligible levels. The latter can account for as much as 2–3% of the product weight (19) and is a significant cost for the process of freezing. Thereby, the outlet temperature of the product from the plug flow prefreezer was set to − 5 °C, a temperature at which approximately 70–80% of the freezable water has already turned into ice. The calculations were carried out using the Nu-Re correlations and the hypothesis of a 50 and 100% increase of the heat transfer coefficient. The results are displayed in **Table 2.**

Comparison of **Table 2** with the corresponding results in **Table 1** shows that a plug flow freezer can be used more successfully for chilling applications. Indeed, the exit temperature of the freezing medium is higher in all cases. Also, for the case of increased heat transfer coefficient and for the higher values of the freezer length, the outlet temperature is high enough to secure the mild thermal treatment of the product. The values of the freezing time remain almost the same as the corresponding ones displayed in **Table 1.** This, at first sight, seems odd, since the lower values of the heat transfer coefficient justify the anticipation of greater freezing times. This is not the case, however, due to the smaller amount of heat that must be removed during chilling applications.

Conclusions

Given the results and the discussion above, it can be concluded that, on a theoretical basis, the application of a plug flow immersion freezer for the freezing of products with small thickness (up to 1 cm), like squid, is very attractive. For products of greater thickness the necessary freezing time becomes so high that the capacity of the freezer is reduced to prohibitively low levels.

The calculated heat transfer coefficient was quite high in all circumstances, at least significantly higher than that achieved with typical commercial air freezers. The results obtained in this paper indicate fairly strongly that a satisfactory high outlet temperature of the freezing medium can be achieved. This allows mild thermal treatment of the product, which in turn is the only advantage of the plug flow freezer over a typical immersion freezer.

Table 2 Application of a plug flow freezer as a chiller

	Nu-Re Correlations			50% increase of h			100% increase of h		
L_{fr} (m)	$T_{\alpha 2}$ (°C)	h (W/m^2 °C)	t_{fr} (s)	$T_{\alpha 2}$ (°C)	h (W/m^2 °C)	t_{fr} (s)	$T_{\alpha 2}$ (°C)	h(W/m^2 °C)	t_{fr} (s)
5	– 26.55	103.1	241.9	– 25.19	154.7	171.6	– 23.96	206.3	137.1
6	– 26.06	84.8	292.3	– 24.51	127.2	207.3	– 23.19	169.6	165.6
7	– 25.62	71.8	342.7	– 23.94	107.8	243.9	– 22.44	143.7	194.2
8	– 25.23	62.5	393.1	– 23.41	93.7	278.8	– 21.81	125.0	222.7
9	– 24.95	56.8	433.4	– 23.00	85.2	306.3	– 21.31	113.6	243.5
10	– 24.62	50.7	483.8	– 22.58	76.0	343.1	– 20.85	101.4	274.1
11	– 23.00	47.6	534.2	– 20.40	71.3	380.2	– 18.18	95.1	302.7
12	– 22.00	44.1	584.6	– 19.15	66.1	416.1	– 16.76	88.2	331.2
13	– 21.05	41.3	635.0	– 17.90	61.9	450.4	– 15.35	82.6	362.9
14	– 20.01	38.7	685.4	– 16.65	58.1	491.4	– 13.91	77.5	396.2
15	– 19.14	36.7	735.8	– 15.56	55.1	529.4	– 12.72	73.5	432.8

$T_{\alpha 2} = -30\,°C$, $T_{p2} = -5\,°C$

Another conclusion that can be drawn from this paper is that the plug flow freezer can potentially be applied as a prefreezer to increase capacity of already existing air freezers. Such an arrangement permits the mild thermal treatment of the product and the minimization of weight losses due to dehydration. In addition, these advantages are not accompanied by increased complexity of the whole installation. The plug flow freezer is a continuous flow freezer, thus allowing the continuous but mainly automatic movement of the product between the two apparatuses and minimizing labour requirements. This feature is usually the main factor discouraging the implementation of a typical immersion freezer in prefreezing applications.

In conclusion it is claimed that the goals of this study were fully implemented on theoretical grounds. Its conclusions must also be confirmed in practice, however. A first step in this direction would be the experimental determination of the heat transfer coefficient and the discovery of an accurate correlation for its computation. Also, the flow phenomena inside the freezer should be examined. This kind of investigation can reveal the most suitable arrangement in order to achieve the maximum possible thermal performance of the freezer.

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