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Journal of Food Engineering 40 (1999) 259–267

JOURNAL OF FOOD ENGINEERING

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Immersion chilling of trays of cooked products

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Received 29 October 1998; accepted 1 March 1999

Abstract

Cooking systems producing complete, or ingredients for, chilled meals are designed to achieve temperatures of 70°C for 2 min in the centre of the food, which should cause a 10^6-fold destruction of Listeria monocytogenes. However, spore-forming micro-organisms will survive this process and multiply if the food is not rapidly reduced to a temperature below 10°C. Experimental investigations have been carried out to study the cooling of different thicknesses of cooked solid–liquid mixtures under a range of immersion chilling conditions. An iterative computer model of the process has been developed and used to extend these data to cover alternative processing conditions and a range of cooked meals. If surface freezing was to be avoided then it was found that only the shallowest (10 mm) tray could be chilled within the limits of the most severe European Guidelines. However, the model also predicted that the 40 mm trays of food would cool within the limits of the Guidelines if oriented differently.

1. Introduction

The United Kingdom Department of Health (1989) defines a cook-chill system as "a catering system based on the full cooking of food followed by fast chilling and storage in controlled low temperature conditions above the freezing point (usually 0–3°C)".

The aim of the cooking process in the cook-chill system is to ensure destruction of vegetative stages of any pathogenic micro-organisms. Normally, the minimum recommended temperature requirements are to achieve 70°C for not less than 2 min in the centre of the food. European Chilled Food Federation Guidelines (1994) state that this should cause a 10^6-fold destruction of *L. monocytogenes*. There is always the possibility that some micro-organisms which produce spores will not be killed by the cooking process. Therefore the temperature of the product should be rapidly reduced through the range from 60°C to 7°C to prevent multiplication. Further reduction to 3°C is required to reduce the growth of spoilage bacteria and pathogens. In addition to the microbiological factors rapid reduction in product temperature aids retention of nutrients which is vital in a system often used for the preparation of meals for the old, infirm and young people.

In the United Kingdom the Department of Health Cook-chill Guidelines (1989) recommend maximum cooling regimes and that special equipment is used to rapidly reduce product temperatures after cooking. Many other countries in Europe have similar Guidelines or recommendations for the cooling of cooked products (Table 1). However, there are little published data on the conditions required to achieve these times when cooling different cooked products.

The UK Guidelines recommend that joints of meat or packs of food should not exceed 2.5 kg or 100 mm in thickness or height. It also advises that containers have lids to help prevent contamination and to minimise dehydration during cooling. The Guidelines also state that the actual chilling process should commence as soon as possible after completion of cooking and certainly within 30 min of leaving the cooking process (this allows for portioning of meals). Smaller portions (less than 50 mm deep) should be chilled to between 0°C and 3°C within 90 min and larger portions to 10°C within 2.5 h after removal from the cooking process. The equipment used to chill products should have performance specifications showing that it is capable of reducing the temperature of a 50 mm thick layer of food from 70°C to 3°C (or less) in a period not exceeding 90 min when fully loaded.

Batch blast air chilling of trays of food is the most common commercially used chilling method. Studies carried out by Evans, Russell and James (1996), showed

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Table 1
Cooling requirements for cooked products in Europe

Country	Temperature range (°C)	Maximum time allowed (h)	Subsequent temperature (°C)
Denmark	65–1	3	<5
France	70–10	2	0–3
West Germany	80–15	2	
	15–2	24	<2
Sweden	80–8	4	<3
UK	70–3	1.5	0–3

that if surface freezing was to be avoided, only shallow (10 mm) trays of food could be cooled within the recommended times using this chilling method. A number of faster cooling systems are available for cooked food. Burfoot, Hayden and Badran (1987) showed that vacuum cooling of hot sauces was substantially faster than air cooling. However, substantial weight losses occur in vacuum cooling (Burfoot, Self, Hudson, Wilkins & James, 1990) and in some cases changes in texture were found (Self, Nute, Burfoot & Moncrief, 1990). Burfoot et al. (1990) stated that immersion cooking and cooling had potential because it was faster than air but produced lower weight losses than vacuum cooling. In other studies of immersion cooling, Nolan (1986) produced a simple method based on a chart to predict the cooling time of meat roasts from a uniform 62.7°C to 4.4°C. The method is applicable to any immersion system with a cooling medium velocity of over 0.15 ms^{-1} and a temperature of between approximately 2°C and −4°C. It predicts that, for example, a 9 kg roast 152 mm high will require 13.3 h to cool in a liquid at 0°C.

Practical and theoretical investigations have been undertaken in this study on the immersion cooling of trays of hot food. Simple predictive methods have been used to extend the experimental data to cover alternative processing conditions and the cooling of other foods. These experiments were designed to provide data that would be directly comparable with the previous air cooling work by Evans et al. The data have been compared with those from this air blast cooling work and with the requirements of the quoted guidelines and recommendations.

2. Experimental procedure

2.1. Practical

A relatively viscous Mexican beef chilli con carne was used as the test dish for these experiments. The chilli was provided by a commercial company and delivered in 5 kg frozen chubs (cylindrical, plastic-wrapped packages). These were stored at -20 ± 2°C until required.

When required, chilli was cut from the chubs, placed in a cooking vessel and reheated until all the product had reached the desired temperature. The temperature of the chilli was measured with a hand-held digital thermometer during reheating (AJT model 2000, accuracy ±0.5°C). The chilli was then transferred to a sealable, lidded steel tray with a plastic liner to contain the food. The tray was placed horizontally in an immersion tank through which brine was circulated at -0.2 ± 0.5°C. The experimental set-up is shown in Fig. 1. This set-up was used as it gave results that could be directly compared to the results from the horizontal trays used in the air cooling work, carried out by Evans et al. (1996).

Heating of the food prior to cooling was terminated when the chilli temperature had reached 65°C in the case of the low flow regime or 80°C in the case of the high flow regime. The differences in bulk starting temperature used in the experiments represents variations in the cooking temperature and transfer times, from the cooking stage of a cook-chill meal to the cooling trays, that may occur in a production setting. A longer time before placing the cooked food into the cooling trays, due to operational variations, would result in a lower initial bulk temperature, and so a shorter cooling time.

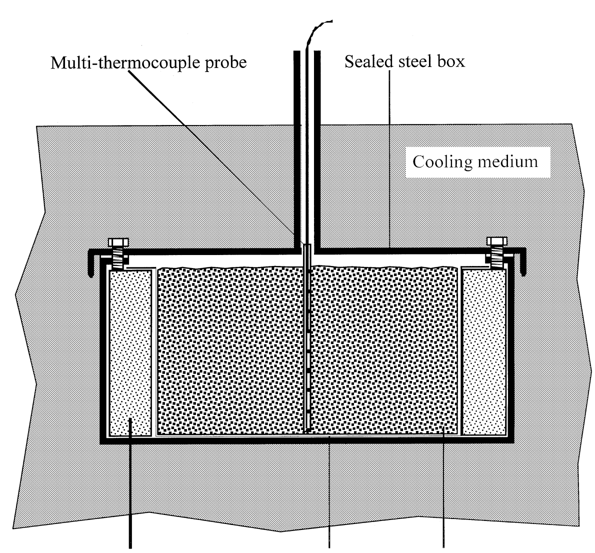

Fig. 1. Cross section of the sealed, lidded trays used in the immersion experiments (not to scale).

The two different starting temperatures were used as a representation of the range of temperatures that have been measured commercially. The model described below was used to predict data for cooling of the food from 65°C under the high flow regime and from 80°C under the low flow regime.

The two different flow regimes were produced by changing the circulation patterns used in the immersion tank. The high flow regime used jets of brine which impinged directly onto the top and bottom surfaces of the horizontal trays of chilli, which were submerged in the recirculating brine tank. The low flow regime used a lower circulation rate and the brine was pumped into the bottom of the tank so that it did not directly impinge on surface of the trays.

The trays used in the investigation had depths of 10, 40 and 80 mm. All the trays had watertight steel lids and sealed-in insulation on the vertical sides to remove edge effects during cooling and so making the food cool in the manner of an infinite slab. This enabled comparisons between the results of these experiments and the air cooling experiments carried out by Evans et al., as well as between the experimental data and the data derived from the models.

Five replicate runs were carried out under each flow condition for each of the three tray depths.

Copper-constantan thermocouples were used for measuring product temperatures throughout the cooling process, connected to a Datascan 7000 series module (Measurement Systems Ltd.). Temperature data was logged every 60 s using Labtech software.

These thermocouples were incorporated into multi-point probes, which consisted of thermocouples held in place by a thin coating of resin on the surface of thin, low-conductance glass-fibre rods. The thermocouples were held in place so that their junctions remained spaced at the correct distance along the probe. These probes were placed vertically in the middle of the food as shown in Fig. 1. A low thermal conductivity rod was used to prevent excess thermal conduction along the probe in the direction of the heat flow in the food. Thin thermocouple wire (0.075 mm diameter wire) was used to minimise thermal conductivity along the wires themselves.

Three thermocouples measured temperatures in the 10 mm thick product, one placed in the geometric centre of the tray, one placed vertically 5 mm above and the other 5 mm below the geometric centre to measure the top and bottom surface temperatures and the centre temperature. The 40 and 80 mm trays had 5 and 9 thermocouples, respectively, spaced 10 mm apart to measure surface and internal temperatures throughout the height of the product through the geometric centre. The brine temperature was measured with two thermocouples upstream and two downstream of the trays.

Temperature-time data were analysed by transformation into straight line data using the logarithmic transformation of the unaccomplished temperature difference, plotted against the cooling time:

$$\ln\left[\frac{T - T_{\mathrm{m}}}{T_{\mathrm{i}} - T_{\mathrm{m}}}\right],$$

where T is the temperature of product at the corresponding time, T_{m} the temperature of cooling medium, and T_{i} the initial temperature of product.

3. Mathematical model

Predictive modelling was carried out using ‘Foodtemp’, a finite difference model of an infinite slab previously developed from the model used in the air cooling of recipe dish meals (Evans et al., 1996). In each case the modelled food thickness was divided into 20 layers, with 21 nodes.

Thermophysical properties for the chilli were predicted by the model using data on the initial freezing point and composition of the product. The initial freezing temperature was taken as the mean freezing point of three representative samples of chilli frozen in a freezer at −18°C. Chemical analyses were carried out on three representative samples to obtain a mean composition (water, protein, fat, carbohydrates, minerals). Foodtemp automatically calculated values of thermal conductivity and diffusivity, enthalpy, heat capacity, density and ice content over a temperature range of −20–90°C, using a module based on the ‘COSTHERM’ program (Miles, van Beek & Veerkamp, 1983).

The model was fitted to the experimental data from the 80 mm tray runs under both high and low flow conditions by varying the heat transfer coefficients at the upper and lower surfaces of the chilli. The upper and lower surface heat transfer coefficients were changed independently in 0.1 W m^{-2} K^{-1} steps until the optimum fit to the experimental data was achieved. The fit was considered to be optimum when the gradient of the exponential phase of the logarithmic transformation of the unaccomplished temperature difference of the experimental data was the same as that of the model output. The surface heat transfer coefficients were then used to extend the experimental data by modelling the 80, 40 and 10 mm trays under low and high flow conditions and low and high starting temperatures.

Surface heat transfer coefficients were also measured using the method described by Cowell and Namor (1974). The metal block used was first insulated on all but one side and encased in a plastic liner similar to that used in the trays to contain the food. The outer side of the plastic liner was then exposed to the two flow regimes in the immersion tank and the cooling data were

Table 2
Measured and predicted cooling times of different thicknesses of chilli at a brine temperature of −0.3°C including standard deviations

Tray depth (mm)	Flow regime	Initial temperature (°C)	Cooling times to 10°C (h)				Cooling times to 3°C (h)			
			Experimental	1 s.d.	Horizontal model	Vertical model	Experimental	1 s.d.	Horizontal model	Vertical model
	Low	65	4.60	0.19	4.85	3.24	7.31	0.25	7.66	5.07
80		80	–	–	5.33	3.53	–	–	8.14	5.37
	High	65	–	–	4.81	3.21	–	–	7.59	5.02
		80	4.93	0.14	5.28	3.51	7.83	0.17	8.05	5.32
	Low	65	1.51	0.10	1.63	0.92	2.57	0.15	2.57	1.43
40		80	–	–	1.79	1.00	–	–	2.73	1.52
	High	65	–	–	1.61	0.90	–	–	2.54	1.41
		80	1.59	0.08	1.76	0.99	2.63	0.11	2.70	1.50
	Low	65	0.22	0.02	0.21	0.10	0.35	0.05	0.33	0.16
10		80	–	–	0.23	0.11	–	–	0.35	0.17
	High	65	–	–	0.20	0.09	–	–	0.32	0.15
		80	0.21	0.01	0.22	0.10	0.34	0.02	0.34	0.16

recorded and analysed to obtain the surface heat transfer coefficients.

The model was also used to investigate the effect of a vertical rather than horizontal tray orientation on the cooling of the chilli under the two cooling regimes and initial product temperatures.

Finally, it was used to predict the cooling times from 70°C to 10°C and 70°C to 3°C, for other cook-chill type foods.

4. Results

4.1. Experimental

At a mean brine temperature of −0.3°C, the average cooling times to 10°C ranged from 0.21 to 4.93 h and those to 3°C from 0.34 to 7.83 h (Table 2). When cooling to 10°C, increasing the product depth from 10 to 40 mm produced a 6.9-fold increase under the low and a 7.6-fold increase under the high flow regime. Increasing the product depth from 10 to 80 mm resulted in increases of 20.9 and 23.5-fold respectively.

The surface heat transfer coefficients were measured as 207.6 and 470.3 W m^{-2} K^{-1} for the low and high flow regime, respectively, using the method described by Cowell and Namor.

The cooling times produced by the high flow regime compared to the low flow regime can not be directly compared because of the different initial temperatures.

The transformed experimental data can be seen in Fig. 2 (slowest cooling position, low flow), Fig. 3 (slowest cooling position, high flow), Fig. 4 (bottom surface, low flow) and Fig. 5 (bottom surface, high flow).

These graphs are plotted so as to be directly comparable to those in the air cooling work carried out by Evans et al. They can be used to predict the influence of brine temperature on the cooling time from 70°C to any given temperature at the slowest cooling position or the bottom (fastest cooling) surface. The graphs for the slowest cooling position will give the total cooling time to the given temperature, whilst those for the fastest cooling surface will show if freezing is likely to occur, should a brine temperature of less than the freezing point of the chilli be used.

Reducing the brine temperature from 2°C to −2°C in the high flow regime reduces the cooling time to 10°C by approximately 18%, 16% and 11% at product depths of

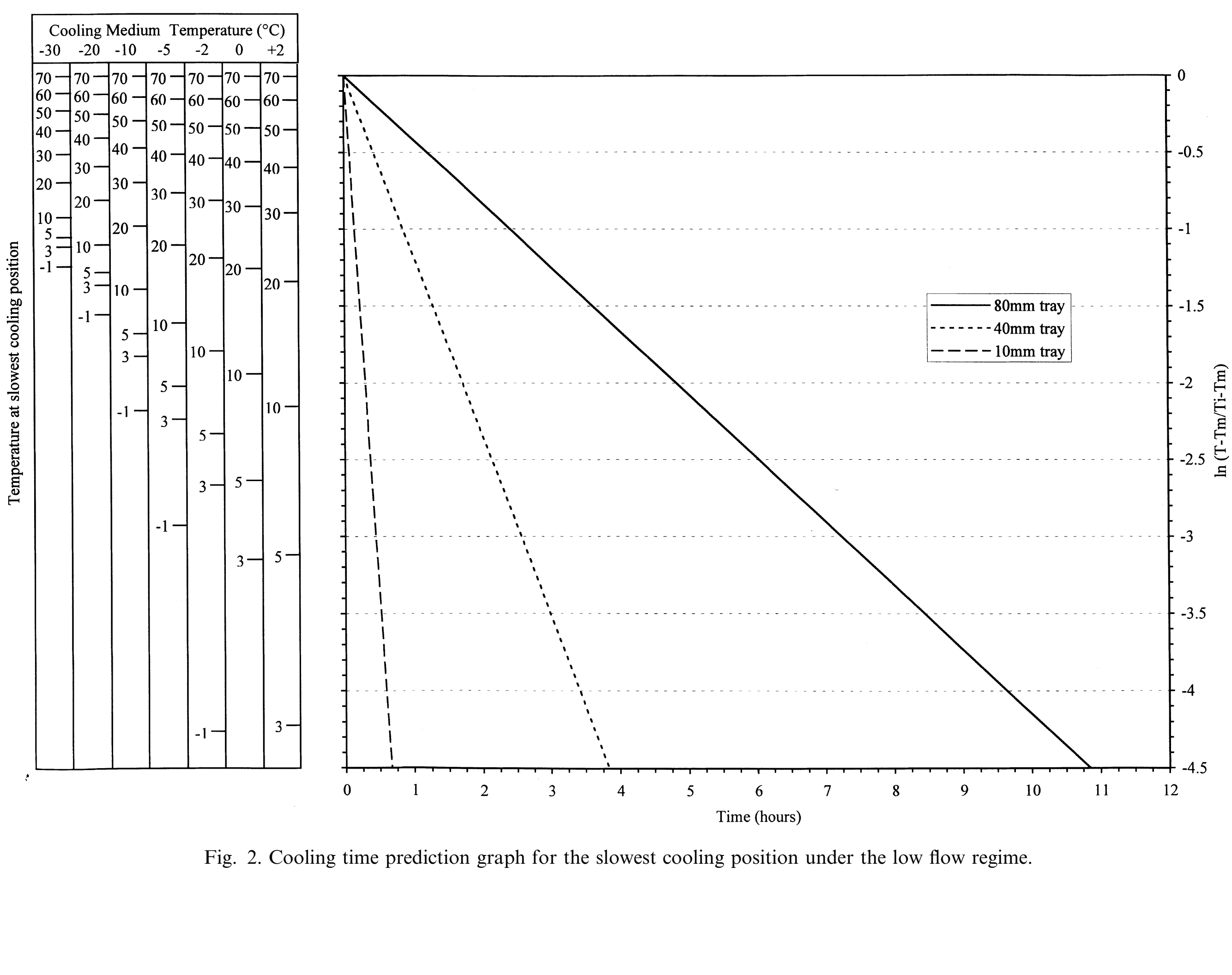

Fig. 2. Cooling time prediction graph for the slowest cooling position under the low flow regime.

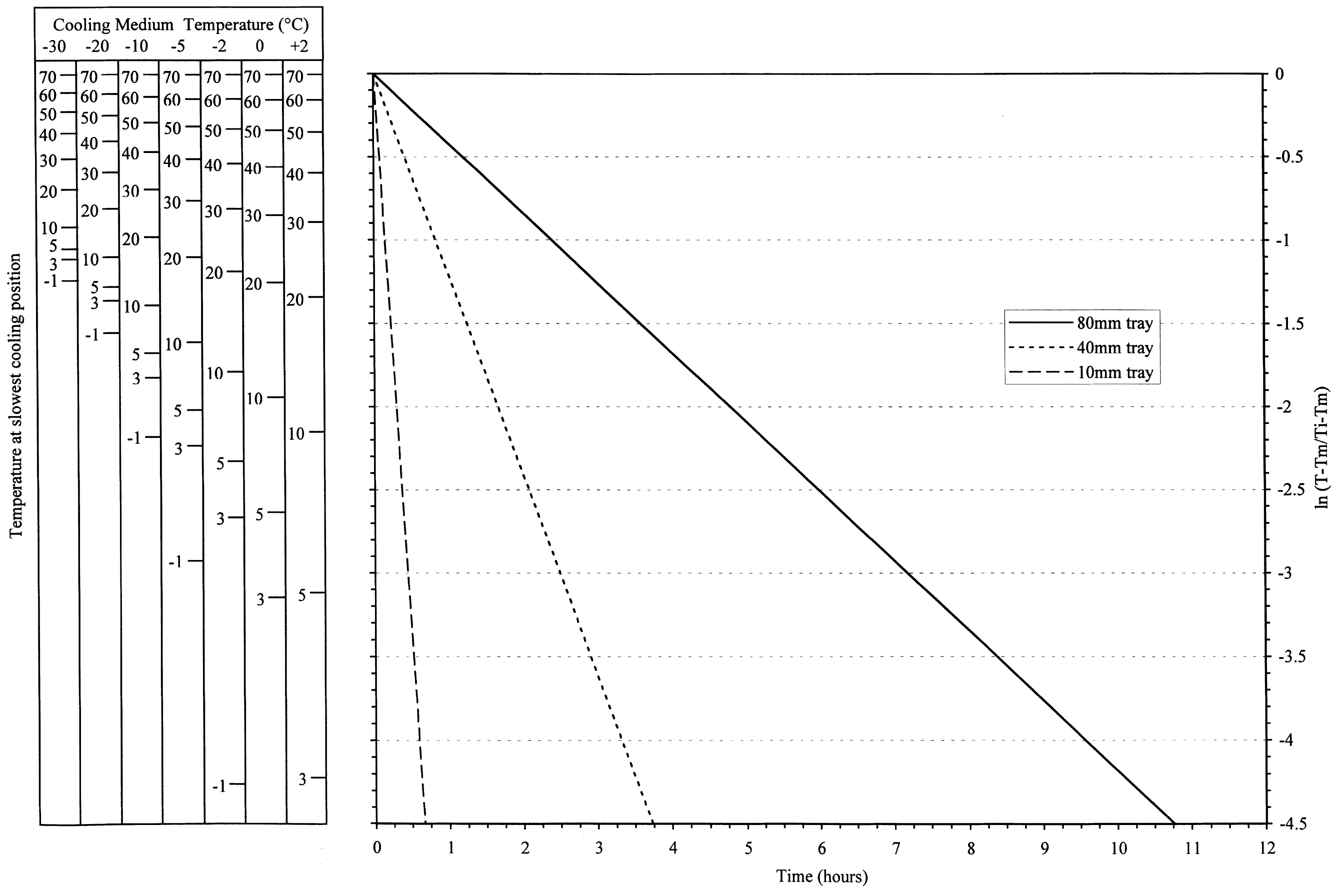

Fig. 3. Cooling time prediction graph for the slowest cooling position under the high flow regime.

10, 40 and 80 mm respectively. Cooling to 3°C the corresponding reductions are approximately 43%, 47% and 47% respectively.

4.2. Model predictions

Heat transfer coefficients of 17.5 W m^{-2} K^{-1} on the top and 167.8 W m^{-2} K^{-1} on the bottom surface provided the optimal fit to the experimental data for the low flow condition over an 80 mm depth. Corresponding figures for the high flow regime were 17.8 and 179.9 W m^{-2} K^{-1}, respectively. These surface heat transfer coefficients were used to model the 40 and 10 mm trays. Cooling times predicted for the different thicknesses, flows and starting temperatures are given in Table 2. The model fitted the experimental results with an error of less than ±10% in all cases.

Changing from a low to high flow condition in the model resulted in a small reduction of 0.01–0.05 h in the cooling time to 10°C. A reduction of less than 1% and approximately 5% was observed for the 80 and 10 mm deep trays, respectively. Reductions in cooling time to 3°C were very similar in magnitude.

Changing the initial temperature from 80°C to 65°C in the model resulted in reduction in cooling time of 0.47 and 0.48 h at a 80 mm tray depth, 0.15 and 0.16 h at 40 mm and 0.02 h at 10 mm. The higher reductions were always predicted for the low flow regime.

Predictions were also carried out using the best fit heat transfer coefficient for the bottom surface on both the top and bottom of the slab. Significant reductions in cooling time to 3°C were predicted by the model (0.17–0.18 h for the 10 mm slab, 1.13–1.21 h for the 40 mm slab and 2.57–2.77 h for the 80 mm deep slab) as shown under the heading of vertical model in Table 2. Percentage reductions in cooling time to 10°C ranged from 33% to 55%.

The data on the initial freezing point and the chemical analysis carried out on the chilli and three other foods (Table 3) were used to calculate thermal properties used in the predictive model. Under all the conditions modelled, the percentage difference in cooling time between the chilli and the three other foods was predicted to be less than 1% for the bolognese and beef curry and less than 4% for the chicken Italian.

5. Discussion and conclusions

The trays used in these experiments should accurately represent trays that are used in real food operations, as

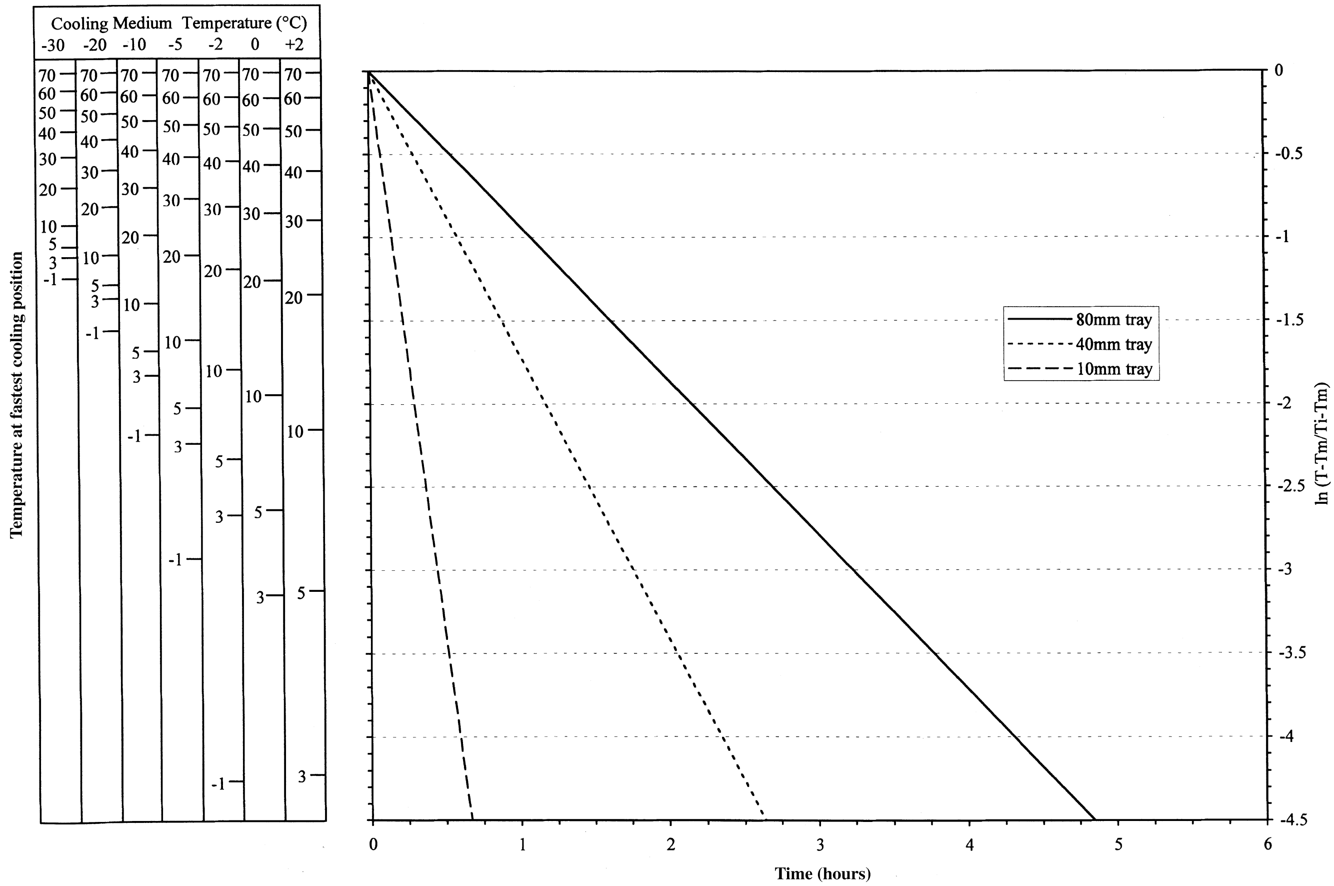

Fig. 4. Cooling time prediction graph for the bottom surface (fastest cooling position) under the low flow regime.

the trays used in food production are typically of large lateral dimensions for minimised handling and so would also cool in a manner similar to an infinite slab.

The experimental and modelling data show clearly that product thickness, initial product starting temperature and cooling medium temperature have a large effect on the cooling time of trays of cooked foods. The small differences in the model results when comparing the chilli with the three other cook-chill foods indicates that the chilli used in the experiments was representative of a wide range of cook-chill foods.

Any predictions calculated from the plots of the logarithmic transformation of the unaccomplished temperature difference will not take into account the lag at the beginning of any cooling process that cools a product from a uniform temperature. A straight line can only be obtained on the graph once the food is cooling in a truly exponential manner; Bailey and Cox (1976) say this occurs approximately 10% into the cooling time. The model was used to predict the differences between the actual cooling time (incorporating the lag) and the calculation made from the gradient of the straight line from unaccomplished temperature difference plot. Under the conditions of the experiments, the calculation from the transformation of the unaccomplished temperature difference underestimated the cooling time by less than 8% in all cases of cooling from 70°C to 10°C and less than 6% in all cases of cooling from 70°C to 3°C. These differences are of less magnitude than the variations between the experimental runs, which were up to 16%. The cooling charts can therefore be used with confidence to provide cooling times for a range of brine temperatures. These charts are also in a format so that they can be directly compared to the air cooling work carried out by Evans et al.

The surface heat transfer coefficients used in the model are, in reality, apparent surface heat transfer coefficients. They are calculated at the surface of the chilli and so represent a lower value than those measured between the cooling medium and the tray surface. The difference between the apparent and actual surface heat transfer figures is a result of the extra thermal resistance from the steel tray, the plastic liner and any air gaps present.

A large difference between the top and bottom apparent surface heat transfer coefficients is obvious under both flow regimes. This is due to air gaps between the top of the chilli layer and the tray lid as a result of the horizontal orientation of the tray. If trays were positioned

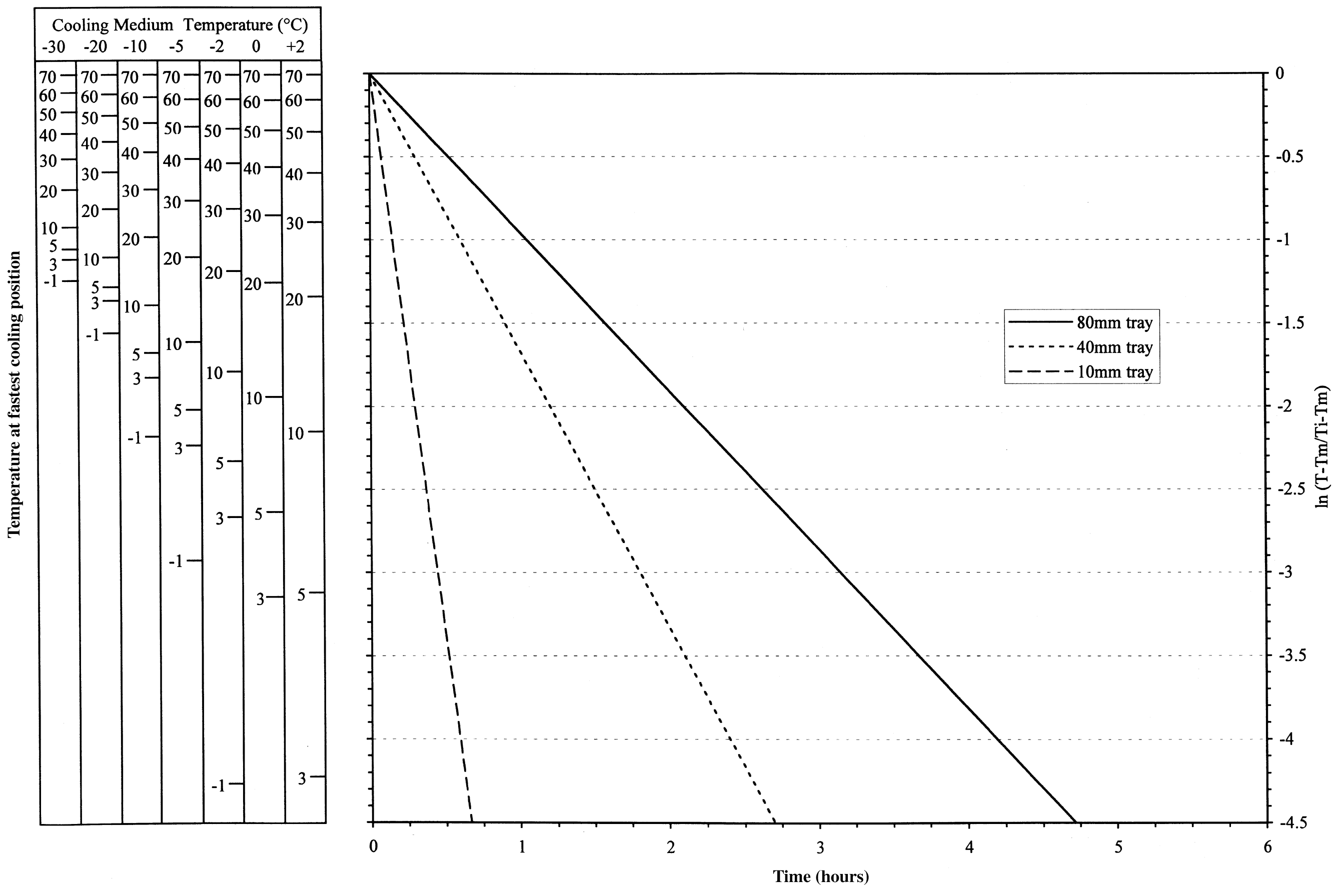

Fig. 5. Cooling time prediction graph for the bottom surface (fastest cooling position) under the high flow regime.

vertically, the food would make good contact with both walls of the tray and the higher apparent surface heat transfer coefficients, as obtained on the bottom of the chilli in these experiments, should be obtained on both surfaces. Modelling this condition, with a brine temperature of −0.3°C, improved cooling times considerably (see the Vertical model results in Table 2).

The model predicted that, using a vertical orientation, both the 10 and 40 mm tray could be cooled within the United Kingdom Guidelines, and the 80 mm tray would be cooled to the required 10°C in a far shorter time. Further predictions show that using a vertical orientation and a brine temperature of −0.3°C, a 66 mm product could be cooled to 10°C in under 2.5 h. The Guidelines stipulate that trays over 50 mm should be cooled to 10°C within 2.5 h and so the predictions for the vertical model show that trays from 0 to 40 mm and 50 to 66 mm can be cooled to within the limits of the Guidelines.

Comparing these results with those for air cooling (Evans et al., 1996), it is clear that brine cooling is substantially faster than blast air. It is also clear that product depth has a greater proportionate effect on cooling time in the immersion system than it does in an air blast system. With air blast cooling the 40 and 80 mm trays to 3°C gave a 4-fold and 10-fold increase in cooling time over the 10 mm trays. Using immersion cooling these figures reached an average of approximately 7.5-fold and 22-fold, respectively.

Table 3
Composition of foods as used in the mathematical model as a percentage by mass

Food	Initial freezing point (°C)	Percentage by mass of components				
		Water	Protein	Fat	Carbohydrate	Minerals
Beef Chilli	−1.5	74.7	7.3	8.1	8.4	1.5
Bolognese Sauce	−1.2	72.5	13.2	6.6	6.7	1.0
Beef Curry	−2.1	70.3	9.4	5.7	13.4	1.2
Chicken Italian	−1.2	85.8	8.5	1.7	3.8	0.2

It would be possible for the cooling times to be further reduced by decreasing the resistance to internal heat transfer, increasing the surface heat transfer rate or reducing the temperature of the cooling medium. The temperature gradient within the food could be decreased by mixing the product during cooling or by using high conductivity inserts. Such devices include high conductance solid metals, thermosyphons and heat pipes. A reduction in the heat transfer resistance on the outside of the product could be achieved by using vacuum bags rather than the steel trays with plastic liners used to contain the food in these experiments. The use of sealed vacuum bags would also reduce the chance of recontamination of the food after the cooling stage as the bags would not need to be opened until the food was required for reheating. The surface heat transfer rate could be increased by increasing the agitation in the cooling medium or by changing the type of cooling medium.

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