Journal of Food Engineering 34 (1997) 179–192

Printed in Great Britain
0260-8774/98 $19.00 + 0.00
PII: S0260-8774(97)00070-8

An Appraisal of the Freezing Capabilities of Tunnel and Spiral Belt Freezers Using Liquid Nitrogen Sprays

Samuel O. Awonorin†

Department of Food Technology, College of Science and Technology, University of Lagos, Abeokuta Campus, P.M.B. 2240, Abeokuta, Ogun State, Nigeria

(Received 24 January 1996; accepted 24 July 1997)

ABSTRACT

A parametric analysis, comparing the heat transfer and operating characteristics of a tunnel and a spiral belt freezer, has been carried out using liquid nitrogen sprays under typical commercial freezing conditions. Experimental data were obtained for a controlled spray pressure of 2·4 bar, and two selected pizza sizes (128 and 180 mm diameter) were used based on a freezing capacity of 500 pizzas per hour. The freezing time of the two pizza samples was between 4·1 and 4·4 min in the spiral belt and tunnel freezers, respectively, and appeared to vary directly with sample mass. The average heat transfer coefficients in the precooling section were 28 and 35 $W\,m^{-2}\,K^{-1}$ in the tunnel and spiral belt freezers, respectively. These values were about 1/6 and 1/5 of the overall heat transfer coefficients in the freezing section, and 1/16 and 1/15 of the average heat transfer coefficients of individual droplets, respectively, while maintaining freezer temperature between −140 and −150°C during freezing. Drip losses were low (0·55 to 0·6%) in the two freezers, and microbial destruction was in the order of six-fold. The mean sensory scores for textural feel of the frozen–thawed samples were not significantly different ($P > 0{\cdot}05$), but panelists detected significant differences ($P < 0{\cdot}05$) among samples on visual appearance.

*Specifications*NOTATION

A Area (m^2)
C A constant in eqn 7

†Present address: Department of Food Science and Technology, University of Agriculture, P.M.B. 2373, Makurdi, Benue State, Nigeria.

Cp	Specific heat at constant pressure ($J\,kg^{-1}\,K^{-1}$)
d	Droplet diameter (m)
D	Characteristic dimension of length in eqn 8 (m)
g	Gravitational constant ($m\,s^{-2}$)
h	Heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
K	Thermal conductivity ($W\,m^{-1}\,K^{-1}$)
m	Mass (kg)
m_p	Product flow rate ($kg\,h^{-1}$)
m^*	Mass velocity of liquid nitrogen ($kg\,m^{-2}\,h^{-1}$)
m_p^*	Production loading density ($kg\,m^{-2}\,h^{-1}$)
n	Power index in eqn 7
q	Rate of heat transfer (W)
t	Time (h)
T_b	Saturation temperature of liquid nitrogen (°C)
T_c	Product centre temperature (°C)
T_e	Temperature in the equilibration zone (°C)
T_s	Surface temperature of food (°C)
T_f	Temperature in the freezing zone (°C)
T_p	Temperature in the precooling zone (°C)
ΔT	Temperature difference ($T_s - T_b$) (K)
V	Velocity ($m\,s^{-1}$)

Greek letters

ρ	Density ($kg\,m^{-3}$)
λ	Latent heat of vaporization ($J\,kg^{-1}$)
μ	Viscosity ($kg\,m\,s^{-1}$)
ε	Fraction of active heat transfer area

Subscripts

an	Air–nitrogen gas
b	Belt
d	Droplet
f	Freezing
l	Liquid
m	Mean
o	Overall
p	Product
v	Vapour
32	Sauter mean

INTRODUCTION

It has been shown in previous experiments and in theory, that the performance of a cryogenic freezer using liquid nitrogen sprays can be effectively improved by controlling the spray pressure and geometry, refrigerant flow rate, and making maximum use of the sensible heat of the cold nitrogen gas during precooling (Holdsworth, 1967; Davidge, 1974; Bonacina *et al.*, 1974; Reynoso & De Michelis, 1988; Awonorin, 1989a, 1993). However, the selection of an efficient or economic freezing equipment is often based on the freezing rates, freezer capacity and running cost, and quality and overall cost of the frozen products.

Liquid nitrogen freezers offer considerable potential for food freezing due to minimum maintenance cost, since such equipment has no moving parts, economy in equipment size and space requirements, and rapid freezing rates, among others (Anon, 1969; Dorney & Glew, 1974; Dinglinger, 1975). So far, the belief in the frozen food industry is that high freezing rates tend to give better quality, provided no undue stress damage is caused by the freezing speed itself. But under normal commercial cryogenic freezing conditions, stress damage rarely occurs. This is because the liquid nitrogen droplets are supported by nitrogen vapour film (Davidge, 1974) as a result of the Leidenfrost boiling phenomenon (Leidenfrost, 1756), which prevents the highly volatile droplets (at $-196°C$) from physically contacting the foods at the temperature range used in cryogenic food freezing (Awonorin & Lamb, 1988, 1990).

There are two common designs of liquid nitrogen freezers available commercially for food freezing — the tunnel and spiral belt equipment. The choice between the two appears to be the space saving and refrigerant consumption rate for any sizable product. These have, to a large extent, influenced the selection of most cryogenic freezers, even when the freezing technique and design specifications are virtually the same. So the cryogenic freezing systems vary with product, and each has a particular application (Briley, 1980). However, the spiral belt freezer is, perhaps, more economical than a tunnel freezer of the same capacity on the basis of reduced refrigerant consumption and hence reduced overall cost of the freezing operation (Davidge, 1973; Awonorin, 1989b).

A parametric study of the performance of a tunnel freezer under commercial production conditions was reported in a companion paper (Awonorin, 1989b). So far, no clear qualitative evidence has been found in the literature which compares those technical factors responsible for the differences in the consumption rates of liquid nitrogen and heat transfer performance in the tunnel and spiral belt freezers using the same operating variables. A comparative analysis of the heat transfer and performance data in the two designs, in relation to product quality, should be of value to the refrigeration engineer.

Thus, the focus of this study was to compare the performance of two selected designs — the tunnel and spiral belt freezers using the same spray characteristics, product output and different product sizes. The parameters studied were: product size and loading density, liquid nitrogen consumption, freezing time, average heat transfer coefficients, microbial load, and sensory evaluation of the frozen products. The results are discussed in relation to existing heat transfer models previously developed for cryogenic freezers.

MATERIALS AND METHODS

Experimental equipment

Two types of liquid nitrogen freezers were used: a tunnel type described previously (Awonorin, 1989b), and a spiral belt type of the same rated output ($305\ kg\ h^{-1}$);

TABLE 1
Relevant Design Specifications for Tunnel and Spiral Belt Freezers

Specifications	*Freezer type*	
	Tunnel	*Spiral belt*
Freezing capacity (kg h^{-1})	310	310
Products residence time (min)	15–20	15–20
Number of tiers	—	10
Usable belt width (m)	1·2	0·25
Usable belt length (m)	6·3	44·0
Overall length of freezer (m)	7·8	3·5
Overall width of freezer (m)	2·0	2·8
Overall height of freezer (m)	2·1	2·8

and product residence time of about 15 to 20 min. Details of the relevant design specifications for the two freezers are presented in Table 1.

Both equipment were supplied with liquid nitrogen from 100 litre Dewar vessels (Polarstream PS) placed on a platform weighing scale to measure the nitrogen consumption (m) over a period of time (t) of the freezing operation as reported earlier (Awonorin, 1989a). Hence, the rate of liquid nitrogen consumption ($\mathrm{d}m/\mathrm{d}t$) was computed.

The experimental set-up and method of operation were the same for the two freezers as reported previously (Awonorin, 1989b), and the spray mean droplet diameter (d_{32}) was estimated to be 140×10^{-6} m leaving the nozzle. This diameter was, therefore, corrected using the procedures described previously (Awonorin, 1988). Hence, the actual d_{32} reaching the pizza surface was estimated to be 126×10^{-6} m.

Sample preparation

Two pizza sizes were used: sample size A weighing on average 0·108 kg, and 0·215 kg for sample B, within 2%. The pizza diameters were approximately 128 and 180 mm for samples A and B, respectively, and provision for temperature measurements near the product surface and thermal centres using thermocouple wires were the same as reported earlier (Awonorin, 1989b).

Experimental procedures

The same procedures adopted in the experiments reported earlier (Awonorin, 1989b), using a tunnel freezer, were also used in this study for the two freezer designs.

The freezing operation was based on a 7 h shift per day, five days per week as follows: quantities of samples A and B were 352 and 170 per hour, respectively, for the tunnel freezer, 285 and 215 per hour for samples A and B, respectively, for the spiral belt freezer. The product loading density (m_{p}^{*}) was determined from the measured product flow rate (m_p) and usable belt area (A_b) of each freezer (Table 1). So

$$m_p^* = m_p / A_b \tag{1}$$

The average temperatures in the precooling (T_p), freezing (T_f) and equilibration (T_e) sections of the two freezers [see fig. 1 of Awonorin (1989b)] were measured with copper–constantan thermocouple wires (0·4 mm diameter) connected to a Comark multipoint temperature recorder. The product temperatures at the thermal centre (T_c) and surface (T_s) at 1·0 mm deep were measured using the recorder. Hence, T_s was treated as transient heat conduction (Awonorin, 1982).

The average initial temperature of the products was 22°C at the beginning of the experiments. The freezing time (t_f) of each pizza sample was estimated from the plots of product centre temperature (T_c) versus time (t), and t_f was taken as the time required for the product temperature to change from 5°C to −5°C as reported elsewhere (Awonorin, 1989b).

The total quantity of frozen products was 8 tonnes per sample size. The flow rate of liquid nitrogen (dm/dt) into the freezer was computed as the change in weight of the Dewar content (dm) divided by the time (dt) required for the change. The values of dt were based on the observation of the actual spraying time of liquid nitrogen, and not the total time of the freezing operation. The energizing time of the thermostatically controlled solenoid valve on the feed line of the spray nozzles was recorded for that purpose. This was considered as an improvement over previous procedures (Awonorin, 1989b), where this factor was not considered. The local mass velocity (m^*) of liquid nitrogen delivered over an area (A_o) at the food surface was determined. Thus

$$m^* = (d/dt)A_o \tag{2}$$

Note that A_o had been measured earlier (Awonorin, 1989b) with a pressure drop of 1·4 bar and nozzle location of 18 cm above the pizza surface.The velocity of air–nitrogen gas (V_{an}) in the precooling section of each freezer was measured with a sensitive eight-blade anemometer (Taylor Instruments, USA).

Drip loss and colony count

At the end of each freezing operation, and for a given pizza size, the drip loss was determined from pre- and post-weight measurements ($N = 10$) until the samples thawed to room temperature (22°C) and the values were expressed as percentages of the initial mass of product.

The total colony count was determined over an area ($25 \times 25\ mm^2$) on samples ($N = 10$). The swab method (Pickett & Miller, 1967) was used, in which the dilutions were plated at 10^{-1} to 10^{-3} on a standard plate count agar, and incubated at 30°C for 48 h. The number of colonies of the unfrozen, and later the frozen, samples was hand-counted using a Coulter counter. This gave an insight into the level of reduction of microbial population due to the freezing effect.

Sensory evaluation

The samples were evaluated subjectively for two attributes: (1) visual appearance after freezing, and (2) textural feel upon thawing the same samples to a uniform temperature of 15°C in a refrigerator. A nine-point hedonic scale (where 1 = very bad, 5 = fair, and 9 = very good) was used to indicate the level of preference of samples by a 10-member trained panel. Each evaluation was repeated twice.

The data were analysed using the analysis of variance, and the comparison among mean values was made using Duncan's multiple range test (Steel & Torrie, 1960).

Heat transfer analysis

An energy balance at the food surface, assuming that the evaporation rate of liquid nitrogen (dm/dt) from the sprays occurred as a result of heat transfer between the boiling liquid nitrogen at a saturation temperature (T_b) and the food surface at a temperature T_s, yields a relationship for the rate of heat transfer, q:

$$q = -\lambda(dm/dt) = h_o A_o \Delta T_m \tag{3}$$

where λ is the latent heat of vaporisation of liquid nitrogen, h_o is the overall heat transfer coefficient, A_o is the cross-sectional area of the sprayed surface, and ΔT_m is the mean temperature difference ($\Delta T_m = T_s - T_b$). Note that T_s is an arithmetic average of temperature measurements at five or more locations on the food surface. Since dm/dt, A_o and ΔT_m were measured, h_o can be computed. Hence, the specific heat flux (q/A_o) at the food surface can be determined from

$$q/A_o = h_o \Delta T_m \tag{4}$$

So by combining eqn 2 and eqn 3, we get

$$h_o = m\lambda/\Delta T_m \tag{5}$$

Equation 5 is of the same form as eqn (34) of a previous paper (Bonacina *et al.*, 1974), which was developed from a heat transfer model proposed by Baumeister *et al.* (1966), except that λ was modified to account for any superheating effect of vapour at the food surface. The modification would increase the value of λ by about 20% (Awonorin, 1982), and was also applied here.The average heat transfer coefficient of individual droplets (h_d) was estimated from the empirical equation proposed earlier (Awonorin & Lamb, 1988):

$$h_d = 13{\cdot}5\ \frac{K_v}{d}\left(\frac{\mu^2_v C_{p_v}\lambda}{K^2_v \Delta T_m}\right)^{0{\cdot}17}\left(\frac{d^3\rho_l\rho_v C_{p_v} g}{\mu_v K_v}\right)^{0{\cdot}25}\left(\frac{C_{p_v}\mu_v}{K_v}\right)^{1{\cdot}75}\left(\frac{\rho_v}{\rho_l}\right)^{0{\cdot}33} \tag{6}$$

The thermo-physical properties of liquid nitrogen, λ and ρ_l, were evaluated at the boiling point (−196°C), and C_{p_v}, K_v, ρ_v and μ_v evaluated at film conditions, i.e. $(T_b + T_s)/2$. Thus, eqn 6 entailed several thermo-physical properties of nitrogen, and can be reduced to a simpler expression:

$$h_d = C d^n_{32} \tag{7}$$

where C (physical properties-dependent) and n (power index of droplet's size influence) have values ranging from 112 and −0·187 (ΔT_m = 175 K) to 94 and −0·195 (ΔT_m = 100 K), respectively, with correlation coefficients ranging between 0·91 and 0·98 at 95% confidence level (Awonorin, 1993).In the precooling section, the heat transfer coefficient (h_c) was estimated using the measured values of air–nitrogen gas velocity (V_{an}) and the characteristic dimension of length (D) from the equation (Earle & Freeman, 1966) shown:

$$h_c D/K_v = 0{\cdot}032(\rho_v D V_{an}/\mu_v)^{0{\cdot}8} \tag{8}$$

(note that when the freezer is in operation, the precooling section will be filled with a substantial amount of nitrogen gas).

RESULTS AND DISCUSSION

Effect of product size and loading density

Table 2 summarizes the freezing schedule for the two freezers. As can be seen, there was a difference in product loading with respect to the usable dimensions of the conveyor belts as related to size of the products. In fact, the permissible number of pizzas per hour was 1408 and 700 for samples A and B in the tunnel freezer, respectively, in contrast to 1152 and 865 in the spiral belt freezer, respectively. Consequently, the total loading density of the tunnel freezer (39 kg m^{-2} h^{-1}) was about 25% higher due to the size and mass of products per unit area of the available belt surface. Hence, by production programming, the same flow rate of products (305 kg h^{-1}) was maintained in each freezer.

Temperature changes and freezing time

In order to enhance the performance of the cryogenic freezer, a substantial reduction of freezer temperature was necessary before the products were fed into the freezer to minimize the Leidenfrost effect (Dinglinger, 1975; Awonorin & Lamb, 1990). The freezing compartments of both freezers were cooled to −150°C in about 9 min at the start of experimental runs, and subsequently the temperature increased

TABLE 2
Freezing Schedule of Pizzas

Parameters	*Freezer type*			
	Tunnel		*Spiral belt*	
Pizza sample	A	B	A	B
Pizza mass (kg)	0·108	0·215	0·108	0·215
Number of pizzas per hour	1 408	700	1 152	864
Flow rate of pizzas (kg h^{-1})	152·06	151·6	123·72	184·61
Pizza loading density (kg m^{-2} h^{-1})	19·82	19·06	12·24	16·92
Liquid nitrogen flow rate (kg h^{-1})	171·8	176·9	143·0	188·6
Mass velocity of liquid nitrogen (kg m^{-2} h^{-1})	347·5	357·8	290·9	381·5
Ratio (mass of nitrogen used/mass of pizza)	1·13	1·21	1·11	1·06
Venting loss of liquid nitrogen				
Mass (kg)	486	550	378	368
Percentage of liquid nitrogen used (%)	5·38	5·67	4·22	4·35

to a maximum of −101 and −120°C in the tunnel and spiral belt freezers during freezing, respectively (Fig. 1).

From a nonstatistical observation, the rate of temperature fall at the product's surface and in the centre was higher in the spiral belt freezer (Fig. 1). The centre temperature fell at a rate of 1·77 and 2·1°C min^{-1} for samples frozen in the tunnel and spiral belt freezers, respectively. The corresponding values at the product's surface were 2·9 and 4·6°C min^{-1}, respectively, and were much faster. But generally, because of the high rates of product temperature changes in the two freezers, there was no distinct freezing plateau from the curves shown in Fig. 1. So the freezing time (t_f) was estimated as the time required for a change between 5 and −5°C at the thermal centre of the products (Awonorin, 1989b). However, the values of t_f, when considered between sample sizes (mass or diameter) and freezer type, were almost the same; these being 4·2 and 4·4 min for samples A and B in the tunnel freezer, respectively, and 4·1 and 4·2 min, respectively, in the spiral belt freezer. Indeed, the freezing time data (Table 3) may be said to vary directly with the mass of pizzas. These figures were within the specified t_f of 4 min for both pizza sizes using either of the two freezers.

Liquid nitrogen consumption

Generally, the mass velocity of liquid nitrogen sprays at the food surface (m^*) increased with increasing product loading density (m^*_p) as shown in Table 2, although with scattered data points. The two parameters are related by:

$$m^* = 105(m^*_p)^{0{\cdot}422} \tag{9}$$

(correlation coefficient $r = 0{\cdot}795$). This implied that the consumption of liquid nitrogen in the freezer increased as the supply of products increased, because a given quantity of products requires the extraction of a certain amount of heat by evaporation of the sprays.The relationship is somehow weak with regard to the overall heat transfer coefficient (h_o) in the freezer (Table 3), where:

$$h_o = 55(m^*)^{0{\cdot}21} \tag{10}$$

($r = 0{\cdot}42$). However, in agreement with eqn 5, an increase in h_o would also imply some increase in the value of m^*. Incidentally, from a study reported by Bonacina *et al.* (1974), m^* would be approximately 221·8 kg m^{-2} h^{-1} when computed using their heat transfer results, since they did not state the value of m^*. In that case, h_o would be 162 W m^{-2} K^{-1} using eqn 10. But this is in reasonable agreement with their value of 128 W m^{-2} K^{-1}; an overestimation by 20% even when the experimental conditions were not entirely the same.In this study, m^* was computed from the experimental data using eqn 2, where the values of dt were based on the actual spraying time (t), and so any losses due to the venting from the Dewar vessel and sprays which did not have any direct contact with the products were not included. Such effects were likely to influence the measured values of m^* and hence the experimental h_o values. Even then, the nozzle position was at a preselected impingement for effective coverage of the products. Unfortunately, because the pizzas were circular, there were unavoidable gaps between pizzas when the conveyor belts were loaded. Such practical problems were to be expected; however, it would appear that the computed values of m^* for the two freezers would be affected equally.

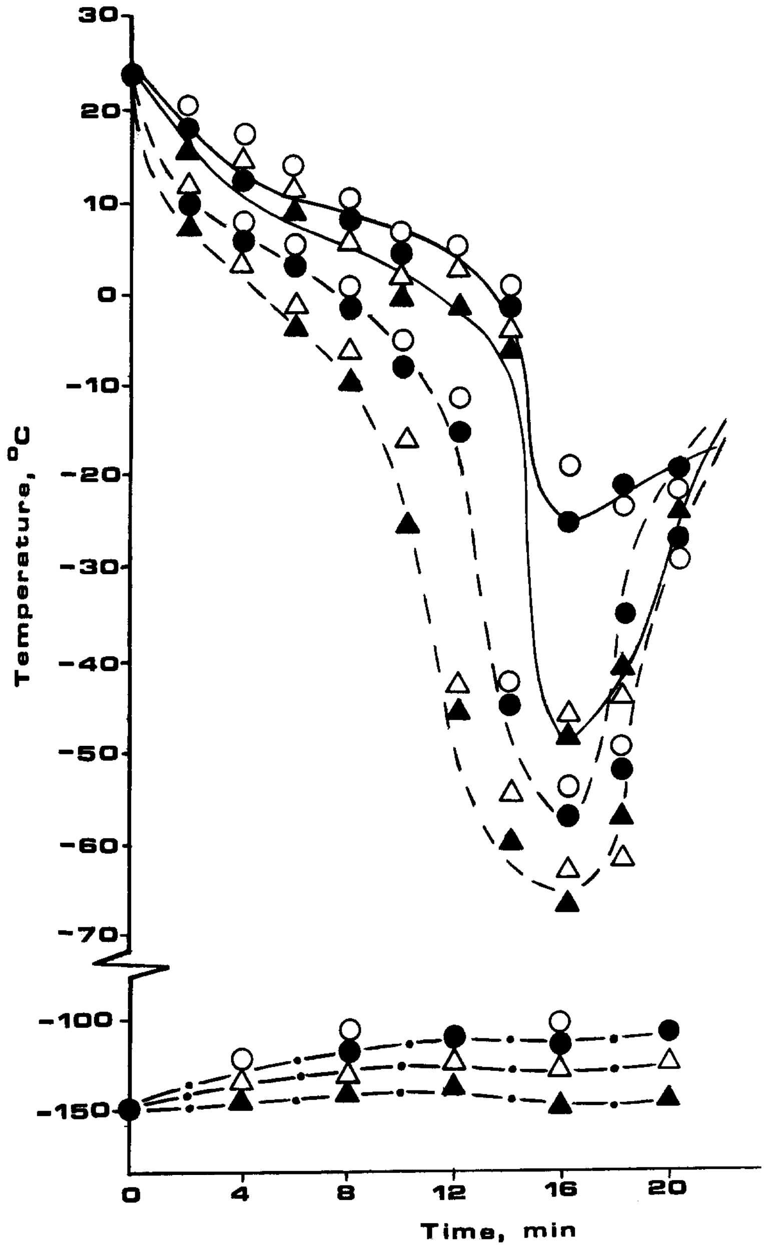

Fig. 1. Changes of product centre and surface temperatures of pizzas with time in the tunnel and spiral belt freezers using liquid nitrogen sprays. Data: —— and --- are the surface and centre temperatures of pizzas, respectively; — — • — — , freezer temperatures; ● and ○ are data points for samples A (128 mm diameter) and B (180 mm diameter) in the tunnel freezer, respectively; ▲ and △ are data points for samples A and B in the spiral belt freezer, respectively. All data points are shown, except where values overlap.

TABLE 3
Experimental heat transfer data for liquid nitrogen freezing of pizzas

Parameters	*Freezer type*			
	Tunnel		*Spiral belt*	
Pizza product				
Sample	A	B	A	B
Initial temperature (°C)	23	23	23	23
Surface temperature (T_s) (°C)	−56	−51	−68	−63
Centre temperature after precooling (°C)	2	−11	0	−33
Centre temperature after freezing (T_c) (°C)	−27	−24	−48	−40
Centre temperature after stabilization (°C)	−19	−19	−23	−21
Precooling zone temperature (T_p) (°C)	−35	−31	−40	−36
Freezing zone temperature (T_f) (°C)	−120	−115	−140	−125
Equilibration zone temperature (T_e) (°C)	5	5	5	5
Mean temperature difference[a] (ΔT_m) (K)	108	113	90	102
Freezing time (t_f) (min)	4·2	4·4	4·1	4·2
Heat transfer coefficient (W m^{-2} K^{-1})				
Precooling zone (h_c)	29	27	32	38
Individual droplets (h_d)	463	452	518	530
Overall average (h_o)	178	173	180	198
Heat flux (q/A_o) (W m^{-2})	19 224	19 624	16 200	20 500

[a]Mean value ($\Delta T_m = T_s - T_b$), where T_s is an average computed with consideration for T_f.

On the basis of the overall consumption of liquid nitrogen, in relation to the amount of products frozen (ratio of mass of liquid nitrogen to mass of products), the spiral belt freezer appears to be slightly more economical (Table 2). Typically, this ratio varied between 1·13 and 1·21 in the tunnel freezer, and between 1·06 and 1·11 in the spiral belt freezer (Table 2).

The venting losses from the Dewar vessel ranged from 5·4 to 5·7% and 4·2 and 4·4% in the tunnel and spiral belt freezers, respectively. These values are of the same order of magnitude as the 5 to 6% reported earlier (Awonorin, 1989b).

Heat transfer parameters

In Table 3, data are presented for the heat transfer coefficients computed: convective in the precooling zone (h_c); convective–conductive (h_d) in the freezing zone for the individual droplets, as a function of the mean droplet diameter actually reaching the food surface; and the overall (h_o), based on the total effect of evaporation from the sprays plus convection in the freezing zone. The radiation effect can be ignored at the temperatures encountered in this study (Awonorin, 1993).

In the precooling zone, h_c values were 28 and 35 W m^{-2} K^{-1} in the tunnel and spiral belt freezers, respectively, which represent only about 1/6 to 1/5 of h_o in both freezers (Table 3). Considering the slightly lower temperatures obtained in the spiral belt freezer (Table 3), it appears that the sensible heat of the cold nitrogen gas was utilized more efficiently, because the rate of liquid nitrogen consumption (Table 2) was also lower than that of the tunnel freezer.

The calculated heat transfer coefficients (h_d) between the food surface and individual droplets using eqn 7 with a Sauter mean droplet diameter of 126×10^{-6} m ranged from an average of 457 W m^{-2} K^{-1} in the tunnel freezer to 525 W m^{-2} K^{-1} in the spiral belt freezer. These values were much higher than those reported (300 to 360 W m^{-2} K^{-1}) for liquid nitrogen droplets at rest on a gelatine slab surface (Awonorin & Lamb, 1988). The effects of droplet impingement and moisture contamination with the sprays might be responsible for the differences as explained elsewhere (Keshock & Bell, 1970; Schoessow *et al.*, 1978; Awonorin, 1982).

The overall heat transfer coefficients (h_o) in the two freezers (173 to 198 W m^{-2} K^{-1}) were higher by about 26 to 35% than the 128 W m^{-2} K^{-1} reported for a typical cryogenic freezer (Bonacina *et al.*, 1974). However, allowing for correction of droplet size due to evaporation between leaving the nozzle and reaching the food surface, the value reported by Bonacina *et al.* (1974) would increase since h varies directly as $\bar{d}_{32}^{-0.2}$ (Awonorin, 1993). This might be expected to reduce the observed difference, but according to the heat transfer model proposed by Bonacina *et al.* (1974), the difference between h_o and h_d was due to a steady state coverage factor (ε), and so:

$$h_o = \varepsilon h_d \tag{11}$$

Typical values of ε ranged between 0·13 and 0·19. But from this investigation, values of ε were much higher (0·35 and 0·38). A number of factors might be responsible for this difference, and will be discussed later. Even then, the computed h_o values are generally of the same magnitude as those reported (225 W m^{-2} K^{-1} on an average basis) in the companion paper on freezing with liquid nitrogen sprays (Awonorin, 1989a).

Qualitatively, the heat flux density (q/A_o) increased as h_o and ΔT_m increased as expected (Table 3), but the magnitude of h_o would also depend on the accurate measurement of m^*.

Physical, microbiological and sensory qualities

The thaw drip of samples frozen in both freezers was of the same magnitude, but negligible in practice. These were 0·55% in the spiral belt freezer and 0·6% in the tunnel freezer (Table 4).

The level of mcirobial contamination or destruction was assessed from the total colony count. The initial average count for the unfrozen samples was $29{\cdot}2 \times 10^3$, and at the end of freezing was $4{\cdot}8 \times 10^3$ (Table 4). This indicates a six-fold microbial damage, and is comparable with the results of Pickett and Miller (1967) on liquid nitrogen (immersion) freezing of turkey carcasses.

The sensory evaluation results are presented in Table 4. The samples frozen in the spiral belt freezer were significantly different ($P < 0{\cdot}05$) from those frozen in the tunnel freezer on visual appearance, although panelists did not detect any significant difference ($P > 0{\cdot}05$) among all the samples based on textural feel when samples were thawed. The latter observation was not surprising since the freezing time of all the samples was generally the same (Table 3), and any freezing damage to the structure of the products which could affect the texture was bound to affect samples from both freezers in the same manner. On the contrary, however, the visual appearance of samples frozen in the spiral belt freezer (Table 4) was preferred ($P < 0{\cdot}05$).

TABLE 4
Thaw Drip, Total Colony Count and Sensory Evaluation Results

Parameters	*Freezer type*			
	Tunnel		*Spiral belt*	
Pizza sample	A	B	A	B
Thaw drip (%)	0·63	0·56	0·59	0·52
Total colony count ($\times 10^3$)				
Initial	28·72	29·55	29·08	29·24
Final	4·56	4·93	4·76	4·87
Mean sensory scores[a]				
Visual appearance[b]	6·8a	7·3ab	8·1b	8·2b
Textural feel[c]	7·6	7·8	7·7	7·9

[a]Means in the same row bearing different letters differ significantly ($P < 0{\cdot}05$).
[b]Frozen state.
[c]Thawed state.

Technical and operational considerations

It can be seen from the present data (Table 2) that the mass velocity of the refrigerant (m^*) is a critical factor in the operation of these freezers. It is evident, from eqn (5), that h_o depends on m^* and so h_o can be improved through the use of higher spray pressure, which would decrease the mean droplet diameter, d_{32} (since $h_o \propto d_{32}^{-0{\cdot}2}$). Therefore, it follows that the width of the belt can be effectively reduced by simply increasing the usable belt length through several tiers ($N = 10$) in the spiral belt freezer for the same throughput. But if products are stacked on one another on the belt to increase the loading density, the overall performance of the freezing plant would decrease as a result of poor spray contact.

It should be noted, however, that an increase in the spray pressure means more m^* would also be delivered per unit time with a change of spray geometry and increased losses of droplets from the food surface. But for a given throughput, a certain amount of m^* is required, whether it is supplied slowly or rapidly, but it can be used more efficiently, especially in lowering the temperatures in the precooling and freezing zones as in spiral belt freezer (Table 3). In this regard, the location of the spray nozzles for maximum coverage of the food surface with sprays, efficient use of the cold gaseous nitrogen for precooling and keeping the freezer temperature below $-100°C$, in order to minimize the Leidenfrost effect, are among the factors which could enhance the freezer performance. Similarly, an increase in spray pressure may lead to a decreased coverage effect since droplet sizes would be reduced (Bonacina *et al.*, 1974); the thermodynamic efficiency of the refrigerant and venting losses from the Dewar vessel would also decrease (Awonorin, 1989b).

CONCLUSIONS

A comparative study of the performances of spiral belt and tunnel freezers has been carried out using controlled variables to evaluate some existing models. The overall conclusions drawn from this investigation are summarized as follows:

(1) The overall heat transfer coefficient in the spiral belt freezer was slightly higher than the tunnel freezer using the same throughput. This was probably due to the economic usage of the cold nitrogen gas for precooling, and lower mean temperature difference which, perhaps, also minimized the Leidenfrost film boiling effect and enhanced the overall heat transfer coefficient. This coefficient ranged from about $175\ \mathrm{W\,m^{-2}\,K^{-1}}$ in the tunnel freezer to $190\ \mathrm{W\,m^{-2}\,K^{-1}}$ in the spiral belt freezer, whilst maintaining between -140 and -150°C in the freezing section of the two freezers.
(2) The convective heat transfer coefficient in the precooling sections of the two freezers was only about 1/6 and 1/5 of the overall heat transfer coefficients in the tunnel and spiral belt freezers, respectively.
(3) The average convective–conductive heat transfer coefficients of the individual droplets were rather large, when compared with the corresponding overall heat transfer coefficients. These were 458 and $525\ \mathrm{W\,m^{-2}\,K^{-1}}$, and about 262 and 276% higher than the overall heat transfer coefficients in the tunnel and spiral belt freezers, respectively.
(4) The local mass velocity of liquid nitrogen used varied directly as the loading density of products, and also influenced the overall heat transfer coefficients in the two freezers. The ratio of the mass of refrigerant consumed to the mass of products being frozen was of the order of 1·17 and 1·09 in the tunnel and spiral belt freezers, respectively. The loss of refrigerant due to venting in the Dewar vessel was estimated to be about 5%.
(5) The average freezing time (t_f) for the two pizza sizes in any of the freezers was about 4·5 min, and appeared to vary directly with sample mass or diameter.
(6) In terms of product qualities, the drip losses were very low (0·55 to 0·6%) and microbial destruction due to the freezing effect was of the order of six-fold in the two freezers. The sensory scores showed no significant difference ($P > 0{\cdot}05$) among all samples on textural feel. However, the samples frozen using the spiral belt freezer were significantly different ($P < 0{\cdot}05$), and preferred on visual appearance.

FUTURE RESEARCH NEEDS

There is need to consider a model for optimizing the freezing process with regard to the operating variables of typical cryogenic freezing equipment. The author is already doing some work in this area.

ACKNOWLEDGEMENTS

The author wishes to thank Mr Roy Chambers and Mr David Goodhew of Humber McVeigh Refrigerated Transport Ltd, South Humberside Industrial Estate, Grimsby, South Humberside DN31 2TD, UK for allowing the use of their liquid nitrogen units.

REFERENCES

Anon, (1969). Food freezing with liquid nitrogen. *Food Technology in New Zealand*, **5**, 1 7–19.

Awonorin, S. O. (1982). Heat transfer to liquid nitrogen droplets during cryogenic refrigeration of foods. PhD Thesis, The University of Leeds, Leeds, UK.

Awonorin, S. O. (1988). Evaporation rates of freely falling liquid nitrogen droplets in air. *Heat Transfer Engineering*, **10**, 1 36–46.

Awonorin, S. O. & Lamb, J. (1988). Measurements of heat transfer coefficient for nitrogen droplets undergoing film boiling on a food surface. *International Journal of Food Science and Technology*, **23**, 4 391–401.

Awonorin, S. O. (1989a). A model for heat transfer in cryogenic food freezing. *International Journal of Food Science and Technology*, **24**, 3 243–259.

Awonorin, S. O. (1989b). Determination of the performance of a cryogenic freezer. *ASHRAE Transactions*, **95**, 1 125–30.

Awonorin, S. O. & Lamb, J. (1990). The Leidenfrost phenomenon: Experimental investigation of the vaporization of nitrogen droplets on a food surface. *Journal of Food Science*, **55**, 3 808–16.

Awonorin, S. O. (1993). Analysis of the heat transfer coefficient for liquid nitrogen droplets in cryogenic freezing of foods. *International Journal of Refrigeration*, **16**, 2 143–51.

Baumeister, K. J., Hamill, T. D. & Schoessow, G. J. (1966). A generalised correlation of vaporisation times of drops in film boiling on a flat plate. In *Proceedings of 3rd International Heat Transfer Conference*, Chicago, American Institute of Chemical Engineering, Vol. 4, pp. 66–72.

Bonacina, C., Comini, G. & Del Giudice, S. (1974). Evaporation from cryogenic liquids sprayed on flat surfaces. In *Proceedings of 5th International Conference*, Tokyo, Vol. B3.11, pp. 130–34.

Briley, G. C. (1980). Energy cost comparisons: cryogenic vs freezing systems. *ASHRAE Journal*, **December**, 30–32.

Davidge, H. (1973). Cryogenics and catering. *Modern Canteen Catering*, **November**, 4

Davidge, H. (1974). Commercial cryogenic processes used for meat freezing. In *Meat Freezing—Why and How?* Meat Research Institute Symposium No. 3, ed. D. L. Cutting. Agricultural Research Council, MRI, Langford, Bristol, 23–24 April, pp. 31.1–31.3.

Dinglinger, G. (1975). Deep freezing of foodstuff with boiling nitrogen. *Kaelte Hamburg*, **28**, 9 320–26.

Dorney, D. C. & Glew, G. (1974). Some observations on the use of liquid nitrogen for freezing precooked food. *Refrigeration and Air Conditioning*, **September**, 26–36.

Earle, R. L. & Freeman, N. W. (1966). Continuous tunnel freezing of boneless meat in cartons. *International Institute of Refrigeration*, **Annexe 1966-1**, 663–69.

Holdsworth, S. D. (1967). Cryogenic freezing. *Food Manufacture*, **July**, 42–47.

Keshock, E. G. & Bell, K. J. (1970). Heat transfer coefficient measurements of liquid nitrogen drops undergoing film boiling. *Advances in Cryogenic Engineering*, **15**, 271–82.

Leidenfrost, J. G. (1756). *De Aquae Communis Nonullis Qualitatibus Tractatus.* Duisburg (translated by C. Wares); *International Journal of Heat and Mass Transfer*, **9** (1966) 1153.

Picket, L. D. & Miller, B. F. (1967). The effect of liquid nitrogen freezing on the taste, tenderness and keeping qualities of dressed turkey. *Poultry Science*, **46**, 1148–53.

Reynoso, R. O. & De Michelis, A. (1988). Simulation of cryogenic batch freezers. *International Journal of Refrigeration*, **11**, 6–10.

Schoessow, G. J., Chmielewski, C. E. & Baumeister, K. J. (1978). Effect of ice contamination on liquid nitrogen drops in film boiling. *Advances in Cryogenic Engineering*, **23**, 295–300.

Steel, R. G. D. & Torrie, J. H. (1960). *Principles and Procedures of Statistics.* McGraw-Hill, New York.