AIR BLAST FREEZERS AND THEIR SIGNIFICANCE TO FOOD FREEZING: A REVIEW

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Abstract. *Air blast freezers are used extensively throughout the world to freeze various food commodities from carcasses to packaged goods. They are popular within the freezing industry due to their versatility to freeze items of any shape and size. The original air blast freezer was designed and patented in New Zealand around 1950. Although there are numerous forms of air blast freezers available today, the fundamental principles of the initial design have changed little over the last 50 years. This paper presents a review of air blast freezers and their significance to the food freezing industry in terms of energy consumption. Different forms of modern blast freezers are discussed along with blast freezer design and a best practice guide.*

Keywords*: blast freezer, batch, refrigeration, energy*

1. INTRODUCTION

Air blast freezers are used to freeze food commodities from a chilled temperature to their desired storage temperature (product dependant) with air temperatures between -35°C and -45°C. Typically, the freezing time varies from 12-48 hours. Slow freezing produces large ice crystals, which grow through cell walls, permitting an accelerated penetration of oxygen, causing rancidity and browning of meat and enhancing the danger of higher drip on thawing. Therefore, rapid freezing is required to maintain food quality as it produces small ice crystals due to a higher number of nucleation points from which ice crystals form.

Air Blast freezing is classified as a forced convection phenomenon where the use of fans increases the products surface heat transfer coefficient and produces a more uniform air temperature throughout the freezer. However, the large fans required, add significantly to the total heat load on the refrigeration system. Unwrapped foods are prone to moisture loss during blast freezing as the absolute humidity of the bulk air is usually lower than that of the air at the surface of the food.

A typical blast freezing refrigeration system consists of a compressor, condenser, expansion valve, evaporator and fans. The compressor(s) that are used in such systems vary between sites. Older systems tend to use single stage or two stage reciprocating compressors, while the current trend is towards screw compressors due to lower maintenance costs.

Although air blast freezers have been used in industry since the 1950's, limited number of technical studies have been published on specific aspects of the topic in the open literature [2, 13, 25, 27, 32, 43, 50, 51], and there is hardly any study that summarises all aspects of blast freezers at one point in a single study. This paper, therefore, presents an overview of blast freezers in view of their historical background, different designs, working principle, energy saving measures and a best practice guide.

2. BLAST FREEZERS AND THEIR ORIGIN TO NEW ZEALAND

In 1882 New Zealand's refrigerated food trade started when carcasses from Oamaru were loaded aboard the S.S Dunedin and frozen using a steam engine powered air cycle refrigeration system [1]. The system worked by cooling compressed air and decompressing it to create a cold air stream which was blown over the carcasses. Initially New Zealand's refrigeration was done entirely on ship. However, there was clearly an economic advantage to freezing on land as this would free up space on the ships to store more cargo. The early freezing rooms typically consisted of bare pipe grids in the ceiling above rails on which sheep carcasses and beef quarters were hung. These freezing rooms relied on the natural convection of cold air, typically around -15°C, and resulted in freezing times up to three days.

Following World War II the world faced a serious food shortage. With a superb climate for agriculture New Zealand was well suited to meet this food demand. A major New Zealand innovation was the air blast freezer which enabled rapid freezing for high export quantities. The air blast freezer used fans to blow air at low temperatures (down to -30°C) over carcasses reducing freezing times to between 10 and 24 hours. This ability to freeze and transport food to distant markets made refrigeration a highly profitable trade and in fact made New Zealand one of the richest countries in the world in the 1950's and 1960's.

The New Zealand company Ellis Hardie Syminton Ltd patented the A189 air-blast freezer in about 1950 [2]. The concept was to use finned surface evaporators to cool the air and large fans to direct the refrigerated air over the carcasses. During the 1950's blast freezing became the dominant method of freezing worldwide and the fundamental principles of carcass freezing changed little over the next 50 years. Prior to the 1950's the beef trade was dominated by quarter beef carcasses. The emergence of the hamburger in America opened a new the market for frozen boneless beef suitable for direct processing. In response to the new boneless product demand, Ellis Hardie Syminton Ltd. in conjunction with Bill Freeman constructed the world's first continuous carton freezer for 27.2kg beef cartons near Palmerston North (New Zealand). The freezer blew refrigerated air as low as -40°C at a velocity around 3 m/s over the cartons and achieved freezing times of 24 hours. Over the next 20-30 years the air-blast freezer became universal in the New Zealand frozen food industry. Several variations were developed, including cross flow and vertical air flow systems and there was a move from batch to continuous production for larger through puts and reduced labor costs. By the 1980's, energy efficiency became an important design parameter. Many potential energy saving initiatives were investigated in terms of both the refrigeration system and the system as a whole, including improved air flow design by altering the product stacking arrangement and the use of baffles and turning vanes, varying the air velocities at different times throughout the freezing process and the effect of product packaging on freezing times. The easiest and most advantageous energy saving device today is the use of variable speed drives (VSD's) on evaporator fans.

3. WHY AIR BLAST FREEZE?

The killing of bacteria is largest in the range -4°C to -10°C due to 'cold-shock,' where their metabolism is disturbed, even stopped. When the freezing rate is slow, the bacteria have time to adapt to the new conditions; hence food must be frozen quickly. There are various methods available for food freezing; these include: air-blast freezers (batch and continuous), fluidized bed freezers, impingement freezers, liquid immersion freezers, plate freezers, liquid nitrogen freezers and carbon dioxide freezers. The major advantage of the air blast freezer is its versatility. Since air is a low viscosity fluid it has the ability to easily follow around irregular surface geometries, thus providing a more uniform freezing rate over the whole product. Other freezing methods such as plate freezing (contact freezing) offer faster cooling times [3] but can only be used with products of a suitable geometry, i.e. a flat surface to match the plate bed.

4. MODERN AIR FREEZER DESIGNS

Air is the most widely used method of freezing food as it is economical, hygienic and relatively non-corrosive to equipment [4]. Various forms of air blast freezers are used in industry [5-17].

1. **Sharp freezer**: or blast room freezer is a cold storage room that relies on natural convection to circulate the cooling air resulting in slow freezing times. This arrangement is sometimes used for bulk products like butter, beef-quarters and fish, but not for processed food products.
2. **Tunnel freezers**: refrigerated air is circulated by large fans over the product confined in an insulated closed room. Meat carcasses are supported by hooks suspended from a conveyor or specially designed racks. The trays or spacers are arranged to provide an air space between each layer of trays. The air can either be cross flow or counter flow, depending on the type of tunnel freezer. Various forms of tunnel freezers exist including:
   2a. **Batch Freezers:** where the product is stacked on pallets (see Figure 1), or hung from hooks in the case of carcasses, and loaded into the freezer using fork hoists. This is an on/off process where the freezer is loaded, run until the meat is frozen to its desired temperature, and then switched off for unloading. Batch blast freezers are best suited for small quantities of varied products [18]. Typically, the heat transfer coefficient is less than 50 W/m²K.

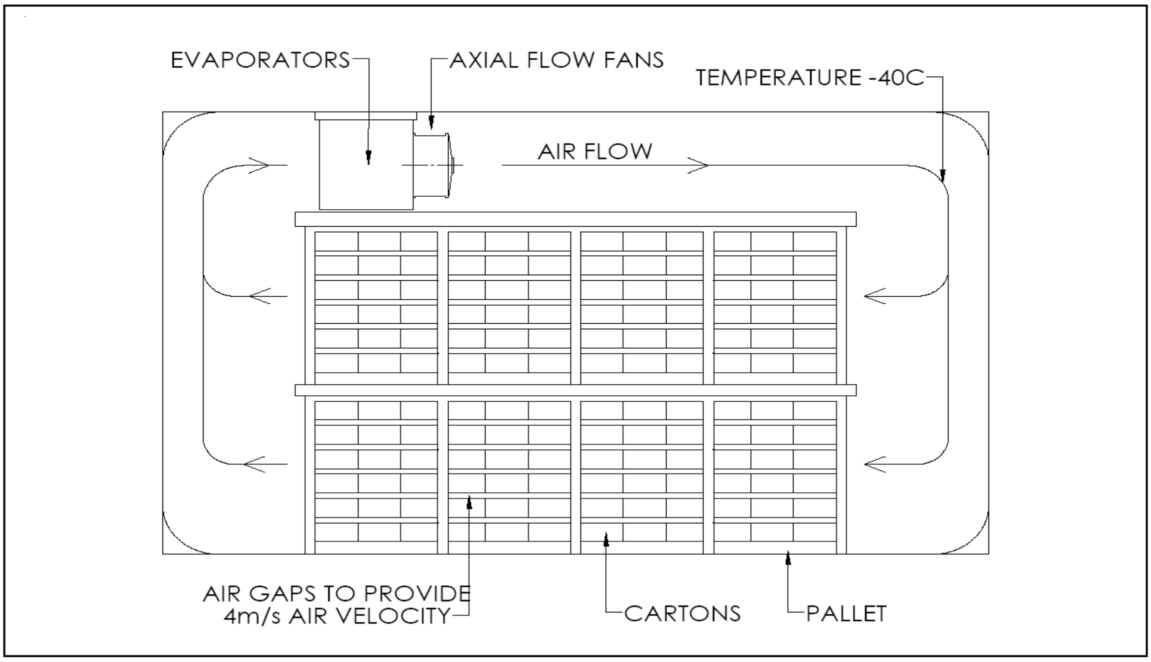

Figure 1: Schematic of a typical batch blast freezer

2b. **Mechanized freezers**: where the pallet racks are fitted with casters or wheels. The racks or trolleys are usually moved on rails by a pushing mechanism, usually hydraulically powered. Such mechanized tunnel freezers are known as push-through tunnels or carrier freezers which have two tiers, one on top of the other. These freezers are designed primarily for packaged goods, as well as carcasses.
Advantages of mechanized freezers over batch freezers include: improved air circulation over the product as it moves at a steady rate through the tunnel; labor costs are considerably decreased as pallets are not manually placed in the freezer; and there is added flexibility of the facility by varying the freezing time with the speed of the ram [19]. Heat transfer coefficients in mechanised freezers are similar to batch freezers being less than 50 W/m²K.

2c. **Belt freezers**: where the product is loaded on a continuous conveyor belt. Modern belt freezers typically employ vertical air flow to force air through the product layer creating good contact with the product. Typically, the heat transfer coefficient of belt freezers varies between 25 and 80 W/m²K. Belt freezer offer the advantage of smaller floor space compared to single belt freezers. There are several forms of belt freezers:

i) **Multi-tier belt freezers**: consist of several conveyor systems positioned one above the other with fans and coils positioned above the top belt. The air flow in belt freezers can either be vertical or horizontal over the product. The most efficient flow is determined by the product characteristics, dimensions, packed or unpacked, as well as degree of processing and composition.

ii) **Spiral belt freezers**: where the belt is coiled in numerous revolutions around one vertical central axis to optimize the use of floor space (see Figure 2). The belt can stack 30 tiers or more, one above the other reducing floor space to a minimum. Spiral freezing is one of the most currently used methods in the freezing industry for large production needs because of its convenience, reduced floor space, flexibility and efficiency [20].

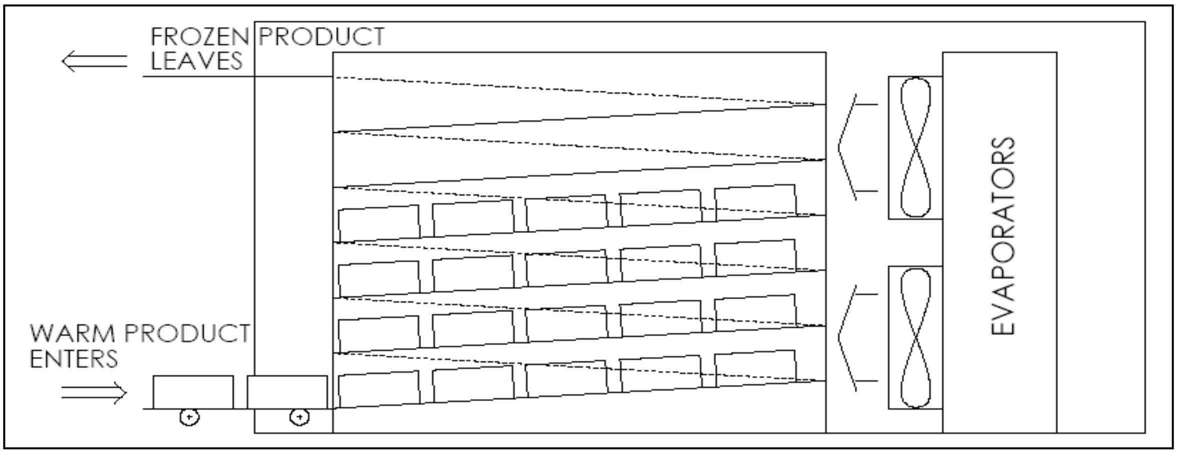

Figure 2: Schematic of a typical spiral Belt freezer

3. **Fluidized bed freezers** (see Figure 3) are used to freeze particulate foods of uniform size and shape such as peas, cut corn, diced carrots, and strawberries. The foods are placed on a mesh conveyor belt and moved through a freezing zone in which cold air is directed upward through the mesh belt and the food particulates begin to tumble and float. This tumbling exposes all sides of the food to the cold air, thus the product is individually quick frozen (IQF). Typically, heat transfer coefficients range from 110 to 160 W/m².

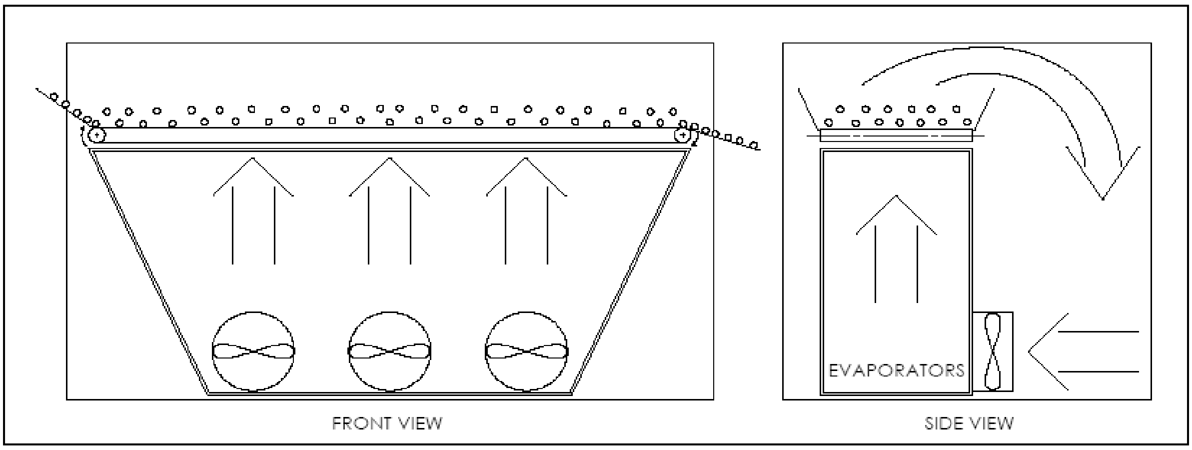

Figure 3: Schematic of a fluidized bed freezer

4. **Impingement jet freezers** are straight-belt freezers involving only one step where the top, or more generally, both faces of the product receive very high velocity air at low temperature via uniformly distributed nozzles. The jets break the stagnant boundary layer surrounding the product, leading to a considerable increase in the heat-transfer coefficient, up to 300 W/m²K. The performance is comparable to cryogenic freezers in relation to freezing time and weight, but at a much lower cost (typically half the price).

Table 1 summarizes the characteristics and operating parameters of the freezers described above. The cooling air temperature for each freezers ranges between -30 and -45°C. With similar cooling air temperatures, it is the air velocity over the product that is the main factor affecting the heat transfer coefficient.

Table 1: Summary of forced convection freezing methods

Freezer type	Product	Air Velocity	H.T.C.* $W/m^2°C$	Capacity	Advantages	Disadvantages
Batch tunnel	Useful for all foods but better for bulk items, particularly carcasses	1.5-6m/s Typically ≈ 4m/s	h < 50 [21]	1-80 tones	i) Low capital cost ii) Versatile, can accommodate various product geometries	i) Long freezing times ii) Relatively low H.T.C*.
Continuous tunnel	Useful for all foods but better for bulk items.	1.5-6m/s Typically ≈ 4m/s	h < 50 [21]	1000-20,000 kg/hr	i) Reduction in down time as the freezer is not stopped for loading ii) Flexible with freezing times	i) Requires additional space ii) Reduced freezing capacity due to frost on evap. coils
Spiral	Suitable for most foods, packaged or unpackaged e.g. poultry, red meat, sea.	3-8m/s	h ≈ 25-80 [22]	500-6000 kg/hr	i) Compact ii) Capable of IQF iii) Higher efficiency than tunnel	i) More expensive than tunnel freezers ii) Hygiene issues
Fluidized bed	IQF small products, 0.5 to 5 cm diameter, e.g. peas, French fries, shrimp,	≈30m/s	h ≈ 110-160 [22]	100 - 20,000 kg/hr	i) Very fast freezing times, comparable to cryogenic only cheaper ii) High efficiency	i) Only suitable for small products of fairly uniform shape and size
Impingement	IQF. Meat patties, fish fillets, Product thickness typically 0-25mm[1]	10-100m/s Typically ≈ 40m/s	h ≈ 250-350 [22]	up to 1200kg/hr	i) Reduced moisture loss ii) Very fast freezing times, similar to cryogenic	i) Only suitable for products of small thickness

***Heat transfer coefficient**

5. CONSUMABLES COMMONLY AIR BLAST FROZEN

Selecting which freezing method to use is usually determined by quality specifications, economics and availability. Each food product has its own unique characteristics which determine their appropriate freezing temperature and freezing rate. Typical products frozen in air blast freezers include but are not limited to:

- Meat - carcasses, cartons, large individually wrapped cuts, cured or processed, hamburger patties
- Poultry - whole bird or pieces, processed or breaded products
- Fish – whole or eviscerated, fillets or small diced pieces, processed or breaded products, shellfish, prawns and shrimp
- Fruits – small size (whole), large size (sliced), purée or pulp
- Vegetables – small and medium size, leafy
- Other – Cheese and butter, dough, bread and baked products, pre-cooked ready meals

6. PRODUCT PACKAGING

It is common practice to freeze meat or fish products in their transport packaging. Packaging is important in air blast freezing as it prevents dehydration, freezer burn and adherence by freezing and oxidation. The detriment of packaging is a decrease in heat transfer and hence an increase in the freezing time due to the insulating properties of the packing material and excess enclosed air. Figure 4 shows a typical temperature versus time graph of packaged and unpackaged meat products in an air-blast freezer.

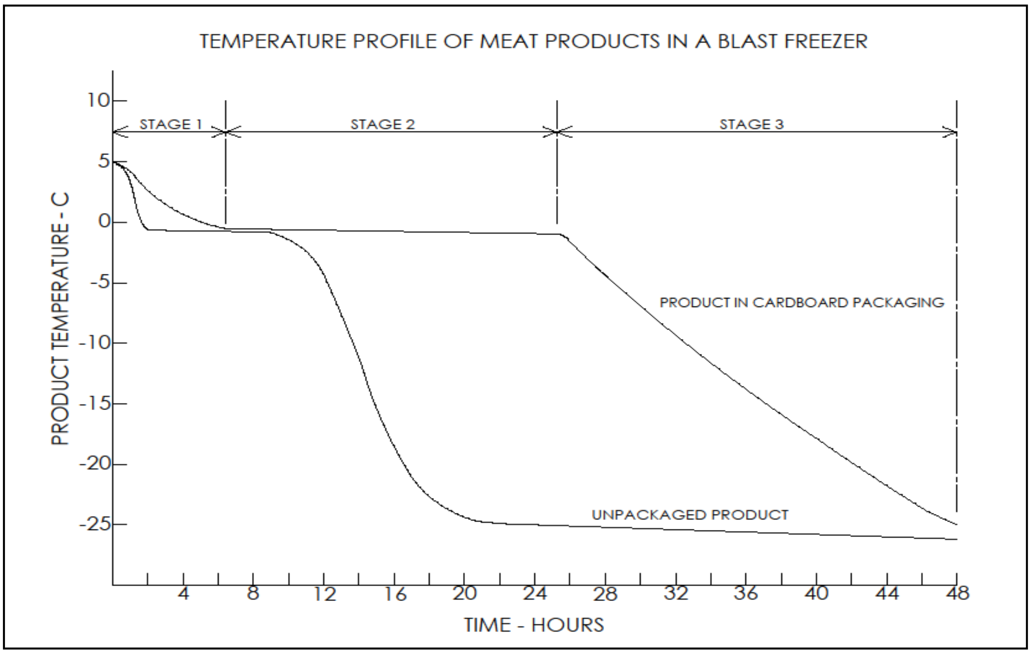

Figure 4: Freezing curves for packaged and unpackaged meat product in an air blast freezer

Figure 4 clearly illustrates the increased freezing time as a result of packaging. Stage 1 refers to the sensible cooling from the product inlet temperature (usually chilled) to freezing, stage 2 the latent heat extracted during crystallisation, and stage 3 the sensible cooling from the freezing temperature to the desired storage temperature. Table 2 shows the heat transfer resistance of packaging for frozen beef and fish that can account for up to 59% of the total resistance when fish is the product being frozen. For beef, the portion of heat transfer resistance from packaging is less at 38%, but still significant.

Food Packaging must perform three functions: i) Control the local environmental conditions to enhance storage life. This is usually met by the packaging layer closest to the food. Typical examples include sealed plastic film and tin-plated cans. ii) Display the product in an attractive manner for the potential buyer. iii) Protect the product during handling and transit. Corrugated cardboard is commonly used which unfortunately is a very good insulator. To reduce freezing times, cartons should use single layer cardboard with a high heat transfer coefficient on the top and bottom as this is where the surface area is largest.

Table 2: Heat transfer resistance of packaging [23]

	Heat transfer resistance (m^2K/W)	
Source of heat transfer resistance	**Frozen fish**	**Frozen beef**
Convective boundary layer external to carton	0.04	0.04
Carton wall	0.06	0.02
Nominal 1mm layer of trapped air between carton and product	0.04	0.04
Product itself between surface and geometric centre	0.03	0.06
Total	0.17	0.16
Heat transfer resistance due to packaging system (%)	**59**	**38**

7. AIR BLAST FREEZER DESIGN AND CURRENT DEVELOPMENTS

Air blast freezers are designed to supply cool air over the food product with a uniform air velocity throughout the freezer. Air blast freezer design is covered extensively in references [24-29]. Most operation problems are related to improper positioning of the pallet or cart in the freezer [30]. Therefore it is imperative the pallets and product is stacked in such a way that the air is free to move over the entire product. The stacking method must enable the cold air to circulate between the trays or boxes unhindered. For carton freezing, a spacer up to 70mm should be implemented to allow sufficient air velocity between cartons [31]. Boast [19] recommends an air space equal to approximately 50% of the product thickness. Air temperature must be at least -35°C, and in some cases -45°C [32]. This equates to a refrigerant evaporation temperature of -42°C and -52°C respectively.

For batch freezers, the literature offers several optimum air velocities dependent on the particular product being frozen. The generally accepted figure is 4 m/s. Although increasing the air velocity will increase surface heat transfer coefficient, it does not necessarily reduce cooling time due to the increase heat load from the fans because fan power, $W \propto V^3$. This increase in fan power increases the running cost usually rendering the increased fan speed uneconomical when compared to slower speeds. Kolbe *et al.* [33] showed that increasing the air velocity above 5 m/s only barely increased the freezing rate. This is because partway through the freezing cycle when the surface layers are frozen, the rate of heat transfer is increasingly controlled by the internal conduction resistance, i.e. the Biot number becomes large.

When sizing evaporators, a frost build-up factor must be considered with fin spacing of no more than 4 fins per inch, Bowater [34]. When air coolers are mounted above a false ceiling, logarithmically spaced air deflectors can be installed to help deflect the air through the 90° turns and help distribute a uniform airflow over the products. Typical batch carton freezers in New Zealand meat plants hold up to 80 tones of meat in 27kg export cartons and operate on a 48 hour scheme of which 44 hours is devoted to freezing. Air is usually forced through the product and evaporators placed at the opposite end from the loading section, then returned through a false ceiling, see fig. 1.

Modern spiral freezer designs eliminate any type of structure and belt support and each tier is supported directly on the previous one (self-stacking belt). The temperature of the refrigerated air is below -30°C, generally being closer to -40°C, with a circulation velocity ranging from 3 to 8 m/s. In simple designs the air flow direction relative to the belt can be horizontal, parallel or vertical (both upwards and downwards). Further design improvements implementing the use of baffles and flow dividers can provide air flow vertically upwards through the lower half of the stack and downwards through the upper half (controlled dual flow). This balances the heat transfer on the two sides of the food, and slightly decreases freezing time and weight loss.

The current state of the art developments are focused on impingement freezers, dual air systems [35] and improving the air flow distribution throughout air blast freezers with the aid of computational fluid dynamics (CFD). Various studies devoted to the application of CFD to air blast freezers have been performed, references [36-43]. CFD delivers detailed information – both in time and space – of the flow field, the temperature and moisture distribution, the shear forces and the heat fluxes. Furthermore, computer visualization gives a direct insight in the process, which allows a fast interpretation of any possible problem. Finally, the model-based procedure allows the evaluation of many *what if* scenarios at little cost compared to the process of prototyping.

8. PRODUCT GEOMETRY

Product geometry plays a significant role in determining freezing time. Most meat plants use a standard carton depth of 160-165 mm. A reduction in carton depth can significantly reduce freezing time. The most important areas of the carton are the top and bottom as this is where the surface area and hence heat transfer is largest.

A New Zealand meat company decided, for logistic purposes, that the base dimension of their meat cartons should be the same. To maintain a constant weight for each carton, the carton's height was varied to cater for different product densities. A. Cleland [23] investigated the effects of the different carton heights on freezing time and found freezing time varied between a linear and a quadratic relationship with height if the air convection heat transfer coefficient was not changed. The tall cartons obstructed the air flow channels in the freezer more than the short cartons, thus they had less air flow over them.

Tan *et al.* [44] set out to determine the factors affecting the freezing process of tilapia fillets of different geometries. A numerical model based on the continuity equation, momentum equations and energy equation was developed. Five different geometries of equal mass were tested, three fish cakes and two spherical: slab, elliptical, disc, spherical and cylindrical respectively. The freezer's air velocity was set at 5 m/s and temperature at -35°C.

The three fish cakes had very similar freezing times ranging from 1.167 (disc) to 1.233 hours (slab) due to their similar thickness and surface area. The freezing time for the sphere was 3.7-3.9 times longer than that of the flat shaped fillets due to the difference in surface area and distance from surface to centre. The cylindrical shaped fillets produced the longest freezing time of 5 hours.

9. ENERGY USAGE AND ENERGY SAVING POTENTIALS

Air blast freezing consumed 8.1 GWh of electricity in New Zealand in 2005 [45] and is the most energy intensive operation in the in the frozen storage industry. Apparent energy use for blast freezing was calculated as 133 kWh/tonne from regression analysis. This is 50% higher than the predicted value from theoretical best practice considerations.

The New Zealand Cold Storage Industry identified blast freezing as an area where a 15% saving could be achieved for many sites, particularly related to reduction in fan power due to improved air flow design. Comparison with overseas survey results showed the NZ use was similar on average. If all facilities surveyed met the theoretical best practice energy consumption limit for blast freezing, this would represent an average energy saving of 33% per tonne of blast frozen product. This figure is supported by a survey on energy efficiency of food refrigeration operations funded by the UK Government Department for Environment, Food and Rural Affairs (defra), who identified blast freezing as an area where a 20-30% energy saving could be achieved [46].

The New Zealand survey covered 13 sites that carried out blast freezing and recorded data over the duration of at least one year. These sites have a wide range of refrigeration systems from multi-stage pump circulation ammonia to single stage direct expansion fluorocarbon systems. The most common refrigerant was ammonia, used at 71% of the sights.

The following measures were identified as potential energy saving solutions:

- Reduce discharge pressure set points
- Raise suction pressure set points
- Variable speed drives (VSD's) for fans
- Improved door protections and management
- Optimise defrost frequency and duration

Other measures to improve blast freezing efficiency include:

- Improve air flow design to reduce fan power for the same effective air velocity over the product, e.g. use of air turning vanes, flat inlet and outlet cones, baffles to prevent air flow short circuiting away from the product
- Increase the time available to freeze the product so can operate the freezer at lower air velocities and higher air temperatures
- Once freezing is completed, reduce fan speeds and increase temperature set-points to storage temperature until unloading can occur
- Load product so that the air flow distribution remains uniform throughout the freezer
- Defrost coils a short period of time after loading a batch freezer so that the coils operate lightly frosted for most of the time

Declining profit margins are forcing cold storage companies to employ energy savings initiatives, load management strategies and more efficient technologies. The most common energy saving measure is the use of off-peak electricity. Variable speed drives (VSDs) on compressors and blast freezer fans were identified as the most easily implemented energy saving new technology. Ambient air defrost systems are becoming more common rather than water or hot gas.

10. INVESTIGATION OF OPPERATING AIR BLAST FREEZERS

Odey [47] investigated performance enhancing measures of a batch air blast freezer. He found that generalised rules of thumb have been used for the design of air flow through blast freezers. Critical aspects of the design and implementation of the airflow circuit are often excluded from the refrigeration contract, resulting in poorly implemented and underperforming facilities.

Typically, the refrigeration contractor's response to poor freezer performance is to increase the fan capacity and power. It was found that simply increasing the air flow by increasing fan speed did not necessarily increase the air speed through the cartons in the freezer. The higher fan speed resulted in negative velocities at the fan inlet due to the formation of a large unstable vortex. As a result more heat was added to the freezer from the fans thus reducing the efficiency.

The following modifications were installed on the air blast freezer:

- Baffling on the top and sides of the freezing chamber
- Fan inlet cone and diffuser
- Air inlet and discharge vanes on corners
- Variable speed drive on fan

Prior to the modifications the air flow entering the fan was highly unstable with significant flow reversal. This turbulence reduced significantly with the above modifications. Most of the pressure drop in the unmodified freezer occurred at the 90 degree turning points, whereas the modified freezer had the largest pressure drop through the product pallets. As a result of the experiment, the existing 11 kW fan motors drawing 8.7 kW were replaced with 3.5 kW motors drawing 4.0 kW. The fans were re-pitched from 30° to 22° to maintain drawn power within the motor capacity. After the modifications satisfactory freezing was being achieved within the specified 48 hour turnaround period.

Figure 5 shows a schematic of a two stage carton blast freezer operating in New Zealand. The system, which includes de-superheating and sub-cooling, operates with a 63kW belt driven Vilter compressor and two 4.0 kW evaporator fans. This system uses R22 and was installed in 1995.

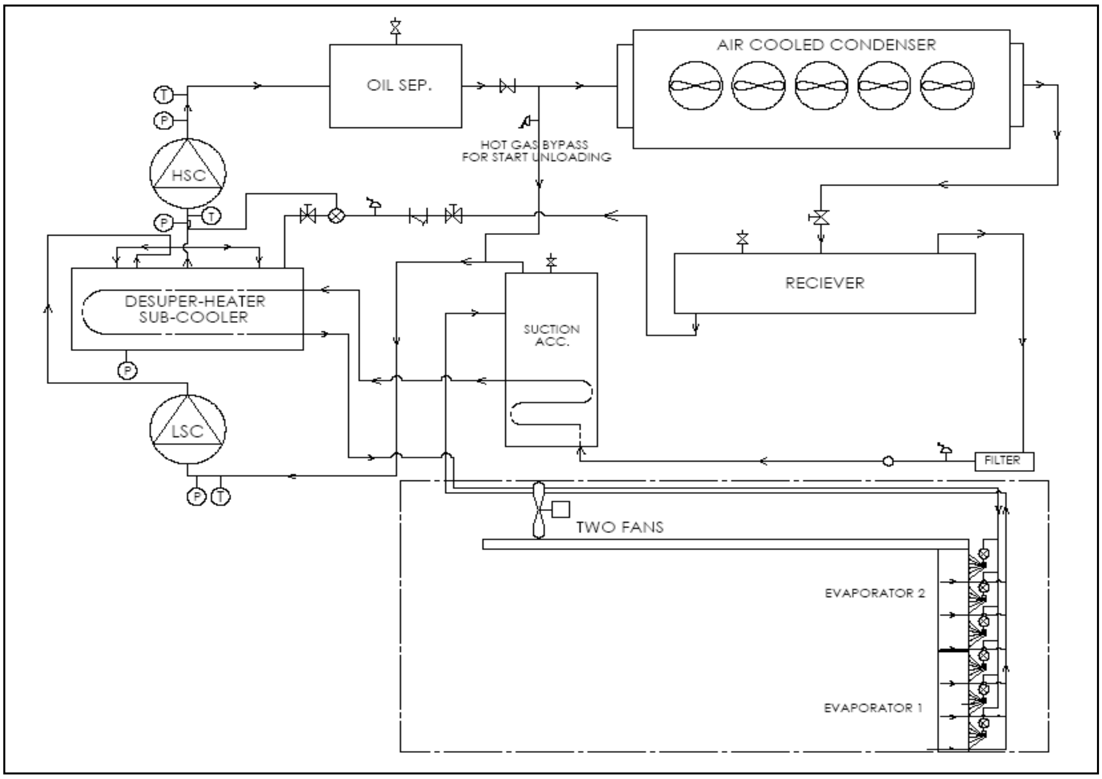

Figure 5: Schematic of a two stage carton blast freezer operating in New Zealand

Under normal operating conditions, the system operates as follows: Superheated vapour enters the low-stage compressor (LSC or booster compressor) from the evaporator and is compressed to the intermediate pressure. The heat of compression is removed by the intercooler. The desuperheated vapour then enters the high stage compressor (HSC) where it is compressed to the condensing pressure at 1400 kPa (guage), then passed through the air cooled condenser. Slightly sub-cooled high pressure liquid exits the condenser and enters the receiver.

It is at this point the refrigerant mass flow is divided, the larger portion of the refrigerant passes through the suction accumulator (for sub-cooling) and the intercooler before reaching the expansion valves. The smaller portion of the high pressure liquid is expanded into the intercooler to desuperheat the LSC vapour and to sub-cool the larger portion of the high pressure liquid before reaching the expansion valves. The intercooler is a horizontally mounted vessel consisting of an inner flooded vessel containing a tube bundle, through which liquid from the receiver is circulated, and a concentric outer vessel that receives the first stage discharge gas and the two-phase mixture from the inner vessel.

The sub-cooled liquid is then divided and enters six expansion valves, three per evaporator, before being further divided into 15 evaporator tubes per TXV by the distributer. The heat from the product, fans, infiltration and the thermal mass of the concrete floor boils the expanded two-phase refrigerant passing through the evaporator coils and superheats the vapour. The superheated vapour then exits the freezer, enters the suction accumulator where the vapour refrigerant is separated from any liquid carryover and also sub-cools the high pressure liquid line before entering the LSC.

Figure 6 shows the pressure enthalpy (P-h) diagram for the two-stage blast freezer system shown above. The P-h diagram represents actual data taken from site. The advantage of two-stage compression and sub cooling is clearly illustrated on the P-h diagrams in fig. 6 (a) with reduced compressor work and an increased evaporator capacity.

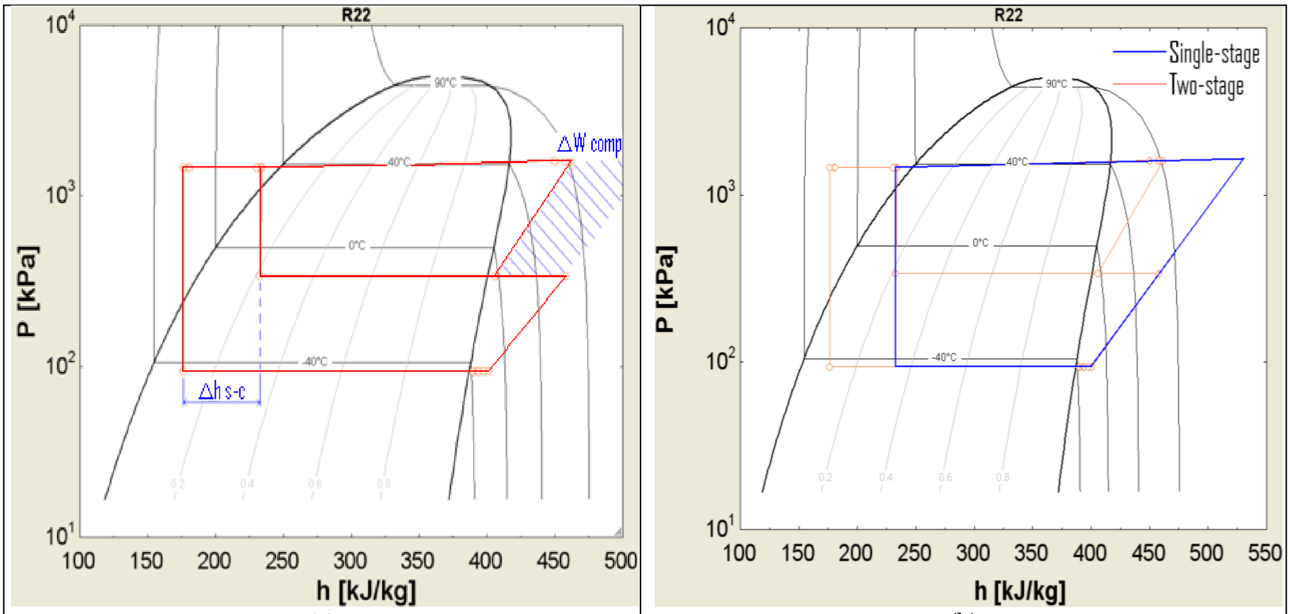

Figure 6: Two-stage P-h diagram from figure 5 system (a) and corresponding theoretical single stage P-h diagram operating with the same suction and discharge pressures (b)

The COPs for the two-stage and single-stage systems are defined by Equations (1) and (2) respectively. The single-stage compressor discharge enthalpy was extrapolated from the P-h diagram in Fig. 6 (b).

Two-stage Coefficient of Performance:

$$COP_{2stg} = \frac{\dot{m}_{LSC}(h_{evap,out} - h_{evap,in})}{\dot{m}_{LSC}(h_{LSC,out} - h_{LSC,in}) + \dot{m}_{HSC}(h_{HSC,out} - h_{HSC,in})} \quad (1)$$

$$COP_{2stg} = 1.73$$

Single-stage Coefficient of Performance:

$$COP_{1stg} = \frac{\dot{m}_{HSC}(h_{1stgC,in} - h_{EXV,1st})}{\dot{m}_{HSC}(h_{1stgC,out} - h_{1stgC,in})} = \frac{h_{1stgC,in} - h_{EXV,1st}}{h_{1stgC,out} - h_{1stgC,in}} \quad (2)$$

$$COP_{1stg} = 1.30$$

Spitting the refrigeration cycle into two stages and sub cooling increases the COP from 1.30 to 1.73. This equates to a 33% increase in efficiency.

Kemp and Chadderton [48] performed a study on the performance of batch blast freezers used to freeze beef cartons and found that designs seem to be based on average product heat load which is insufficient to handle the initial peak heat load. This problem is especially prevalent with hot-bone meat. Insufficient cooling capacity generally occurs at the beginning of the freezing process when the product heat load is being released at a peak rate that far exceeds the average rate, as shown in Figure 7. This problem is compounded as very few blast freezer systems manage to maintain their design cooling capacity. As a result of the peak heat load rate above the average, the room temperature rises above the specified design temperature meaning the design freezing time cannot be met. Ultimately, the higher initial heat load rate must be taken into account when designing blast freezers to ensure full product freezing within the specified time.

Bowater [34] states it is necessary to size evaporators at least 50% higher than the average refrigeration load for 24 hour freezes to account for the high initial heat load. For 48 hour freezes this requirement is not so critical. Other factors effecting cooling time include overloading of the freezers. Blast freezers are designed to handle a maximum heat load. Overloading to meet throughput demands will result in higher cooling loads and therefore longer cooling times.

Changes in product packaging have to be taken into account when sizing air blast freezer throughput. Mannapperuma *et al.* [49] found the surface heat transfer coefficient of whole, unpackaged chickens reduced by an order magnitude when the chickens were wrapped in plastic and stored in vented boxes. Kemp and Chadderton [47] surveyed a plant which changed the type of cardboard packaging used. As a result freezing time was increased by 8 hours. The change of packaging was determined as the major cause of the plant's freezing problems.

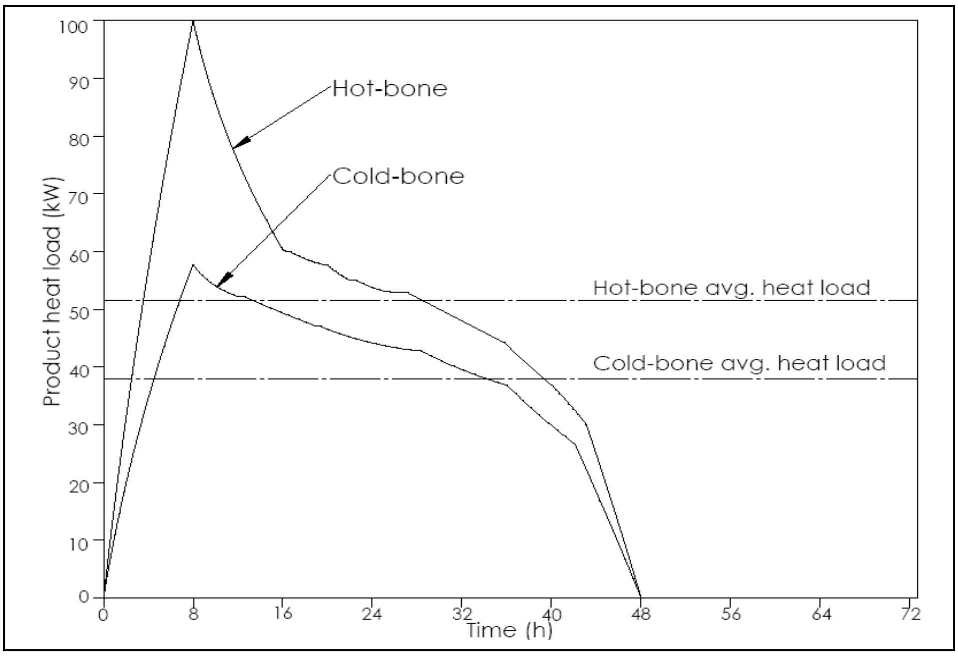

Figure 7: Product heat load characteristics for hot-boned and cold-boned beef cartons [47]

11. ENERGY EFFICIENT OPERATING STRSTEGIES

Table 3 summarizes the findings of a report on best practice guide to industrial refrigeration produced by Sustainability Victoria [50]. The report emphasised taking the "whole-system" approach when designing new systems as this presents the greatest opportunity to incorporate energy efficiency throughout the whole process, unhindered by the constraints that may be posed by existing equipment. The whole-system approach entails considering the system operation as a whole rather than just focusing on individual components as each component has flow-on effects that impact on other components, and therefore the efficiency of the system as a whole. The report recommends the use of a control system that is responsive to the compressor head pressure. Electronic expansion valves should be used where possible and have their controls linked to the head pressure control system.

Table 3: Potential energy savings for industrial refrigeration systems [50]

Method	**Energy Savings Potential**
Electronic expansion valves	20%
VSD on compressor motors	20%
VSD condenser fans	2-3% of total refrigeration cost
Evaporator pressure regulators	2% for each degree in increase in suction temperature
Reduced temperature lift	3-4% improvement for 1°C reduction
Conversion from liquid injection to external oil coolers	Over 3%
Refrigeration system replacement (If over 10 years old)	Up to 30-40%
Refrigerant selection	3-10%

12. CONCLUSIONS

Air blast freezing plays a large role in the meat trade, particularly for countries like New Zealand where the export of agricultural products is a pillar for the economy. Although other freezing methods such as plate freezers offer faster cooling times and higher efficiencies, air blast freezers will continue to play a large role in the meat industry due to their versatility and low capital cost. There is very little data in the open literature regarding the number and condition of blast freezers in operation. Such data would be of great aid for further research into the energy consumption and potential energy savings of blast freezers.

Within the current operating air blast freezers, there are numerous energy saving measures available. The most common and beneficial is the use of VSD's on fans, with an energy saving potential up to 44%. Other, cheaper and simpler energy saving measures include air baffles, air turning vanes, fan inlet cone and outlet diffuser, and improved user operating procedures.

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