Innovative In-Line Chilling/Freezing System for Fresh Meat Products packed in Corrugated Cardboard Cartons

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Executive Summary

An innovative large scale three-temperature zone (TriZone) continuous in-line automatic air blast chilling/freezing system for the chilling and freezing of fresh hot boned meat in corrugated cardboard cartons is presented.

Both chilling and freezing processes take place within the same machine. The three temperature zones are divided by means of panels and moving doors. The carton unit mass may be varied within wide ranges. The same applies to carton dimensions. Cartons may be processed automatically with or without lids at variable retention times and zone temperatures to suit the products and the desired outcomes.

The refrigeration plant servicing the automatic blast chilling/freezing unit is a three-stage ammonia/carbon dioxide (NH_3/CO_2) cascade refrigeration system with screw compressors in all three compression stages. The employment of the high-density refrigerant CO_2 combined with the application of multiple temperature zones deliver improved energy efficiencies compared with an equivalent ammonia refrigeration system.

The TriZone system is capable of accommodating the cooling rates for hot boned meat as stipulated by the Australian Quarantine and Inspection Service (AQIS). This was hitherto only possible in contact freezing systems employing NH_3 refrigerant evaporating at approximately -40°C. Introducing CO_2 as a refrigerant enables significantly lower air temperatures to be achieved in an economical, energy efficient and safe manner.

The marginally higher unit energy consumption for the TriZone system when freezing hot boned product is in most cases more than off-set by the significantly greater materials handling flexibility. In pre-chilled meat freezing applications where initial cooling rates are not critical, the TriZone system energy consumption is at the same level or less than for conventional contact freezer/blast chiller systems due to higher evaporating temperatures brought about by longer retention times.

Confining <u>all</u> reticulated ammonia to the engine room combined with a reduction in ammonia charge by a factor of 20 to 40 and elimination of <u>all</u> flexible refrigerant connections improve operator safety significantly compared with conventional contact freezing systems. In addition, the system meets the requirements of major international insurance underwriters with respect to the elimination of reticulated ammonia from equipment in all refrigerated spaces.

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Introduction

The automatic and semi-automatic cross flow chilling tunnels for meat packed in cartons have been used in the Australian meat industry since about the 1960s.

In the early 1980s, the large-scale plate freezer for freezing of chilled and hot boned meat was introduced to the Australian Meat Industry. The plate freezer was designed to achieve rapid initial temperature reduction of the hot boned product and to conserve energy generally by employing the contact freezing principle.

Older versions of the automatic cross flow chilling tunnels where the cooling medium (air) flows perpendicular to the product flow were in many cases unable to achieve the chilling regimes stipulated for hot boned meat. This was a result of several factors including non-uniform air velocity distribution across the product, less than adequate air velocities across the product generally and failure to achieve co-current product versus airflow.

The older cross flow type freezing tunnels had similar technical shortfalls as those of the cross flow chilling tunnels. In addition, the energy consumption was comparatively high due to the requirement to circulate relatively large amounts of air across the longitudinal cross section of the tunnel in order to achieve adequate air velocities across the cartons for good surface to air film coefficients.

Many of the more modern chilling tunnels available on the market today remain of the cross-flow type. The shortcomings of these machines in terms of chilling time, product exit temperature accuracy and energy consumption are well documented. Modern co-current end-flow tunnels with variable retention time at every product level as presented in this paper address these issues.

The 24-hour cycle large-scale contact-freezing concept will conserve significant amounts of energy when compared with older style cross flow type 48-hour cycle air blast freezing tunnels. As will be shown in this paper, the energy efficiency of the modern end-flow variable retention 24-hour cycle time air blast chilling/freezing system has improved to such an extent that it presents a viable alternative to contact freezing.

In addition, modern end-flow variable retention time tunnels have no shortcomings in terms of producing product, which may be palletized automatically at freezer exit and they feature far greater flexibility with respect to product sizes, product types and intelligent integration into the overall logistics of a meat processing plant.

The most recent technical development in air blast chilling/freezing tunnels is the so-called TriZone tunnel. These are fully automatic three temperature zone tunnels capable of chilling and freezing various types of products – hot boned as well as cold boned, lid on as well as lid off – within the same machine.

The TriZone concept has been made possible with the re-discovery of refrigerant CO_2 (R744). By employing this low temperature, high-density refrigerant in modern, automatic air blast freezing tunnels, significantly lower air temperatures can be achieved more economically than hitherto possible with traditional ammonia refrigerant.

The main advantages associated with the TriZone tunnel as compared with the traditional combination of plate freezers and single retention time chilling tunnels are:

- Significantly improved operator safety by containing all ammonia refrigerant in the engine room and by reducing the ammonia refrigerant charge by a factor of between 20 and 40,
- First air blast freezing tunnel capable of meeting AQIS product temperature versus time requirements since the introduction of the large scale contact freezers in Australia in the 1980'ies,
- Improved energy efficiency compared with conventional blast freezing systems firstly by dividing the freezing compartment into two temperature zones, secondly by employing CO_2 refrigerant and thirdly by intelligent control of engine room operating conditions and fan speed in response to product flow,
- Automatic processing to AQIS product temperature versus time requirements of hot boned chilled product by alternating between low temperature and medium temperature zones,
- A 24 hour turnaround time for hot boned, frozen product may be achieved comfortably, improved energy efficiency may be achieved by extending the retention time after the initial rapid chill of the hot boned product,
- Significantly greater levels of automation minimizing labour costs,
- Equal or lower equipment investment.

System Descriptions

Conventional Chilling/Freezing Plant

The conventional chilling/freezing facility for a meat processing plant producing a given mix of chilled and frozen product is shown in Figure 1 in plan view. This shows a combination of a number of contact (plate) freezers and an automatic chilling tunnel of the cross-flow type.

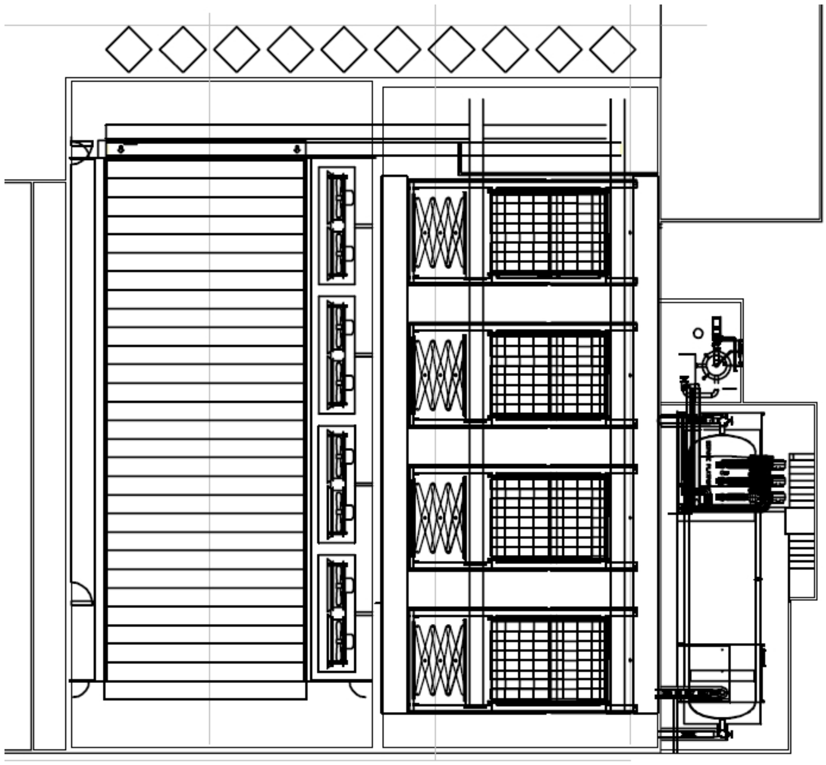

Fig.1. Conventional carton chilling/freezing plant in plan view.

The contact freezers shown above may be of the manual load/unload, semi-automatic load/unload or fully automatic load/unload type depending on capital budget. The loading mechanism shown above is of the scissor type at constant level.

In most cases the chill tunnel retention time is fixed. Often fan speed is also fixed. Leaving product temperatures are in many cases attempted controlled by controlling the temperature of the chilling medium – in this case the air temperature leaving the air coolers.

In the case of the manually loaded/unloaded contact freezer and to some extent the semi-automatically loaded/unloaded versions, the freezing process is by definition a batch process.

Progressively loaded/unloaded contact freezers may emulate a true in-line continuous freezing process. However, the flexibility and energy efficiency associated with alternating freezing medium temperatures are not readily available in contact freezers due to commonality of suction headers connecting the individual plates to the central engine room.

In fig. 1 is also shown the very large accumulator required for large-scale contact freezer installations. The great majority of contact freezers in the meat industry employ refrigerant ammonia. A few installations have, however, also been designed around secondary refrigerants such as glycol or potassium carbonate based fluids.

In large-scale contact freezer installations using refrigerant ammonia, the approximate ammonia system charge is around 3,500 kg per 750 meat cartons. Installations for the freezing of 5,000 cartons per day will typically hold 20 to 25 metric tons of ammonia. The necessary ammonia accumulator size is 40 to 45 m^3 as a result of the need to hold 110% to 120% of the total ammonia (NH_3) charge.

These large quantities of ammonia refrigerant in contact freezer installations are of a serious safety concern mainly to legislators. This safety concern is aggravated by the operating principle of a contact freezer with extensive employment of flexible refrigerant connections, which are subjected to movement on a daily basis during normal production periods.

More importantly, recent uncontrolled releases of ammonia from contact freezer installations in the Australian meat industry have attracted the attention of Authorities charged with the task of enforcing the Occupational Health and Safety legislation in place in all Australian States and Territories.

Occupational Health and Safety legislation is now such that uncontrolled releases of toxic substances including ammonia will transform the site of the incident into a forensic site. The consequence is that the operator(s) in charge are only authorized to take actions to terminate the release. Further actions including recommencement of meat plant operations are in the hands of the Authorities.

New In-Line Chilling/Freezing Plant

In addition to improvements in operator safety, the major objectives set during the development of the alternative chilling/freezing system for meat cartons were in summary:

- Suitability for automatic processing of cold boned as well as hot boned meat products packed in cartons of varying thermal resistances, of varying dimensions and of varying levels of packaging finish i.e. lid on or lid off,

- Compliance with AQIS hot boned product temperature versus time requirements for both chilled as well as frozen product,

- Inclusion of chilled space dehumidification to maintain carton moisture levels and hence carton integrity during chilling,

- Maintenance of carton dimensional integrity during chilling as well as freezing,

- To form a logical element of a fully automatic materials handling system for the meat processing plant,

- To provide a buffer which can accommodate variations in production throughput for chilled as well as frozen products,

- Incorporate greater levels of flexibility in the mix ratio between chilled and frozen products,

- Production reactive i.e. loading independent of unloading and vice versa,

- To share capital intensive elements of the materials handling equipment between the system segment processing frozen product and the system segment processing chilled product,

- Simplification of materials handling systems upstream and downstream of the chilling/freezing plant when compared with present concepts,

- Incorporation of relatively inexpensive pre-sorting and post-sorting functions,

- Inclusion up front or later of computerized monitoring (SCADA system), product tracking, inventory control and DNA tracking,

- Improved temperature control of the chilled product by employment of co-current flow between the cooling medium and the product,

- Employment of natural refrigerants only,

- Up-time >98% based on 24 hour/7 days/week continuous full load operation,

- Achieve energy consumption values in kWh per unit mass product processed comparable with present conventional methods of processing,

- Significantly extended intervals between defrosts in order to further minimize efficiency losses and process temperature fluctuations,

- Elimination of any refrigerant management problems, which are inherent in conventional chilling/contact freezing systems

The result of the development is the TriZone automatic air blast chilling/freezing tunnel as shown in fig. 2.

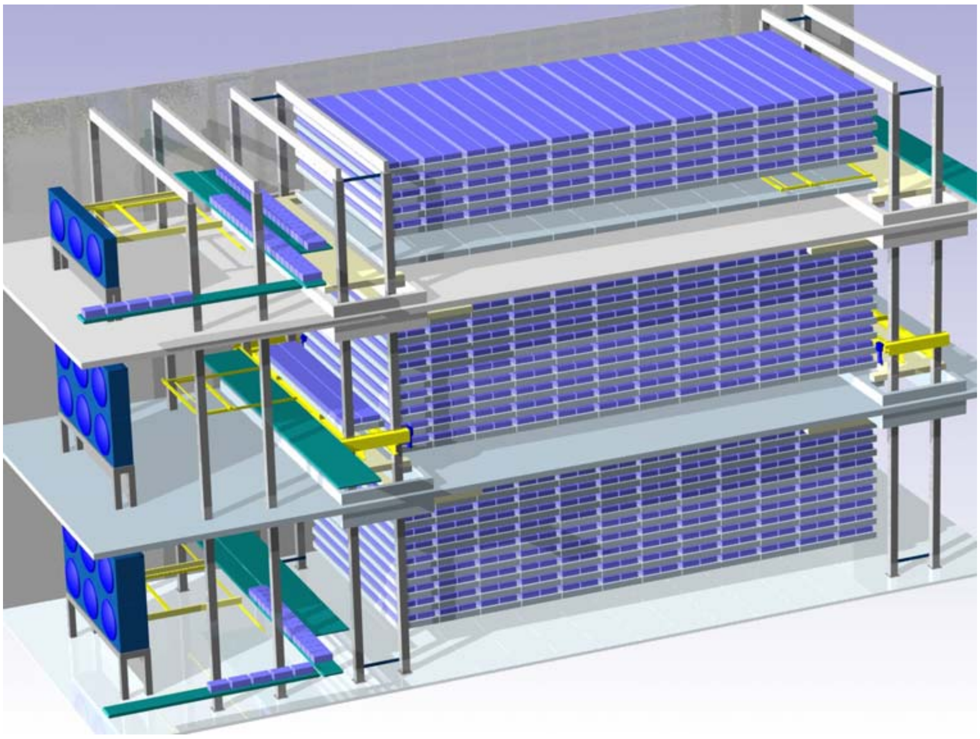

Fig. 2. Automatic TriZone air blast chilling/freezing tunnel

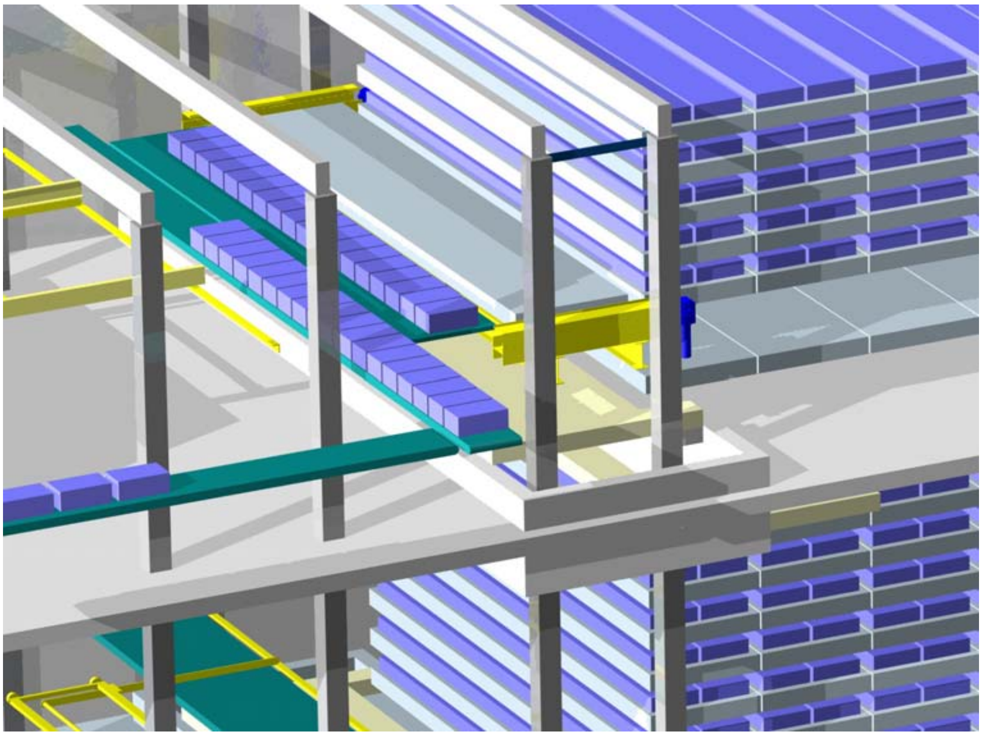

Fig. 3. Vertical Separation with Moving Doors

This new system achieves all the objectives set out above and presents a cost effective and technically sound alternative to the conventional chilling and freezing methods in use in the Australian and New Zealand meat industries today.

The tunnel features both a chiller and a dual zone freezer section. A common elevator system is used to load and unload each section. Internal partitions and special doors that isolate each zone as the elevator passes between the chilling and freezing sections separate the three sections as shown in fig. 3.

This ensures that while the elevator is common, each zone will operate within its own strict criteria without influence from the other zone when the doors are closed. The effect of the doors and partitions is that the three zones operate independently of each other in a thermodynamic sense.

Each zone has an individual set of evaporators, which circulate cold air through the products situated at the various storage levels. By modulating engine room operating conditions (compressor suction pressures) the air temperature may be controlled. The air quantity and hence air velocity across the products may also be controlled by modulating the fan speeds.

The ability to control air temperatures, air speeds and process times in response to product variables (flow, packaging, dimensions, temperatures and properties) as well as desired product conditions at tunnel exit are paramount. Not only will this ensure exact control of process and hence product conditions, it will also ensure energy efficiencies hitherto unattainable in air blast freezing systems.

Normally, temperatures in the freezing compartments are -44 to -50°C in freezing zone 1, -35 to -38°C in freezing zone 2 and –5 to -8°C in the chilling zone.

In the majority of situations, the chilled products stay in the chilling zone, but chilled product could proceed through two sections, if required. As an example, hot boned product to be chilled may be subjected to a shock chill for a comparatively short duration in either freezing zone 1 or freezing zone 2 prior to entering the chilling section for final processing.

Such a process may also be suitable for chilled offal, tops on product or retail ready packs requiring a small, but quick reduction in temperature.

In order to maximize energy conservation during the freezing process without jeopardizing the cooling rate for the initial rapid chill, the hot boned product destined for freezing is exposed to two temperature zones.

The first zone operates at approximately -50°C air temperature leaving the air coolers. The product enters the first zone at the point where the cold air stream exits the air coolers. The product then travels co-currently with the air stream and exits the first zone where the air stream turns 180° and returns to the first zone air coolers.

The product is retained for approximately 9 to 10 hours in the first zone to ensure that a core temperature < +7.0°C is achieved under all circumstances. The mass average temperature upon exit from the first zone is ≤ -2.0°C.

Upon exit from the first zone, the product has entered the latent heat removal zone. Approximately 66% or 2/3 of the entire latent product heat is removed in the -50°C zone.

The fan speed in the first zone is comparatively high to achieve rapid core temperature reduction ensuring minimal bacteriological growth and compliance with AQIS requirements for hot boned meat.

Following a short equilibration period, which represents the transfer time in the materials handling system, the product enters the second temperature zone. This zone is maintained at approximately -38°C and the air velocity across the product is reduced in order to conserve energy.

In the second zone, the product freezing is completed and the balance of the latent product heat (approximately 1/3) is removed. The retention time in zone 2 is approximately 10 to 12 hours.

In zone 2 the product travels in counter flow with the air stream. This ensures that the product achieves the lowest possible core temperature because it will be exposed to the cold air stream leaving the air coolers immediately prior to exit from this zone. The product core temperature following a total process time of 20 to 22 hours is < -12.0°C. The corresponding mass average temperature (equilibrated temperature) is < -22°C.

Although the total theoretical design cycle time available is 24 hours to suit the operation of the balance of the meat processing plant, it is necessary to account for carton packing inconsistencies, which may require marginally extended retention times. The design cycle time has therefore been taken at ~22 hours to allow 2 hours extra time, if required for such carton inconsistencies.

For superior energy efficiency and operator safety, the TriZone tunnel is connected to a three stage CO_2/NH_3 cascade refrigeration system as shown in fig. 4. With this plant concept all ammonia (NH_3) is contained within the confines of the engine room.

The chiller section is serviced by circulating a volatile evaporating secondary refrigerant (in this case CO_2 or R744). The two freezer zones are connected to dedicated CO_2 compressors at two suction pressure levels.

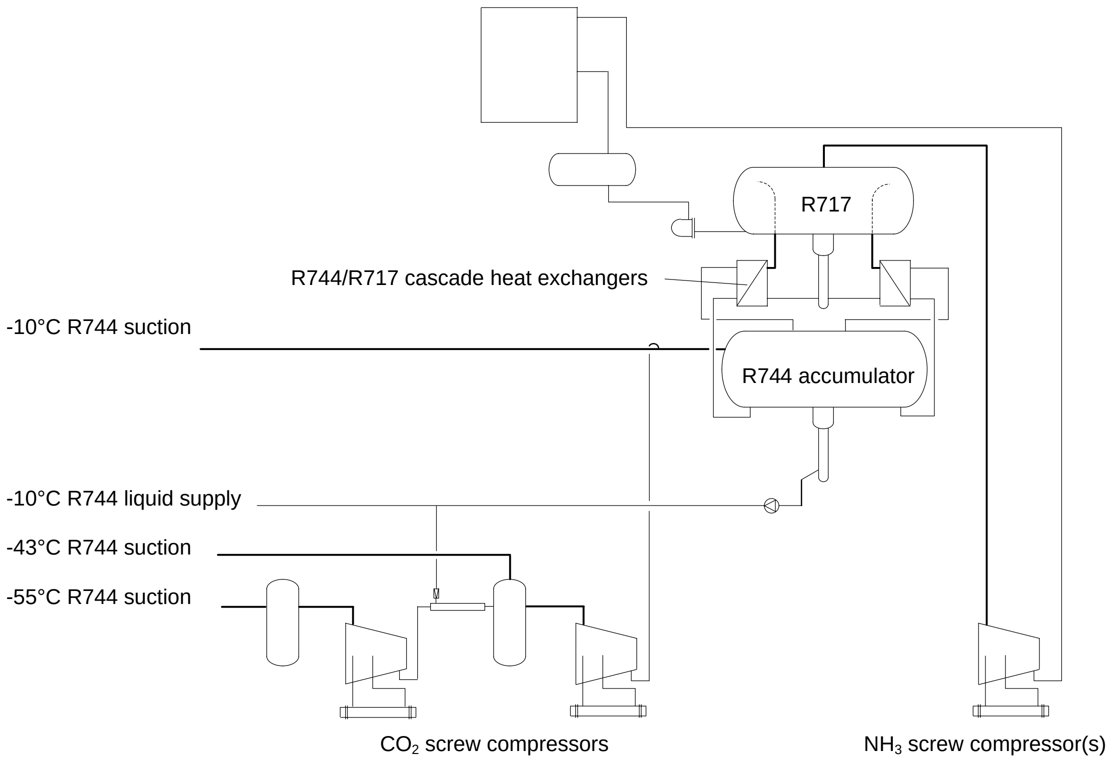

Fig. 4. Cascade type NH_3/CO_2 refrigeration system with three temperature levels

These CO_2 compressors may be of the screw or reciprocating type and combined into a dual stage compression package. Reciprocating CO_2 machines feature greater efficiency than the screw compressors presently available on the market. Reciprocating compressors are, however, in this case not suitable for the -55°C level due the low condensing temperature.

The second CO_2 compression stage condenses against an ammonia refrigeration plant via CO_2/NH_3 cascade heat exchangers.

The possibility of connecting the dual stage CO_2 plant to an existing ammonia refrigeration system of the conventional type exists. This opens up the possibility for retrofits as well as for the addition of a glycol or reticulated high temperature CO_2 circuit for process rooms. Within limits, this also enables staging of investments, if required.

There are various downstream automation options available which provide full automation from boning room to full pallets by grade or order make up. These options are tailor-designed for specific requirements from proven sub-systems and are not the subject of this paper.

The TriZone system is capable of post cooling sortation to deliver two-stage product separation for chilled and frozen products. The design provides multiple separations in the chiller or freezer sections, if applicable.

The system is hence capable of providing unique separation for up to 4 major products with all the minor separation being mixed on one system or say 3 major separations and 2 minor groupings for further separation post cooling.

Post cooling (and when no further product is being loaded for 8 hours) all the major grades may be discharged in unique pallet lots and some of the minor grades can be automatically cycled into further 4 or 5 separations and discharged in pallet lots during the non-production hours.

The very small volume(s) may be sorted manually on a carousel. With this method > 90% of the production can be sorted automatically into unique product streams (depending on product mix), refer fig. 5.

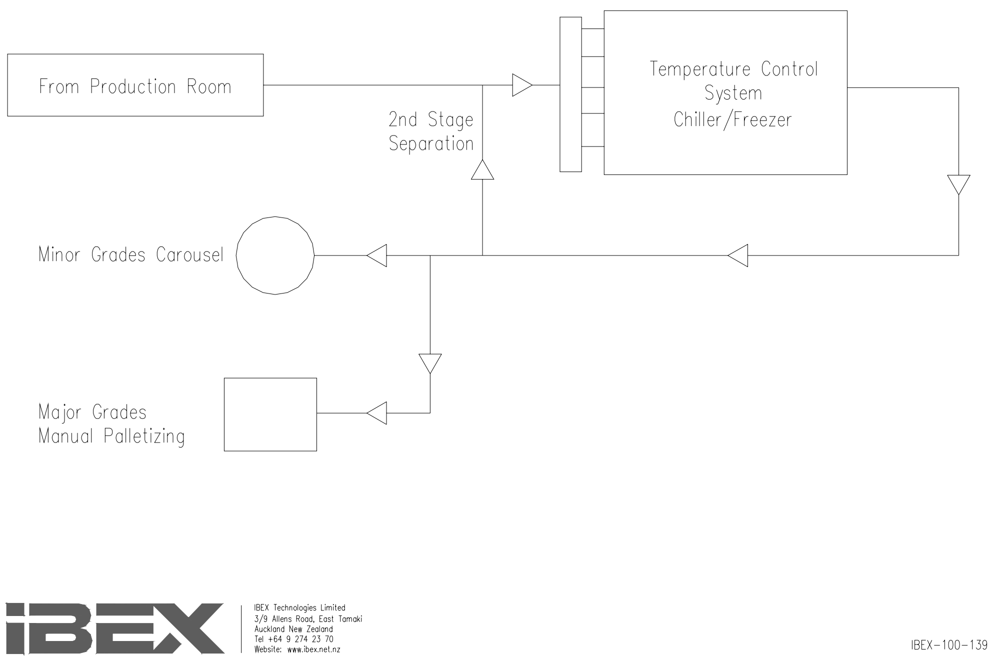

Fig. 5. Product Flow Automation

Providing the full compliment of carriers is installed initially then the system can be used as a temporary holding store and collating system.

Retention Times, Chilled and Frozen Products

The chilling and/or freezing time of a given product with certain physical and dimensional characteristics from an initial temperature to the final (design) temperature is influenced by the following factors:

1. Temperature of the cooling medium
2. The surface heat transfer between the cooling medium and the product
3. The exposure of the product to the cooling medium (one, two or three-dimensional)

The meat carton retention times in table 1 below are for a TriZone tunnel air blast situation and are predicted by means of computer simulation using the RADS software developed by Massey University, Palmerston North, New Zealand.

The prediction is valid for standard 27.2 kg frozen meat cartons (chilled 20 kg) with the approximate dimensions 600x400x165 mm thick packed in corrugated C-flute cardboard cartons with an estimated thermal resistance of approximately 0.048 m^2K/W. The initial product temperature is approximately 30°C.

PRODUCT →	**CHILLED**	**FROZEN**	
Zone	-	1	2
Temperature, °C	-7	-50	-38
Air velocity across the product, m/s	4.0	6.0	4.0
Estimated Retention time	15	9.3	10.5

Table 1. Retention times for Chilled and Frozen Product

The sum of the retention times in zones 1 and 2 is <24 hours in order to incorporate a safety margin for carton inconsistencies. This ensures that a total process time of 24 hours or less may be achieved also in less favourable situations.

Energy Consumption for Chilled and Frozen Products

The estimated energy inputs per unit mass of chilled and frozen product are provided in table 2. These are for hot boned products with an entering temperature of around 30°C. The leaving chilled product mass average temperature is 0°C. The leaving frozen product core temperature is ≤-12°C corresponding to a mass average temperature of -22°C.

The example in table 2 is based on a meat processing facility producing 5,000 frozen cartons daily (over 10 hours) and 15,000 chilled cartons daily (over 10 hours). The unit masses are 27 kg and 20 kg respectively. The carton inlet temperature is 30°C for both the chilled as well as the frozen product. The chilled product is not subjected to any shock chill in the freezing zone(s) in the thermal calculations.

PRODUCT →	**CHILLED**	**FROZEN**	
Zone	-	1	2
Temperature, °C	-7	-50	-38
Retention time, hours	15.0	9.3	10.5
Average inlet product mass flow, kg/s	8.33	3.75	3.75
Product heat removal, kW	566.7	986.1	508.1
Total refrigeration plant capacity required, kW	587.6	1056	561.7
Suction line loss, K	0.1	0.5	0.5
Saturated compressor suction temperature, °C	-14.0	-55.0	-43.0
R744 compressor shaft power allocation, kW	0	430.8	136.3
R717 compressor shaft power allocation, kW	158.8	401.8	186.8
Condenser fan allocation, kW	12.3	31.2	14.4
Condenser spray water pump allocation, kW	1.5	3.7	1.8
Refrigerant pump allocation, kW	3.4	3.2	1.6
Total system shaft power, kW	217.5	920.0	385.2
Overall average system electrical efficiency	0.85	0.85	0.85
Total system energy input per ton processed, kWh/t	12.8	80.2	33.6
Total system energy input per ton processed, kWh/t		113.8	

Table 2. Estimated energy inputs for chilled and frozen products.

Due to the continuous, in-line nature of the TriZone tunnel, the processing capacity of the freezing segments is not necessarily limited to 5000 cartons daily.

In the above example, the last carton of a production day entering the zone 1 freezer segment at around 17.00 hours will exit zone 1 around 02.30. Zone 1 is empty after this time and will remain empty until production starts the following day. This last carton will then be ready for palletizing around 15.00 hours the next day when it exists zone 2.

In a situation where a meat processing plant is operating more than 10 hours daily (several shifts), the freezing system is therefore capable of a continuous processing capacity of 13.5 tons/hour or 500 cartons/hour. This represents a quantity of 12,000 cartons on a 24-hour basis.

Energy savings are possible by extending the retention time in zone 2 to 36 hours. When the product enters zone 2, the mass average temperature is around -2°C and the rate of temperature reduction in the product is hence no longer critical.

Extending the retention time in zone 2 to around 36 hours by increasing the zone 2 holding capacity will enable the required core temperature of -12°C to be achieved using air temperatures around -15°C and very low air movement hence conserving fan power. This will reduce the zone 2 power consumption to 18 kWh/t and hence the total energy input to <100 kWh/t.

Temperature versus Time Regimes for Hot Boned Products

The Australian Quarantine and Inspection Service (AQIS) stipulate cooling times for hot boned meat. These times are a function of the initial temperature of the product and the decontamination prior to boning.

In table 3 are reproduced the current cooling rates for hot boned meat, which according to AQIS must be achieved.

Initial temperature °C	Time in minutes for product to fall to 7°C in the case of no decontamination prior to boning	Time in minutes for product to fall to 7°C in the case of effective decontamination prior to boning
40	376	554
39	386	570
38	399	589
37	414	608
36	431	631
35	450	665
34	468	685
33	486	710
32	505	736
31	525	765
30	547	795
29	568	824
28	593	864
27	620	905
26	651	944
25	683	990
24	720	1045
23	760	1104
22	805	1194
21	854	>1200

Table 3. Cooling rates as a function of time for hot boned meat as stipulated by AQIS

The initial temperature is measured after boning and prior to carton closure as:

(a) Single primal cuts – the highest surface temperature of a single cut, whether wrapped or unwrapped, prior to being subject to further refrigeration, or

(b) Bulk packed carton meat – the highest temperature determined within a carton prior to being subject to further refrigeration.

The initial rapid chilling regime for hot boned meat in corrugated cartons, which may be achieved in the first (-50°C) zone of the TriZone tunnel is shown in fig. 6 and fig. 7.

The computer model used slices the carton in three different directions and calculates the equilibrium temperature at the nodes in such a manner that the overall heat balance is 100% ±0.1%.

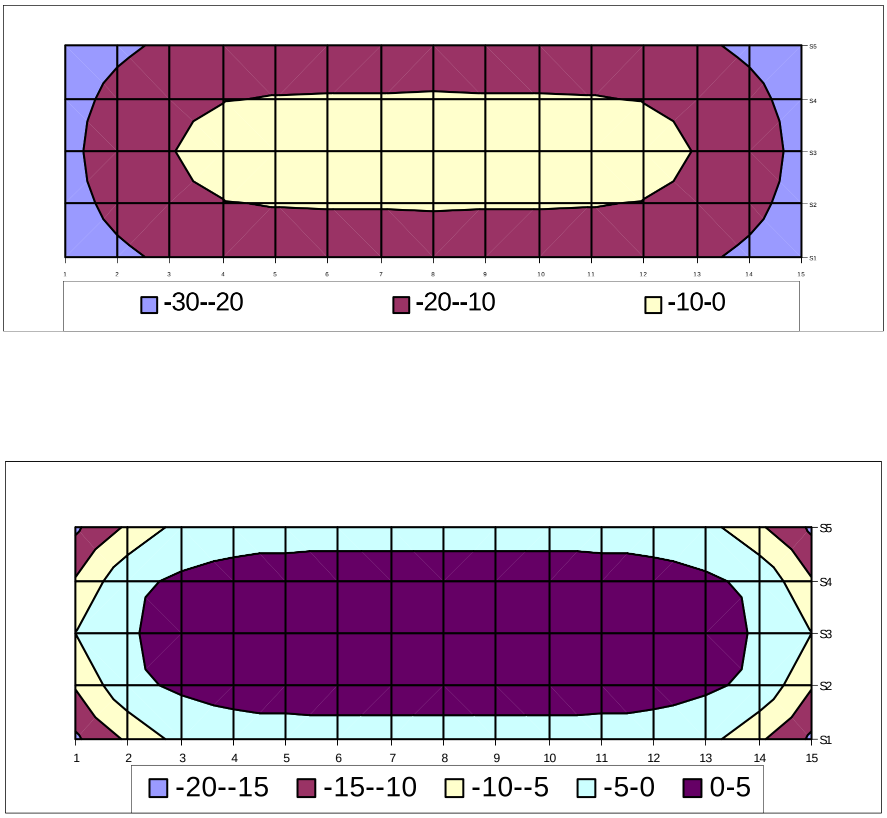

Fig. 6. Slices from the top and centre looking down on the carton

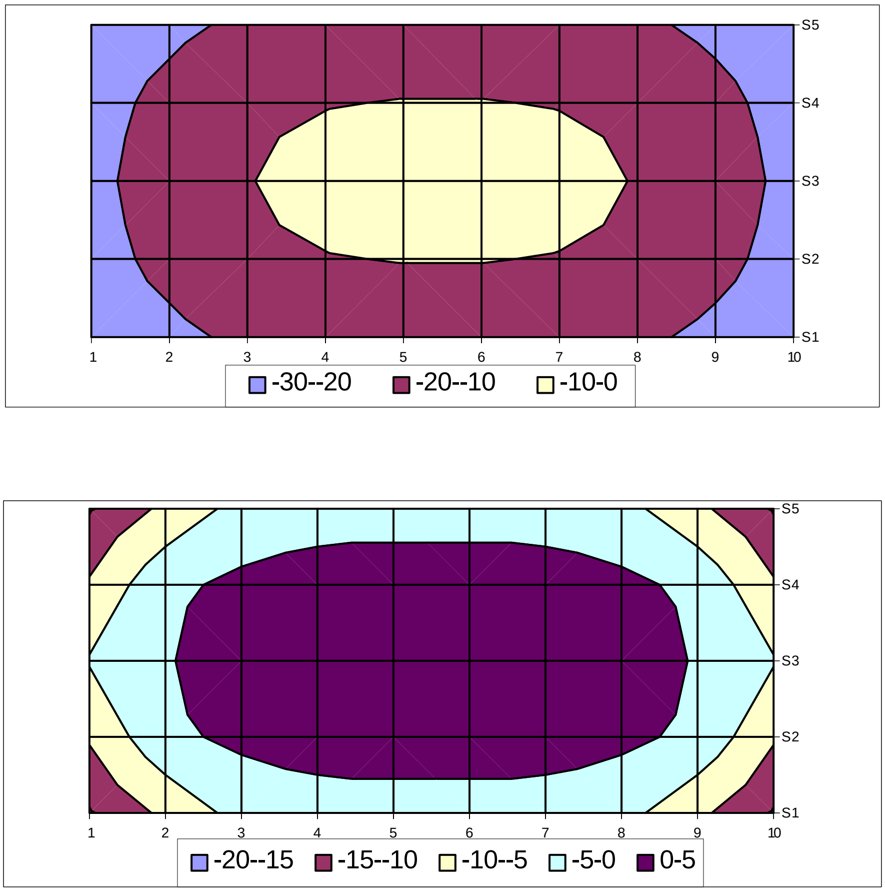

Fig. 7. Slices from the end and centre looking end on into the box

Fig. 6 shows the plan view of the box; fig. 7 shows the end view following 9.3 hours of exposure to the conditions in zone 1 of the TriZone tunnel. The various temperature zones are visualized by means of colours. The lowest temperatures are present towards the top and the end respectively.

It is evident that all temperatures within the box either fall within the 0 to 5°C zone or within temperature zones representing lower temperatures. This is inside the requirements stipulated by AQIS for meat of this temperature and without prior decontamination.

Air Blast Freezing versus Plate Freezing

The energy consumption associated with freezing the product in a TriZone air blast chilling/freezing tunnel versus freezing the same product in a contact freezer is of particular interest to meat processors.

To prepare a fair comparison between the two freezing concepts in terms of energy usage, it is important to determine the necessary temperatures of the freezing media to achieve the required process outcomes, refer table 4.

The total freezing cycle time for the TriZone freezing tunnel is 9.3+10.5 (time in zone 1 + time in zone 2) = 19.8 hours. The freezing cycle time (clamp time) for the contact freezer is maximum 21 hours in order to enable loading/unloading and freezing to occur within the 24 hour cycle limit.

In each case the cartons are of identical dimensions and properties. In each case the thermal resistance of the carton material is identical. Any differences in the required temperatures of the freezing media are therefore related only to the freezing method employed.

For the TriZone tunnel, the temperatures of the freezing media are determined by means of computer simulation using the RADS software developed by Massey University, Palmerston North, New Zealand. Simplified freezing time formulae cannot be used in this instance due to the varying temperatures of the freezing media during the freezing process.

The initial determination of the required temperature of the freezing medium is, in the case of the contact freezer, made using simplified freezing time formulae [2][3]. This is possible because the freezing medium temperature is assumed constant throughout the batch process.

Freezing concept	TriZone Tunnel	Contact Freezer
Thermal conductivity of the product below the freezing point (average temperature ~-11°C), W/mK	1.345	1.345
Product density above the freezing point, kg/m³	1000	1000
Product density below the freezing point, kg/m³	950	950
Product specific heat above the freezing point, kJ/kgK	3.40	3.40
Product specific heat below the freezing point, kJ/kgK	1.78	1.78
Latent heat of fusion, kJ/kg	254	254
C+, MJ/m³K	3.40	3.40
C-, MJ/m³K	1.69	1.69
Freezing point, °C	-2	-2
ΔH (0/-10), MJ/m³	274	274
Initial product temperature, °C	30	30
Final product core temperature, °C	-12	-12
Final product mass average temperature, °C	-22	-19
Thermal resistance of carton material, m²K/W	$4.8*10^{-2}$	$4.8*10^{-2}$

Thermal resistance of 0.3 mm thick poly bag, m²K/W	$1.76*10^{-3}$	$1.76*10^{-3}$
Thermal resistance of air gaps within carton, m²K/W	0.06 (~1.5 mm avg.)	0.004 (~0.10 mm avg.)
Thermal resistance from exterior of plate surface to refrigerant (δ_{Al} = 0.006 m, λ_{Al} = 210 W/mK), m²K/W	-	$2.86*10^{-5}$
Oil fouling resistance within contact freezer (oil film thickness 0.05 mm, λ_{OIL} = 0.12W/mK), m²K/W	-	$4.17*10^{-4}$
Surface film coefficient within plate freezer (d_{HYDR}=0.039 m, cavity length 4 m, 48 cavities, 24 passes, n_{CIRC}=50 to 1, mass flow density = 90.9 kg/sm^2, $\Delta p_R \cong$ 0.3K), W/m²K	-	821
Film coefficient, carton/air (α_o=12.5*w$^{0.6}$), W/m²K	36.6/28.7	-
Total thermal resistances freezing medium/product, m²K/W	0.137/0.145	0.0554
Heat transfer coefficients freezing medium/product, W/m²K	7.29/6.92	18.04
Product shape	Brick	Infinite slab
Thickness, m	0.165	0.165
Width, m	0.400	-
Length, m	0.600	-
Required temperature of freezing medium, °C	-50.0/-38.0	-39.0
Freezing time, hours	19.8	21.0

Table 4. Required freezing medium temperatures for TriZone tunnel versus contact freezer.

The thermal carton resistance of 0.048 m^{2}K/W has not been estimated in detail, but it is a relatively optimistic assessment compared with estimates found in technical reports in relation to freezing trials of meat in cartons [1].

Table 4 clearly shows that contact freezer performance for meat packed in corrugated cardboard cartons is severely inhibited not only by the carton material, but also by variations in contact caused by air gaps, differences in carton heights or curled up plastic wrapping material in the top of the box.

The result of the theoretical estimation of freezing medium temperatures shown in table 4 is in good agreement with practice. Many contact freezer installations in the meat industry are designed around -38°C to -40°C evaporating temperature in the freezers with saturated compressor suction temperatures around -43°C achieved in practical operation.

In order to compare the energy consumptions fairly, both the TriZone tunnel and the contact freezer are assumed connected to new dedicated refrigeration plants.

In the case of the TriZone tunnel, the refrigeration plant is a triple stage NH_3/CO_2 cascade refrigeration system as shown in fig. 4. In the case of the contact freezer, the refrigeration system is a dual stage ammonia refrigeration system of the conventional type comprising screw compressors with slide valve capacity control in both compression stages.

In both cases, the materials handling energy consumption is assumed to be identical as are the dehumidification costs.

The wet and dry suction line losses are different by 3.0K for the two installations due to the significantly greater refrigerant overfeed rates associated with contact freezers and due to the different refrigerant properties in the TriZone refrigeration system (NH_3/CO_2) compared with the contact freezer refrigeration system (NH_3).

Refrigerant CO_2 is a high-density refrigerant. At the relevant evaporating temperatures, the incremental saturated temperature change for a given pressure change is significantly lower than for traditional refrigerants including NH_3, refer fig. 8.

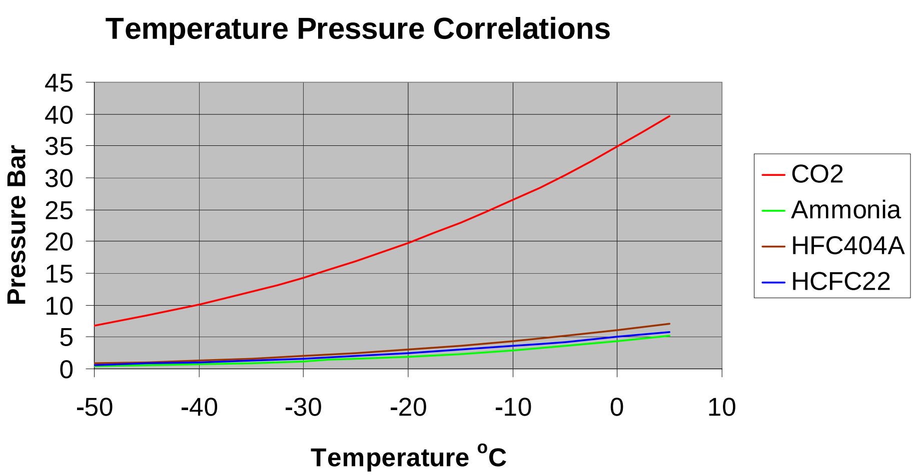

Fig. 8. Temperature – pressure relationships for various refrigerants.

The consequence of this is that relatively small refrigerant line pressure drops in traditional NH_3 plants will give rise to much greater saturated temperature line losses than when using CO_2.

Elevated overfeed rates, as found in most contact freezer refrigeration systems, cause greater line pressure drops than in plants with overfeed rates in the range below 5 to 1.

A 250NB stop valve will, at 600 kW capacity and an overfeed rate of 4 to 1, have a temperature drop of 0.32K at -38°C saturated line temperature. The same valve at the same line temperature, but with 40 to 1 overfeed rate will feature a pressure drop of 2.24K or 7 times more. Both values are for NH_3.

In many contact freezer installations, the refrigerant, when exiting the individual plates, travels through a flexible refrigerant hose, enters a vertical header, exits this vertical header at the bottom, enters a 90° elbow, travels at floor level, then enters another 90° elbow from where the liquid/gas mixture flows through a vertical riser and then enters the main horizontal wet return line to the accumulator.

The estimated line pressure drop from the most remote of say four contact freezers to the accumulator assuming a 2.5 m vertical header in a typical freezer installation with correctly sized pipe lines and a refrigerant overfeed rate of 40 to 1 is estimated at 4 to 5K.

This pressure drop penalizes the compressor performance significantly (20 to 25%) and in some practical contact freezer installations, penalties of this magnitude have been identified.

Contact Freezing Energy Requirement

This example is for a relatively large facility producing 5,000 frozen cartons daily from 30°C to -12°C centre temperature. The cartons have a unit mass of 27 kg.

Freezer type →	Contact freezer
Conduction, kW	7.2
Infiltration, kW	4.9
Lighting, kW	2.5
Total product quantity processed, kg	135,000
C_+, kJ/kgK	3.4
Freezing point, °C	-2.0
C_-, kJ/kgK	1.78
Latent heat of fusion, kJ/kg	254
Initial product temperature, °C	30
Final product core temperature, °C	-12
Final product mass average temperature, °C	-19
Total product heat removal per batch, MJ	53,063
Cycle time, hours	21.0

Average product heat removal, kW (kJ/s)	701.9
Total refrigeration plant capacity required, kW	716.5
Suction line loss, K	3.5
Required saturated compressor suction temperatures, °C	-42.5
Booster shaft power, kW	199.6
Compressor shaft power, kW	230.2
Condensing temperature, °C	33.0
Condenser heat rejection, kW	1144
Condenser fans, kW	19.1
Condenser spray water pumps, kW	2.3
Refrigerant pump(s), kW	17.4
Evaporator fans, kW	0
Total system shaft power, kW	471.1
Overall average system efficiency	0.85
Total system energy input per cycle, kWh	11639
System energy input/t, kWh/t	86.2

Table 5. Energy consumption of contact freezer

From the above it may be concluded that the TriZone tunnel requires approximately 12% to 24% more energy input per unit product processed than the equivalent contact freezing system. The difference is affected by the retention time in zone 2.

In return, the Trizone system offers vastly improved operator safety, significantly reduces insurance risks and is enormously flexible both with respect to the number of production shifts, but also with respect to product dimensions, product packaging and chilling regimes.

For pre-chilled meat where the initial rapid chilling rate is unnecessary, a DualZone chilling/freezing system may be employed. The unit energy consumption for frozen product is in this system comparable with or a little lower than for contact freezing systems due to extended retention times and elevated evaporating temperatures.

Chilling Energy Requirement Comparison

This comparison is between the chilling segment of a TriZone automatic end flow co-current tunnel and an equivalent cross flow tunnel. The tunnel chilling capacity is 15,000 off 20 kg meat cartons being chilled from 30°C to 0°C in 15 hours.

The end-flow TriZone tunnel achieves an air velocity w_o=6 m/s across the product for a total maximum fan shaft power of 52.2 kW (9 off ø1250 mm fans absorbing 5.8 kW each). The total free area for air flow is 12.2 m^2.

Although the TriZone system is designed for 6 m/s, achieving the required chilling performance in the tunnel requires an air velocity across the product of 4 m/s, refer table 1. The fan shaft power is therefore reduced to $52.2*(4/6)^3/0.85$ = 18.4 kW assuming frequency converter and motor efficiencies combined of 85%.

The equivalent cross-flow unit requires an air circulation rate of ~438 m^3/s to achieve w_o=6.0 m/s across the product.

This is estimated by assuming a typical 11x12 carrier machine with a total of 114 carriers in the air stream. The center distance of the carriers is 600 mm – the total length of the processing section hence becomes 114/2*0.6 = 34.2 m.

With a vertical center distance between shelves within the carriers of 0.36 m, the carrier height becomes 11x0.36 = 3.96 m. The free airflow face in cross flow configuration hence calculates as 3.96x34.2-57x11x0.60x0.165 = 73 m^2. The airflow required becomes 73x6 = 438 m^3/s.

The corresponding fan shaft power in the latter case is around 100 kW corrected for speed and using high efficiency 6 pole ø1500 mm fans. This gives rise to a substantial power penalty for the cross-flow unit of ~82 kW.

	TriZone Chill Tunnel	Cross Flow Chill Tunnel
Total product quantity processed, kg	300,000	300,000
C_+, kJ/kgK	3.4	3.4
Total product heat removal, MJ	30,600	30,600
Cycle time, hours	15	15
Average product heat, kW (kJ/s)	566.7	566.7
Fans, kW	18.4	100
Total refrigeration plant capacity required, kW	606.0	696.6
Suction line loss, K	0.1	1.0
Required saturated compressor suction temperature, °C	-14.0	-11.0
Compressor shaft power, kW	174.1	182.0
Condensing temperature, °C	33.0	33.0
Condenser heat rejection, kW	780.0	870.0
Condenser fans, kW	13.0	14.5
Condenser spray water pumps, kW	1.6	1.8
Refrigerant pump(s), kW	3.4	1.7
Evaporator fans, kW	18.4	100
Total system shaft power, kW	210.5	300.0
Overall average electrical efficiency	0.85	0.85
Total energy input per cycle, kWh	3715	5294
System energy input/t, kWh/t	12.4	17.6

Table 6. Chilling energy requirements, TriZone versus cross-flow chilling tunnel

The TriZone system in this comparison features 30% improvement in energy efficiency.

The combined annual energy cost comparison for a daily product mix comprising 5,000 off 27 kg frozen cartons and 15,000 off 20 kg chilled cartons becomes as shown in table 7. This is based on the system energy input values derived in tables 5 and 6 and 36 hours retention in zone 2 of the TriZone system. The unit electricity cost has been assumed at $80/MWh and the number of full production days at 250 p.a.

	TriZone tunnel combined with three stage R744/R717 cascade refrigeration system	Contact freezing plant combined with cross-flow chill tunnel and serviced by dual stage R717 liquid overfeed refrigeration system
Frozen product	$265,000	$233,000
Chilled product	$75,000	$106,000
Total	$340,000	$339,000

Table 7. Annual energy costs for TriZone tunnel compared with conventional system

For a meat processing plant producing the product mix assumed above, the annual energy costs associated with the TriZone tunnel system is approximately identical to the energy costs associated with a conventional plant.

Safety Issues and Safety Legislation

The TriZone tunnel system contains all ammonia refrigerant within the confines of the engine room. Compared with conventional contact freezing systems combined with chilling tunnels, the ammonia charge associated with the TriZone system is 20 to 40 times less.

Personnel cannot occupy the materials handling section of the TriZone tunnel. All access doors are alarmed and CO_2 detection equipment is provided within the insulated enclosure.

The elimination of all ammonia refrigerant within the materials handling section of the TriZone tunnel will impact favourably on the insurability of the equipment and also on the insurance premiums generally.

Major international insurance underwriters are constantly attempting to minimize risks by way of minimizing the system charges of toxic substances and by reducing the extent to which these fluids are reticulated within the facility insured. The same applies to legislators internationally [7].

Practice has shown that the probability of refrigerant leaks is significantly greater in contact freezing applications than in systems where all refrigerant connections are fixed (non-flexible). There have also been incidents where poor house keeping (failure to defrost, failure to remove ice formations and general operator errors) have led to uncontrolled releases of liquefied ammonia refrigerant in contact freezing systems.

Occupational Health and Safety Legislation in most Australian States and Territories is clear with respect to uncontrolled releases of toxic substances. Such incidents transform the site where the incident occurs into a forensic site.

Once a site is a forensic site, the owner/operator is not permitted to interfere with the equipment, which was the cause of the uncontrolled release of the toxic substance. The owner/operator has the duty to take action to terminate the release and is then required to inform the relevant Authorities of the incident.

Re-commencement of operations is not permitted until the owner/operator has demonstrated to the satisfaction of the Authorities in charge that actions have been taken to prevent future uncontrolled releases of toxic substances. Owners/operators of large-scale contact freezing systems containing ammonia are likely to increasingly face difficulties with respect to convincing O H & S inspectors that such systems are safe.

With respect to safety, the two major driving forces behind the continued advancement of CO_2/NH_3 cascade technology in the world are operator safety and fire safety. The TriZone system addresses both of these issues.

Capital Costs

Current indications are that the TriZone system offers a capital cost advantage between 0 and 15% compared with conventional contact freezer/chilling tunnel systems.

This is based on comparisons between systems, which are functionally identical with respect to production and automation levels. The range of 0 to 15% reflects the differences in site conditions and production mix from application to application.

Conclusion

The new TriZone chilling/freezing system for fresh meat packed in corrugated cardboard cartons is presented as a financially viable, technically and environmentally sound alternative to conventional chilling/freezing systems. In addition, the system addresses the inherent insurance and occupational health and safety issues associated with commonly used contact freezing systems containing very large charges of ammonia.

On a system comparison basis with identical functions and identical levels of system automation, the capital costs of the TriZone system is equal to or about 15% less than conventional systems comprising a single retention time blast chilling tunnel combined with a number of batch type contact freezers.

As a result of the employment of CO_2 refrigerant as well as the introduction of multiple compression stages and multiple temperature zones, the energy consumption per unit mass of product frozen/chilled is the same or a little higher than conventional systems depending on product mix between chilled and frozen.

Confining all ammonia refrigerant to the engine room combined with a reduction in ammonia charge by a factor of 20 to 40 greatly improves operator safety. In addition, the minimization of fire hazards due to the elimination of reticulated refrigerant in all refrigerated spaces may in some cases have a favourable impact on insurance premiums.

The high levels of production flexibility with respect to product sizes, product types, product packaging, product unit mass, retention times, post cooling separation, product storage and product collation are considered highly advantageous to meat processors and food processors in general.

Facilities producing chilled meat, which has been hot boned, are often faced with multiple materials handling efforts. Firstly, the hot boned product is subjected to an initial rapid chill in a conventional batch type air blast freezer. Following this, the product is transferred to an air blast chiller.

This chilling process for hot boned product may be carried out automatically in the TriZone system in accordance with a pre-determined temperature/time pattern. Firstly the product is subjected to the Zone 1 environment for the initial rapid chill and then transferred to the chill zone for completion. Similar processes may be implemented for retail ready products.

The materials handling and freezing principles described in this paper have been proven in a number of single and dual temperature zone installations in Australia and overseas. One dual temperature zone system, which is in operation in Australia, discharges chilled and frozen meat products, which are subsequently collated in pallet lots and palletized automatically.

The employment of a dehumidification system at the TriZone product entry air lock ensures dew points of around -45°C to -50°C. This extends defrost intervals to several months thus further minimizing energy consumption and temperature variations.

In conclusion, the system presented is considered a real alternative to the conventional chilling/freezing systems in use today. Energy efficiency and materials handling flexibility have been greatly improved. Operator safety has been significantly increased and fire risk greatly minimized. Capital costs are similar to or less than conventional systems when equal levels of automation and functionality are compared.

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