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Optimisation of Refrigeration and Heat Pump Designs for Meat Processing Plants

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1. Introduction

Most meat processing plants are designed and constructed in a piecemeal manner by the various specialists who cover their particular discipline. Consequently it is usual for a refrigeration specialist to calculate the refrigeration loads of the plant and design a refrigeration system as economically as possible to meet the plant requirements. Likewise, when it comes to the requirements of other services, such as hot water and steam, other specialists are used to determine the requirements and they, in turn, economise the design of their side of the plant.

Most large meat processing plants incorporate their own by-products department associated with the drying of waste material and further processing into tallow and stock feed. This process therefore generates a large amount of waste heat as the water is evaporated. Again, specialist contractors are used to determine the most suitable plant for the needs of the meat works.

The purpose of this Paper is to integrate these three particular technologies and to analyse the most suitable overall plant to optimise its total energy requirements, bearing in mind that there is considerable waste heat available from the refrigeration plant and the by-products sector, while there is a large, relatively low temperature, heat requirement necessary to produce the hot water. It is particularly important to employ specialists in the design of meat processing works and the management of them as without this overall analysis it would be impossible for the individual equipment designers to arrive at a suitable optimum configuration.

Furthermore, specialists designing heat pumps have no way of selling their systems into such plants without a specialist in the Industry tabulating the heat pump's requirements and integrating it into the other specialist services of the plant. Inevitably the heat pump designer does not know the overall heat balance of the plant and, particularly in Europe, the quality of the meat works management is so low that there would be no way of the management providing the supplier with any accurate information. Consequently, the opportunity of making a sale and economising on energy is lost. This Paper attempts to fill this gap.

2. The Heat Balance

Bearing in mind that all meat processing plants require refrigeration and hot water and have waste heat, these specific aspects can be summarised as follows:

2.1 Refrigeration

The refrigeration requirements for any meat works are divided between the following sections within the plant.

(i) Air Conditioning

This is required for the maintenance of processing areas at a temperature of no higher than 10^0C and refers particularly to the boning operation. The required refrigeration saturated suction temperature in the engine room is approximately 0^0C.

(ii) Meal Chilling

Any modern meat works requires the carcasses to be chilled following the dressing operation at an air temperature of at least -1^0C which requires a refrigeration saturated suction temperature of at least –10^0C.

(iii) Freezing

Most meat works require a capability to either freeze carcasses or freeze boneless meat produced in the boning room, as well as offals. Freezing can be carried out either over 24 hrs or over 48 hrs and will require air temperatures respectively of -35°C and -25°C with corresponding refrigeration saturated suction temperatures of -43°C and -32°C.

(iv) Cold Storage

Plants that produce frozen products must always have a requirement for cold storage at a temperature of no higher than -18°C, which will require a refrigeration saturated suction temperature of approximately -25°C.

The above requirements can be summarised as shown in Table 1.

The requirements as set out in Table 1 will be analysed to determine the most economic system design.

2.2 Heat Requirements

Heat is required basically for two main services within a meat works - the production of hot water and the evaporation of water out of the product in the by-product section. Hot water is usually required in three services as follows. Exact temperatures vary from plant to plant. The water temperatures for a typical abattoir are shown in Table 2.

The by-products department requires steam at 6.5 bar for the evaporation process.

2.3 By-Products Plant Waste Heat

In the process of evaporating water from the by-products, the water is driven off at a temperature of 100°C and atmospheric pressure. This relatively high temperature heat is sufficient to make a contribution to the hot water requirement of the plant.

2.4 Refrigeration Waste Heat

Large amounts of low temperature waste heat approaching 35°C are released by the refrigeration plant and this waste heat is very rarely used. The main purpose of this Paper is to analyse whether there is an economic case for its use.

3. Typical Plants for Consideration

For the purpose of this Paper and in order to arrive at a practical answer to the question of how waste heat can be utilised, three typical plant sizes will be taken into account as follows, and analysed accordingly.

TABLE 1

		Air temperature	Max saturated suct. temp
(1)	Air conditioning requirements	10°C	5°C
(2)	Chilling	-1°C	-10°C
(3)	Cold storage requirement	-18°C	-25°C
(4)	Carcass freezing and 48 hour carton freeze	-25°C	-32°C
(5)	24 hour carton freeze	-35°C	-43°C

TABLE 2

*	Sterilizing	82°C
*	Wash down	65°C
*	Basins, showers and carcass wash	43°C

3.1 Small European Plant

Capacity: 200 cattle/day
1500 pigs/day
1000 sheep/day

Most of these plants and particularly those in the UK are unlikely to have a by-products department, the waste material being sold in unprocessed form to specialized centralized by-products processors.

3.2 Medium Sized Overseas Plant

Capacity: 550 cattle/day
1500 pigs/day
6000 sheep/day

There will be very few occasions where such a plant did not have a by-products department which would require steam and which would, in turn, be producing large quantities of waste heat.

3.3 Large Southern Hemisphere Plant (Typical New Zealand Plant)

Capacity: 750 cattle/day
150 pigs/day
20,000 sheep/day

All such plants would have a by-products facility producing large quantities of waste heat. The small pig throughput is typical to provide local pork requirements while the beef and sheep are for export.

4. Refrigeration Design

Bearing in mind the variables which exist on a meat works site associated with waste heat, its utilisation, hot water heating and refrigeration, the part of the plant which is fixed with regard to its basic design is nevertheless the refrigeration plant. This is simply because the basic refrigeration load exists for each part of the system, as described above, and the engineer must optimise the plant to meet these refrigeration loads, keeping capital costs to the minimum and at the same time producing the most economic plant with respect to the consumption of electricity. There is no option, as there is in the case of the by-products process, for refrigeration to be contracted out to third parties.

As explained above, most meat plants, particularly large units, would theoretically have five separate refrigeration sections covering air conditioning, chilling, carcass freezing, carton freezing, and cold storage.

It is usual in practice for the five separate suctions to be found uneconomic on capital cost, although highly efficient on electricity usage, and as a result the plant is usually simplified into three suctions as shown in Table 3.

The reason for these three evaporating temperatures usually being chosen is that the air conditioning and cold storage loads are small in relation to the other services required and therefore the inefficiencies so caused by combination are minimal.

TABLE 3

*	-10^{0}C Sat. suct. temperature	Air conditioning and meat chilling
*	-32^{0}C Sat. suct. temperature	Carcass freezing, 48 hour carton freezing and cold storage
*	-43^{0}C Sat. suct. temperatue	24 hour carton freezing

With regard to the -43^{0}C saturation suction temperatures, this is increasingly becoming less common as with more emphasis in the last 10 years being placed on energy saving most plants freeze cartons over a 48 hr period, rather than 24 hrs.

There are two fundamentally different principles that can be used for the design of refrigeration plant.

(a) *Packaged Systems.* The plants are self contained and can be located close to the load requirement. Refrigerant 22 or 502 are commonly employed in such systems so that single stage compressors can be used.

(b) *Centralised Engine Room Concept.* Pumped recirculation compressor/condenser plant is housed in a centralised location to keep expensive lines and line losses to a minimum. The use of R22 or R717 based on two stage systems for low temperatures results in low electricity consumption. The concentration of all waste condenser heat in one location allows economies for hot water production.

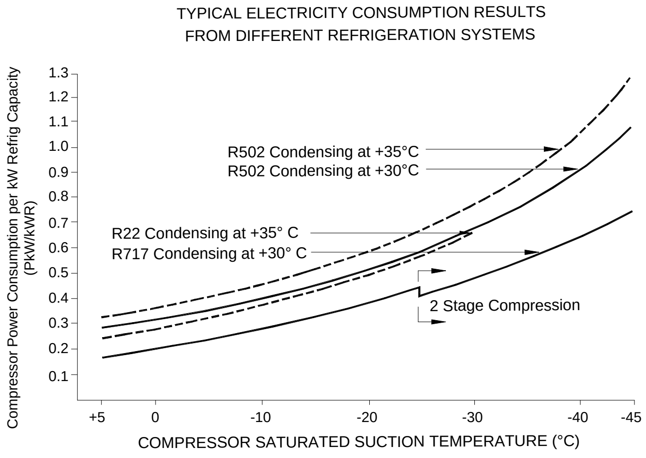

Fig. 1. Typical electricity consumption results from different refrigeration systems

Figure 1 gives a summary of typical electrical consumption figures for the above systems and refrigerants. It soon becomes obvious that the only sensible solutions for large meat processing plants is a choice between either pumped R717 or R22 systems.

Thus most refrigeration requirements on a large meat works is for large refrigeration loads at 2 saturated suction temperatures, i.e. -10^{0}C and -32^{0}C. The usual practice is to design a two stage plant with booster compressors operating at the low pressure, discharging into an intercooler which, in turn, is then serviced by the second stage compressors. The intercooler in turn is used to provide refrigeration to the -10^{0}C services.

With the introduction of screw compressors, there is a case for eliminating the two stage operation and working the -32^{0}C on a single stage basis. This system is perfectly acceptable and in fact provides the optimum solution to reduce capital cost keeping running costs at an acceptable level, but only if sub-cooled liquid is fed to the low stage vessel via the high stage suction. The two alternatives are shown in Figs 2 and 3 and it can be seen that the single stage option will significantly reduce capital cost.

With regard to the electricity consumption, Fig. 4 shows that the two stage system working with sub-cooled liquid has only a very marginal increase in electricity consumption.

We would conclude, therefore, that the refrigeration plant design for most typical meat works operations should be based on Fig. 3, utilising single stage plant with sub cooled liquid feed using screw compressors, servicing two saturated suction temperatures of -10^{0}C and -32^{0}C.

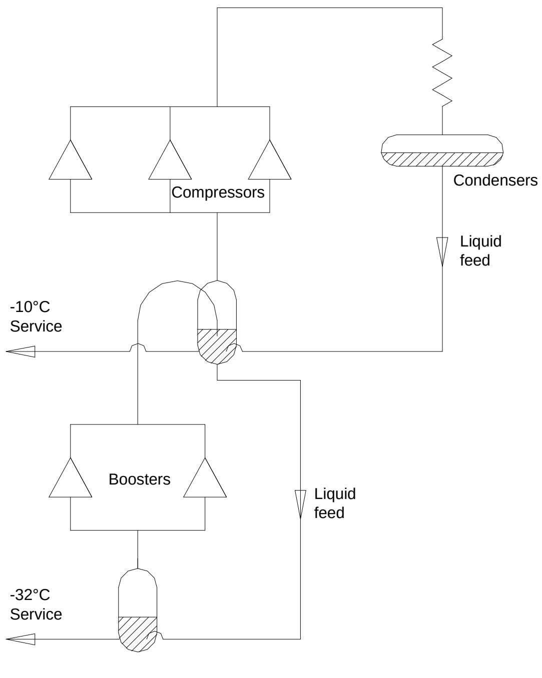

Fig. 2. Typical two stage configuration

Having reached this conclusion, we list in Table 4 the refrigeration requirements for the three typical plant types shown above, together with the condenser waste heat rejection rate, all taken as an average over a typical 24 hr period.

The remainder of this Paper will conclude as to whether the waste heat produced from the condenser plant can be satisfactorily used to cut down on the total energy requirements of the plant.

5. Hot Water Requirements

From extensive experience in the management and design of meat works, the three plants under consideration, we know, will require approximate quantities of hot water as shown in Table 5.

The quantities convert into an overall 24 hour hot water heating requirement as shown in Table 6.

The heat requirements associated with the 43⁰C water supply, due to its relatively low temperature, could be met quite adequately by the refrigeration plant condenser waste heat provided that a suitable heat pump was provided to transfer heat from the refrigeration condensers into the cold water supply.

6. By-Product Waste Heat Availability

From our experience in the management and operation of meat processing plants, we give in Table 7 the approximate values of waste heat rejection at a temperature of 100⁰C which would be available from the by-products plant against each of the three types of meat works under consideration.

7. Refrigeration Waste Heat Availability Versus Hot Water Requirements

Table 8 summarises the heat balance, it can be seen that the small European plant, having no by-products department, has no option under normal circumstances, to produce all its hot water, other than by burning fossil fuels in a steam or hot water boiler. It is the writer's contention however that the waste heat from the refrigeration plant can be suitably upgraded by a heat pump and it can be seen that the condenser waste heat available is some four times the 43⁰C water requirement. A typical Small European Plant has been operating successfully in this way with a heat pump for a number of years.

Turning now to the medium and large sized plants normally seen overseas, it can be seen that the waste heat from the by-products department is in no way sufficient to generate all the hot water requirements of the works and again the condenser waste heat could be used via a heat pump to produce all the works' 43⁰C water, there being again some twice as much waste heat available compared with the heat required.

8. Heat Pump Potential

Figure 5 shows a typical arrangement for a heat pump working on R 12 and pumping the heat from the refrigeration condenser

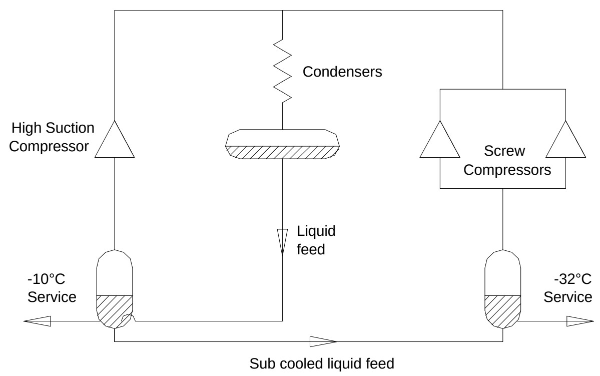

Fig. 3. Single stage with sub-cooling

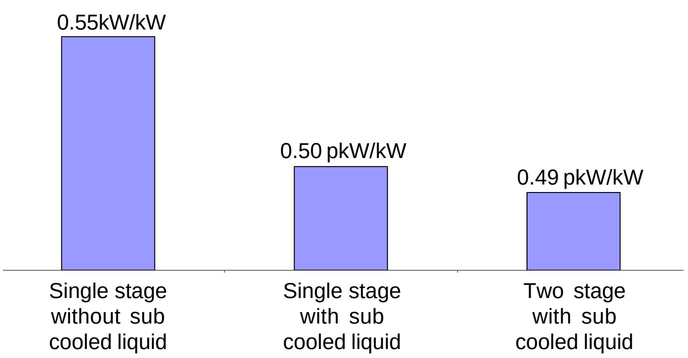

Fig. 4. Power consumption figures comparing single stage with two stage plant (saturated suction temperature -32⁰C)

TABLE 4
Refrigeration requirements for three plant types

	kW			
	-10⁰C ref load	-32⁰C ref load	Condenser waste heat	Waste heat kJ x 1000 per day
Small plant	522kW (148 TR)	77kW (22TR)	670kW (191TR)	57,900
Medium plant	1319kW (375 TR)	1248kW (355 TR)	2785kW (792 TR)	240,600
Large plant	1143kW (325 TR)	4131Kw (1175 TR)	5626kW (1600 TR)	486,100

Note: ( ) denotes Tons Refrigerattion

TABLE 5

	Cubic metres / 24 hours		
	82⁰C	65⁰C	43⁰C
Small plant	108	115	162
Medium plant	456	972	1367
Large plant	737	1572	2211

TABLE 6
Hot water heating requirements for three plant types

	kJ x 1000 / 24 hours			
	82⁰C	65⁰C	43⁰C	Total
Small plant	29,000	22,600	17,000	68,600
Medium plant	122,300	191,400	143,200	456,900
Large plant	197,600	309,600	231,600	738,800

TABLE 7

	kJ x 1000 / 24 hours
Small plant	0*
Medium plant	62,500
Large plant	98,500

* No Rendering

TABLE 8
Waste heat versus hot water requirements

kJ x 1000 / 24 hours

	Hot water requirement	By-product waste heat	Hot water remaining heat requirement	43^0C Water heat requirement	Condenser waste heat	Maximum heat pump output
Small plant	68,600	nil	68,600	17,000	57,900	67,600
Medium plant	456,900	62,000	394,900	143,200	240,600	280,700
Large plant	738,800	98,500	640,300	231,600	486,100	567,100

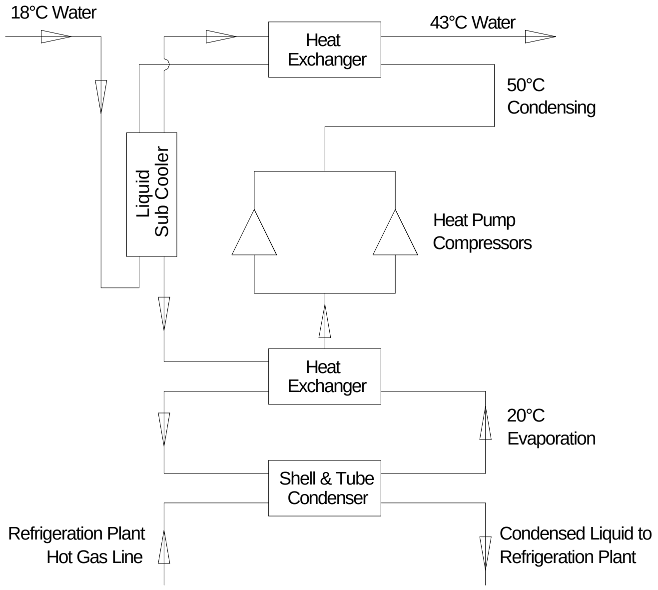

Fig. 5. Typical arrangemennt for a heat pump working on R12

source to a temperature of 50^0C from which the 43^0C hot water requirement can be met. The heat pump is of a simple design but uses sub-cooling from the incoming cold water supply and on the basis of using an evaporator temperature of 20^0C and a condensing temperature of 50^0C, and the effective sub cooling, the coefficient of performance of the heat pump can theoretically rise to 7 or above. Under practical conditions and as far as this Paper's calculations are concerned, a COP of 6 will be assumed as more practical.

From the above assessment of hot water heating requirements it has been shown that condenser waste heat can be turned to 43^0C water in all of the three plants analysed. Average conditions have been taken over a full day's production and as in practice there are large variations in refrigeration loads and hot water requirements, it will be necessary to install hot water tanks to act as storage buffers to even out the daily requirements. In large meat works it has been common for many years to have such tanks to use the by-products waste heat. Additional tanks may be required depending on the particular plant/heat balance.

On the basis of electricity charges of 5p/kW hour and a coefficient of performance for the heat pump of 6, then the electricity cost for generating 43^0C water will be approximately 0.231 pence per 1000 kJ heat recovered. However, because the condenser heat available is so much in excess of the heat required, the heat pump would be programmed to run only when

TABLE 9
Daily costs & savings in water heating

	Daily 43^0C water (kJ x 1000)	Heat pump electricity cost £	Conventional cost £	Possible energy saving £
Small plant	17,000	26.01	40.29	14.28
Medium plant	143,200	219.10	339.28	120.28
Large plant	231,600	354.35	548.89	194.54

maximum demand was low, i.e. the electricity charge to the heat pump would be an energy charge only at 3.3 pence per kW per hour. This will give a cost of 0.153 pence per 1000 kJ.

Using a conventional boiler with an efficiency of 80% and fuel oil at 39,600 kJ per kg at a cost of £75/tonne, the cost of heat water by fuel oil will be 0.237 pence per 1000 kJ.

Table 9 shows the daily costs for the production of 43^0C water using the refrigeration waste heat and heat pump compared with generating the same hot water using a conventional boiler for the three plants in question, based on the above figures.

It can be seen that operating for over 250 days/year will show a fuel cost saving of approximately £3570 per annum for small UK type plants, up to approximately £48,635 per annum for large overseas operations. It is the writer's opinion that compact heat pump plant situated in the actual engine room location, drawing heat from the refrigeration condenser plant, could be purchased and installed at a cost not greatly in excess of these yearly savings figures and thus could be paid off within two years of installation.

For the large application to produce the full 230 million kJ per day, two small packaged 1275 cubic metre per hour screw compressors would easily meet the hot water load at 43^0C as shown in Table 9.

Another way of attempting to optimize the heat pump possibilities is to run the pump over as extended a period as possible and to use the full electricity tariff at 0.231 pence per 1000 kJ of heat recovered. By working the pump continously it would then be possible to heat all hot water to 43^0C before heating further by conventional means the higher temperature quantities. By proceeding in this way the 43^0C water quantities to be heated by the pump would be as follows:

Small plant	40,400 kJ x 1000/day
Medium plant	292,800 kJ x 1000/day
Large plant	473,500 kJ x 1000/day

TABLE 10
Daily costs & savings in water heating

	Daily 43^{0}C water (kJ x 1000)	Heat pump electricity cost £	Conventional cost £	Possible energy saving £
Small plant	40,300	50.40	95.51	45.11
Medium plant	280,700	351.01	665.26	314.25
Large plant	473,400	591.99	1121.95	529.96

Comparing this figures with Table 8, double the amount of water could be serviced by the heat pump but at the full electricity tariff. Table 8 also indicated that there is sufficient heat available to do this from the heat pump. Working in this way savings, as shown in Table 10, should be possilbe, resulting in the small plant saving some £11,250/year while the large plant should save up to £132,500/year.

There is a real demand for a packaged heat pump unit to meet the above requirements and the refrigeration manufacturers should be looking to come up with a suitalble automatic economic unit.

9. Conclusion

In designing the optimum refrigeration plant for most modern meat works, it is best to rationalise the refrigeration suctions to two pressures at an evaporation temperature of -10^{0}C and -32^{0}C. This arrangement gives good electricity consumption while allowing capital costs to be kept to a minimum using single stage screw compressors. The -32^{0}C suction must use sub cooled liquid. The refrigerant should be R717 or R22 with pumped circulation. Single stage packaged plants are too energy inefficient.

Further economies can be achieved by utilising the meat works by-products department to generate high temperature sterilising and wash down water by installing a by-products waste heat recovery plant. This arrangement will allow lower temperature hot water to be generated efficiently by a heat pump arrangement working between the refrigeration condenser waste heat source and a special hot water heat exchanger.

Such a system could save a large meat works some £49,000 per annum in energy costs, allowing the heat pump capital cost to be recovered within two years.

The alternative arrangement is to heat all hot water to 43^{0}C which would mean continous heat pump operation and the use of a full electrical tariff charge. However, using typical electrical tariff charge rates saving and working in this way could save up to £133,000/year. The arrangement to be used would depend upon local tariff arrangements and specific works requirements.

Heat pump design specialists should concentrate on systems to operate at higher temperatures as if an economic system can be achieved, hot wash down water at 65^{0}C could also be generated in this fashion with additional savings. The heat pump condensation temperature would then have to rise from 50^{0}C to 72^{0}C. Exact economies depend very much upon the present fluctuations in fuel prices.

A further saving by using such heat pump systems arises from the lowering of the refrigeration plant condensing pressure or cutting back on condenser capital cost, the former producing significant additional savings to the plant energy account. No allowance in the above savings has been made for this additional benefit.