ENERGY SAVINGS THROUGH LIQUID PRESSURE AMPLIFICATION IN A DAIRY PLANT REFRIGERATION SYSTEM

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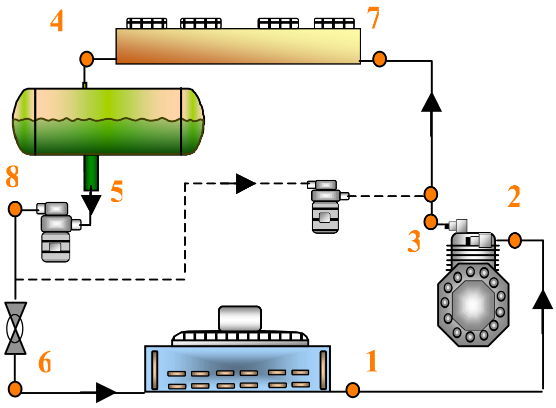

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Introduction

The Dairy sector is one of the major refrigeration energy users in the food industry. Significant energy and financial savings can be achieved by adopting new refrigeration technologies and practices. One such technology which has been available on the market for direct expansion evaporator vapour compression systems for a number of years but has not as yet found wide application is Liquid Pressure Amplification (LPA).

The LPA technology utilises a refrigerant pump in the liquid line after the receiver to maintain a high enough pressure differential across the expansion valve to compensate for the pressure drop in long liquid lines. This allows the condenser pressure to be varied in line with variations in the ambient temperature leading to lower discharge pressures during periods of low ambient temperatures and lower compressor power consumption. Operation at lower pressures also increases the refrigeration capacity of the system enabling it to cope with increased load demands.

LPA can be applied to new refrigeration plant and as a retrofit to existing plant. LPA also enables the use of liquid injection into the discharge line of the compressor which desuperheats the refrigerant vapour before entering the condenser. This increases the capacity of the condenser, which in turn enables operation of the plant at lower condensing temperatures.

This case study considers the application of a LPA and liquid injection to a cold store at a dairy plant in Northern Ireland. Before the application of the technology the cold store had difficulty maintaining temperature during periods of high ambient temperatures, with a drift of 5°C from design. The main aim of the case-study is to investigate the performance of the LPA technology as installed at the plant and estimate the energy savings and environmental performance of the system.

Method

Data obtained for a short period before and after commissioning of the LPA technology on 17 May 2008, through a web based monitoring system were used to investigate the performance of the system and energy savings achievable. The refrigeration system was comprehensively instrumented with pressure and temperature sensors to measure temperatures and pressures at different points in the cycle. Other parameters monitored included the ambient temperature and the power consumption of the compressor.

The data were extrapolated over a whole year and through system simulation were used to evaluate the seasonal performance and energy savings potential of the system.

Description of Facility

The case study described here concerns a 100 kW cold room refrigeration system at a dairy plant. A schematic diagram of the system is shown in Figure 1.

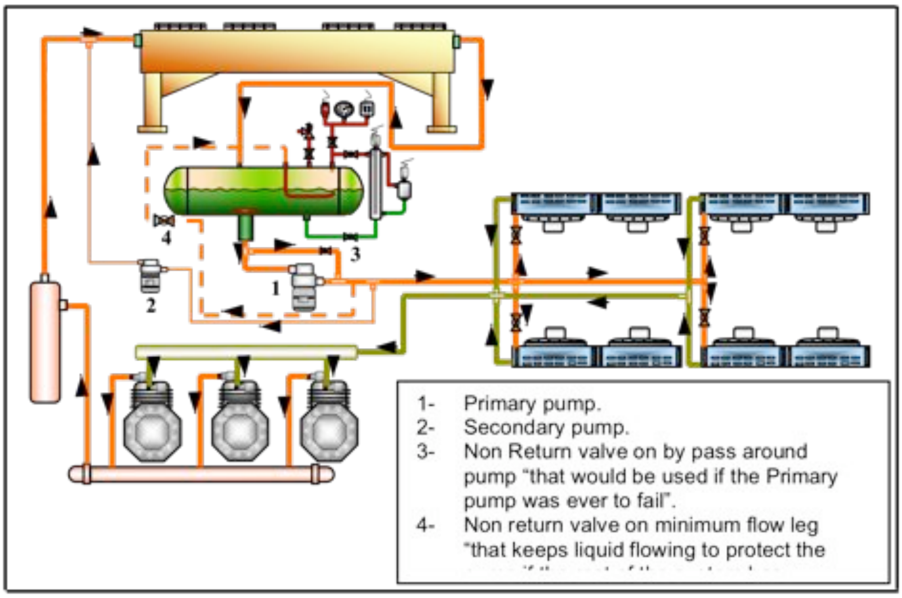


Figure 1: Cold room plant with LPA system

The LPA refrigeration system is one of three refrigeration systems used to maintain a cold storage space of 1049 m² floor area at a temperature of 4°C.

The system employs three Bitzer 6G30.2 semi hermetic compressors and a Searle MDG205 6D condenser feeding 4 evaporator coils in the cold room. The refrigerant employed is R404a. A liquid delivery (LPA) pump Hy-save 875IND is fitted into the liquid line whereas another pump Hy-save 809IND is used to provide liquid injection to the compressor discharge line, Figure 2.

Figure 2: Refrigeration System Components

LPA Technology

The Liquid Pressure Amplification technology raises the pressure of the liquid refrigerant to suppress flash gas formation. This allows the minimum condenser 'head' pressure to float downward with ambient temperature, increasing the efficiency of the refrigeration cycle.

Effect of Lower Head Pressure:

At fixed ambient temperature and cooling load, lowering the head pressure of the system will result in [1]:

- A decrease in compressor energy consumption.
- A small increase in compressor capacity.
- An increase in condenser fan energy consumption.
- A lower compression ratio leading to longer compressor life.

Factors limiting the reduction in head pressure are:

- Required minimum pressure difference across the expansion valve for proper operation of thermostatic expansion valves.
- Condenser and evaporator coil size/capacity.
- Use of compressor discharge gas heat recovery.
- Requirements for hot gas defrosting if employed.

Determination of System Minimum Head Pressure

The minimum head pressure that a refrigeration system can work with should be above the summation of the evaporating pressure, the minimum required pressure differential across the valve and the pressure drop in the liquid line (from liquid receiver to the expansion device), and the pressure drop in the condenser.

To increase the overall efficiency of refrigeration systems, LPA can be supplemented by liquid injection into the discharge line to desuperheat the discharge gas. Desuperheating using small quantities of liquid injection (around 5% of the total circulation rate) makes more efficient use of the condenser- less heat transfer area is used to desuperheat the gas and more area is available for two phase heat transfer. This leads to lower condensing temperature and higher cycle efficiency.

LPA Performance Analysis

Data for two days before the retrofit and four days after the installation of the LPA and liquid injection pumps have been used for the analysis. The variation of condensing temperature, evaporating temperature, liquid line temperature and outdoor temperature is shown in Figure 3.

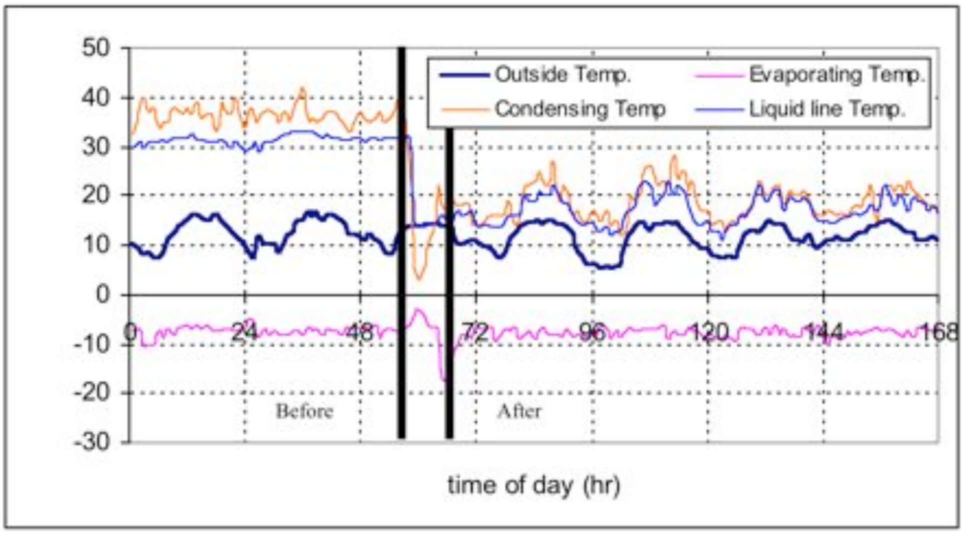


Figure 3: Temperature Variation before and after the LPA Retrofit

It can be seen that the variation of the ambient temperature for the six day period was very similar before and after the installation of the LPA and hence it can be reasonably assumed that the comparative results between the two systems are independent of ambient temperatures. Figure 3 shows that the condensing temperature was maintained fairly constant before the installation of the LPA at an average value of 36°C. It can also be seen that the condensing temperature was fairly independent of the ambient temperature as the head pressure was controlled at a fixed setting of around 17.0 bar.

The variation of the liquid line temperature shows a small dependence on the ambient temperature, rising during the day and dropping during the night. This is due to the better heat transfer and subcooling of the refrigerant liquid at lower ambient temperatures. The refrigeration effect (refrigerant enthalpy difference) across the evaporator coils before and after the retrofit of the LPA was found to increase from around 120 kJ/kg to around 150 kJ/kg (Figure 4).

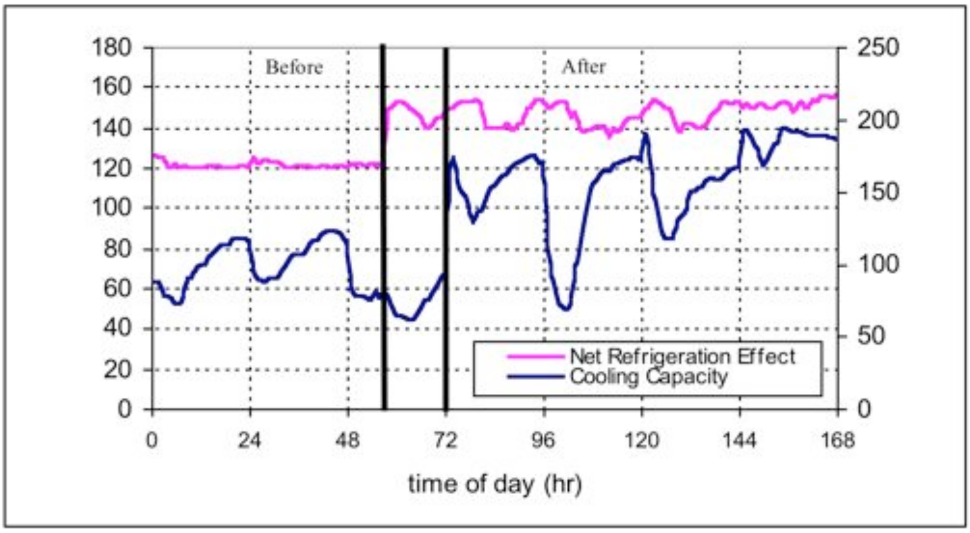


Figure 4. Variation of Cooling Load before& after the LPA Retrofit

Figure 6 shows the variation of compressor suction and discharge pressures and temperatures in the system before and after the retrofit. It can be seen that the discharge pressure dropped from 17 bar to around 9.8 bar after the retrofit, whilst the discharge temperature dropped from 64°C to 44°C. The suction pressure and temperature remained fairly constant.

Figure 6 shows the variation of the compressor power consumption, which was obtained by multiplying the work done by the compressor by the refrigerant mass flow rate. The average compressor power was around 44.3 kW and 32.6 kW after, representing a 26% reduction.

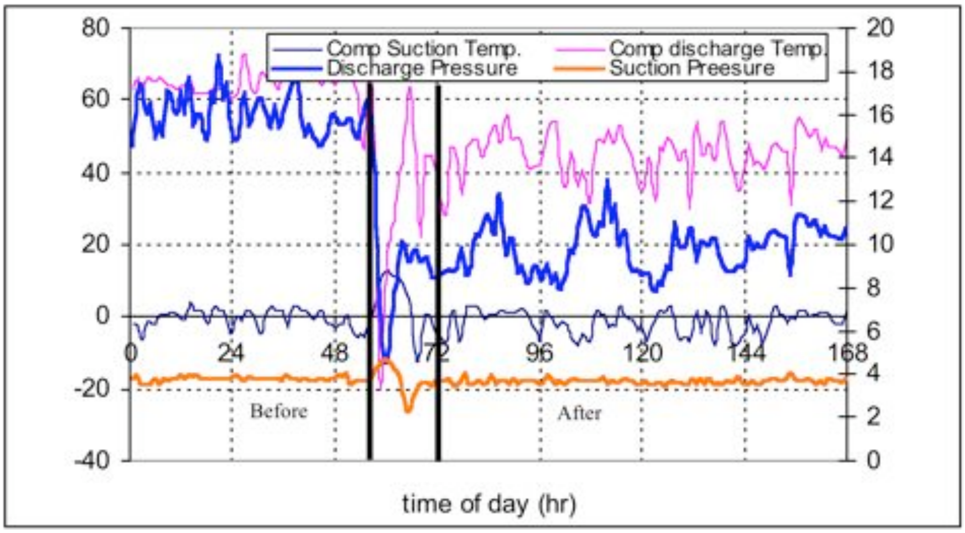


Figure 5: Variation of Compressor Temperature and Pressure before and after the LPA Retrofit

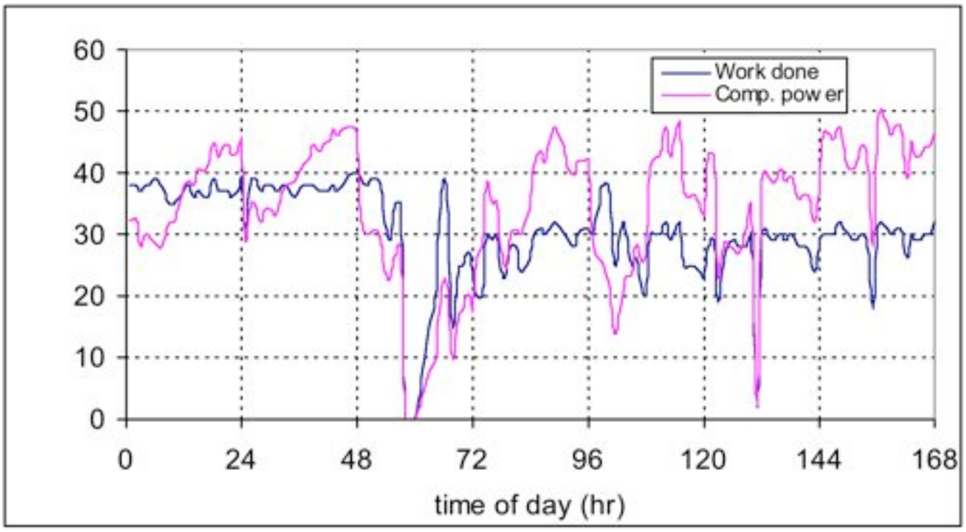


Figure 6. Variation of Compressor Power Consumption before and after the Retrofit

Theoretical Analysis:

Cycle analysis:

The EES software was used to analyse the cycle. Figure 7 shows the pressure-enthalpy diagram of the system before and after the retrofit of the LPA. Steady state conditions were assumed and average values were taken from the measured data.

Figure 7 shows that reducing the head pressure from 16.6 to 10.4 bar increases the refrigeration effect of the system and reduces the work done by the compressor. There is however, a slight increase in the heat rejected by the condenser to the ambient which in a real system will increase the power consumption of the condenser fans. The enthalpy values at the various points in the cycle are given in Figure 7 and the resulting energy flows in Table 1.

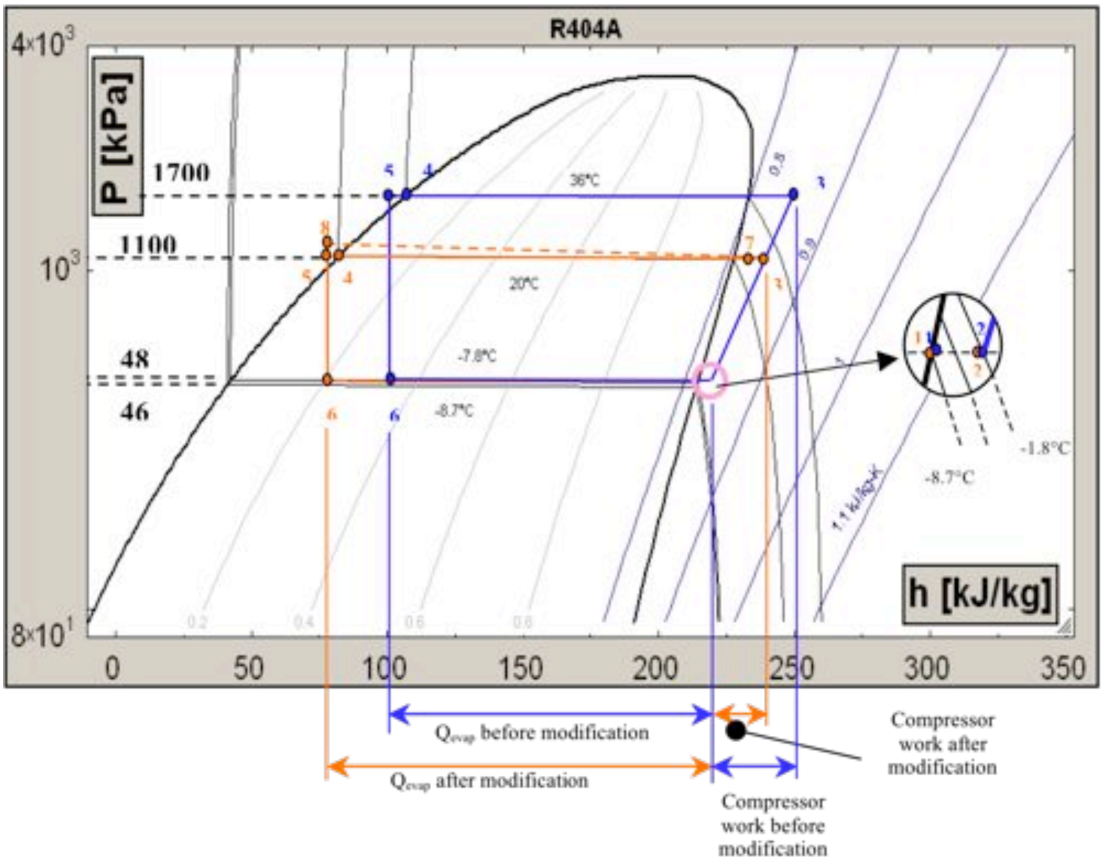
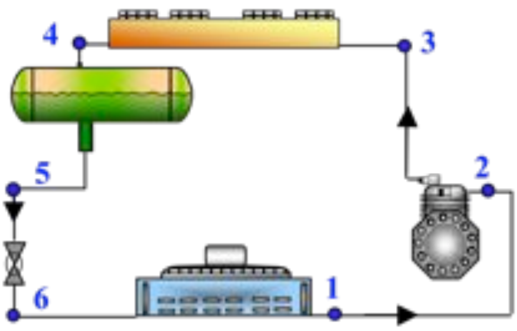


Figure 7: p-h diagram of refrigeration cycle before and after the LPA retrofit

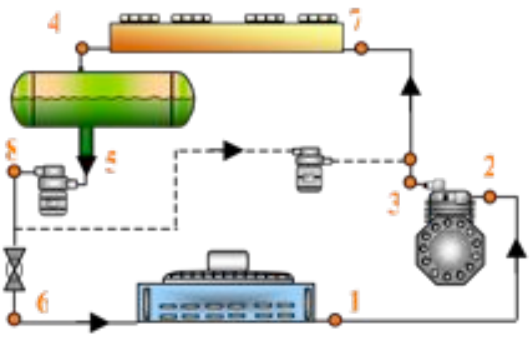
It can be seen from Table 1 that the use of LPA in conjunction with floating head pressure control offers the potential to decrease compressor power consumption by 25%. The capacity of the evaporator coil increases by 22% and the heat rejected at the condenser by 7%.

Sort	h_i [kJ/kg]	P_i [kPa]	T_i
[1]	213.7	453.9	-8.7
[2]	220	453.9	-1.8
[3]	266.2	1664	64
[4]	106.8	1664	36
[5]	100.6	1664	32
[6]	100.6	453.9	-8.7



Before the retrofit

Sort	h_i [kJ/kg]	P_i [kPa]	T_i
[1]	213.7	453.9	-8.7
[2]	220	453.9	-1.8
[3]	254	1043	44
[4]	78.96	1043	18
[5]	74.6	1043	15
[6]	74.6	453.9	-8.7
[7]	245.5	1043	35.82
[8]	74.6		



After the retrofit

Figure 8: Temperatures, pressures and enthalpies of the cycle before& after the LPA retrofit

Table1: Compressor power, cooling capacity and heat rejection

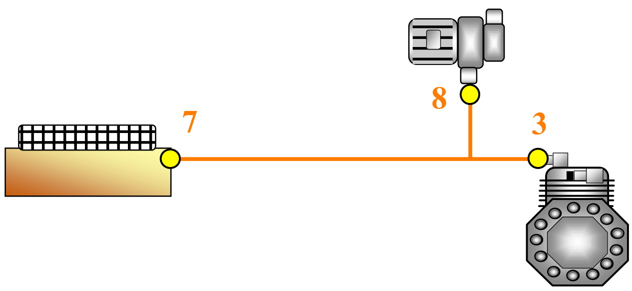
Components	Before the retrofit	After the retrofit	Saving %
Composer power consumption kW	44.3	32.6	25
Heat rejected at condenser kW	152.9	164	- 7
Heat absorbed at evaporator kW	80	103	22
Super-heating °C	6.9	6.9	-
Sub-cooling °C	4	3	-

Figure 8 also shows the temperatures, pressures and enthalpies of the refrigeration cycle with LPA and liquid injection. The inlet conditions to the condenser were established based on the quantity of refrigerant liquid injected into the compressor discharge line. Assuming the injected refrigerant mass flow rate to the discharge line of the compressor is 5% of the total mass flow rate, the inlet condenser temperature drops from 44°C to 36°C. The inlet condenser enthalpy was evaluated using the energy balance equation.

$$\dot{m}_8 = 0.05\ \dot{m}_3$$

$$\dot{m}_3\ h_3 + \dot{m}_8\ h_8 = (\dot{m}_8 + \dot{m}_3)\ h_7$$

$$h_7 = (h_3 + 0.05\ h_8)/1.05$$



The results are shown in Table 2. Liquid injection results in 8.1 kW of cooling of the discharge gas and 4% reduction in heat rejection at the condenser compared to LPA without liquid injection. Table 2 shows that injecting 5% of the total mass flow rate into the discharge line causes a reduction of around 4 % in the condenser fan power .

Table 2: Effect of liquid refrigerant injection on heat rejection at the condenser.

Heat rejection at the condenser	Heat Rejected kW	Fan Power kW	Increment of condenser fan power
Without modification	152.9	13.6	-
With modification, but no injection	168	14.9	9%
With modification, but with 5% of the total refrigerant mass flow rate injection	159.8	14.2	4.3%

Annual system simulations:

To determine the potential energy savings of LPA over a year the refrigeration plant at the dairy plant was modelled using a refrigeration system model built within the TRNSYS simulation environment. A comparison between actual and simulation results for the compressor power consumption is shown in Figure 9.

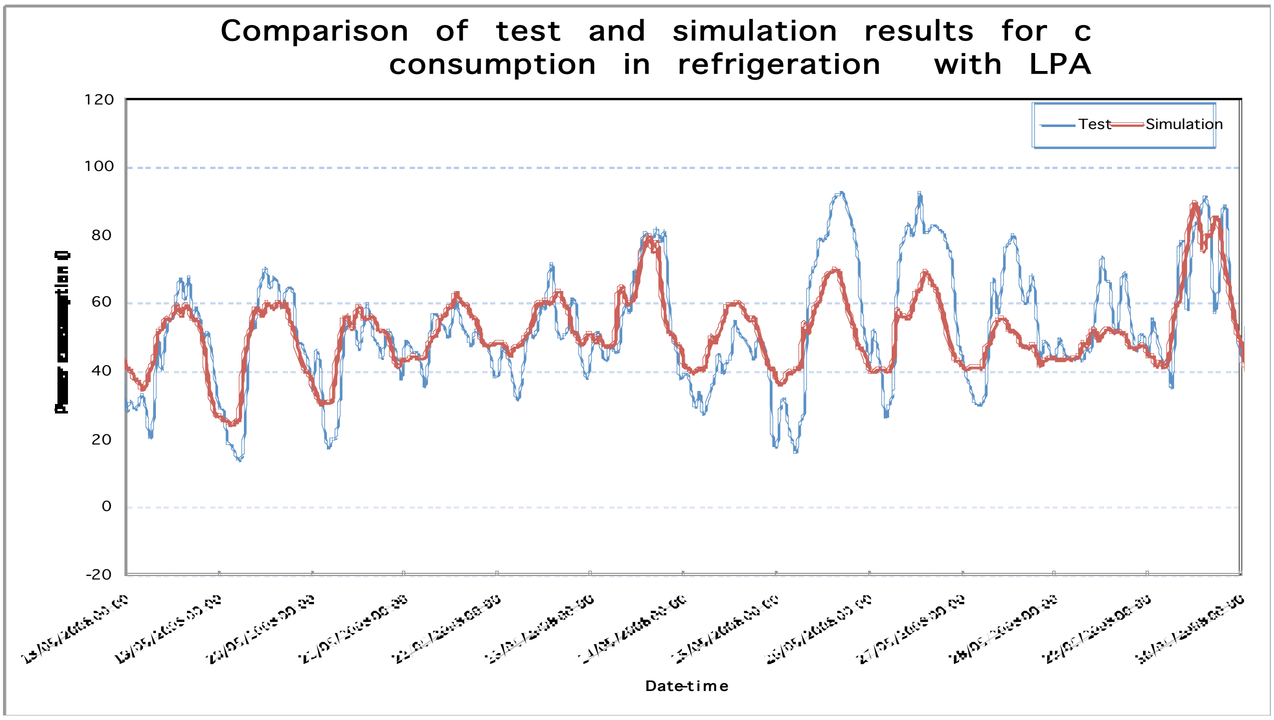


Figure 9. Comparison between actual and simulation results for compressor power consumption

It can be seen that the simulation can predict reasonably well the actual power consumption of the compressors. The differences that can be seen between the two values is mainly due to the difficulty in accurately modelling the load on the refrigeration plant which is not only a function of ambient temperature but also the operating schedule of the cold room and doorway traffic.

The benefits of LPA arise from the fact that it allows the condensing pressure to be reduced in line with reductions in the ambient temperature. LPA is therefore used in conjunction with floating head pressure control. In conventional head pressure control the condensing temperature and hence pressure is controlled to a fixed value above the ambient temperature. This temperature differential is normally 10°C. There is, however, a minimum value below which the head pressure cannot be reduced as a minimum pressure differential is required across the thermostatic expansion valve to ensure satisfactory operation. For R404A and chilled food applications (evaporating temperature -7°C to -10°C) the minimum condensing temperature will be around 20°C.

With the use of LPA, the pressure before the expansion valve can be increased to overcome the liquid line pressure drop as well as the pressure drop in the condenser. This allows the head pressure of the system to be reduced further than is possible without LPA.

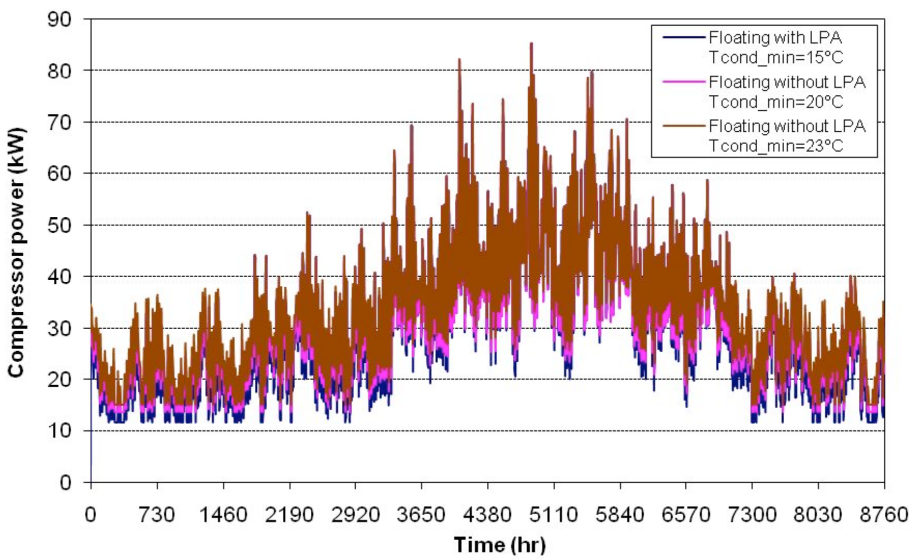


Figure 10: Hourly variation of compressor power consumption in Belfast

For the purpose of seasonal simulations, minimum condensing temperatures of 23°C and 20°C were assumed for the conventional floating head pressure control system and 15°C for the LPA system. Two locations with different ambient temperatures were also used for the simulations, Belfast and London. The variation of the compressor power consumption for the three minimum condensing temperatures is shown in Figures 10 and 11 for the two locations respectively.

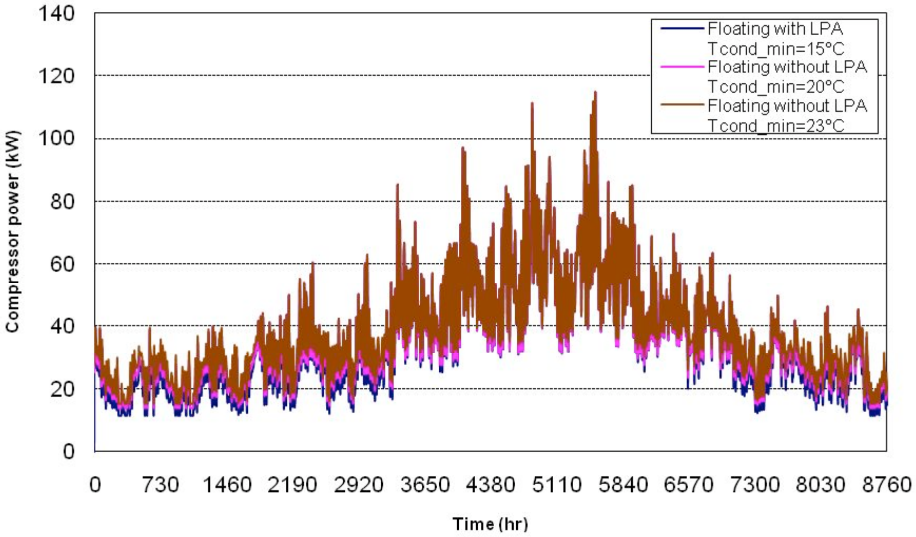


Figure 11: Hourly variation of compressor power consumption in London

The results are summarised in Table 3.

Location	Tcond_min (°C)	LPA installation	Annual compressor power consumption (kWh)	Additional energy consumption compared to LPA (%)
Belfast	15	Y	265312	-
	20	N	277548	4.4
	23	N	292477	10.2
London	15	Y	317226	-
	20	N	326888	3
	23	N	339816	7.1

Table 3: Seasonal compressor energy consumption

It can be seen that the use of LPA that allows further reductions in the condensing temperature than is possible with floating head pressure control alone, results in additional energy savings. The savings are higher in areas with lower ambient temperature.

Conclusions:

Liquid pressure amplification allows operation at lower condensing pressures than is possible with floating head pressure control alone. The energy savings will depend on the minimum allowable pressure differential across the thermostatic expansion valve and the ambient temperature. The use of liquid injection in combination with LPA will increase further the energy savings possible due to the desuperheating of the discharge refrigerant gas, which will increase the condenser capacity and thus reduce the difference between the ambient and condensing temperature.

The analysis in this case study has shown that the use of LPA in conjunction with liquid injection can lead to up to 10% energy savings over and above those achievable with floating head pressure alone. The level of energy savings that can be achieved with LPA is system specific and each application will require careful consideration of the savings against the capital cost of the technology.

References:

1. Reindl, D. T., Hong, H. "Evaluation of liquid pressure amplifier technology". International Journal of Air-Conditioning and Refrigeration. Vol. 13, No. 3 (2005)/ pp. 119-127.

2. DOE, "Liquid Refrigerant Pumping Technology for Improving Refrigeration Performance and Capacity". Prepared by the New Technology demonstration Program. U.S. Department of Energy, 1995.