ADVANCES IN SUPERMARKET REFRIGERATION SYSTEMS

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ABSTRACT

Present supermarket refrigeration systems require very large refrigerant charges for their operation and can consume as much 1-1.5 million kWh annually. Several new approaches, such as distributed, secondary loop, low-charge multiplex, and advanced self-contained refrigeration systems, are available that utilize significantly less refrigerant. Analyses show that if properly designed and implemented, these advanced systems can reduce annual energy consumption by over 10% and total equivalent warming impact (TEWI) by as much as 60%. Integration of refrigeration and store HVAC operation is also possible through use of heat pumps. Analyses show that integrating the refrigeration and HVAC functions in this manner can potentially reduce combined operating costs by over 10%. Field testing programs are underway to verify the practicality of achieving these projected savings.

1. INTRODUCTION AND BACKGROUND

Supermarkets are one of the most energy-intensive types of commercial buildings. Significant energy is used to maintain chilled and frozen food in both product display cases and storage refrigerators. The refrigeration systems also produce a large amount of rejected heat that can be recovered and used by heat pumps or other equipment to provide space and water heating for store requirements. Typical supermarkets with approximately 3700 - 5600 m^2 of sales area consume on the order of 2 - 3 million kWh annually for total store energy use. One of the largest uses of energy in supermarkets is for refrigeration. Perishable products must be kept refrigerated during display and for storage. Typical energy consumption for supermarket refrigeration is on the order of half of the store's total. Compressors and condensers account for 60-70% of refrigeration energy consumption. The remainder is consumed by the display and storage cooler fans, display case lighting, evaporator defrosting, and for anti-sweat heaters used to prevent condensate from forming on doors and outside surfaces of display cases.

Figure 1 shows a representative layout for a supermarket showing refrigerated display cases and storage areas located generally around the store perimeter. The most commonly used refrigeration system for supermarkets today is the multiplex direct expansion system. All display cases and cold store rooms use direct expansion air-refrigerant coils that are connected to the system compressors in a remote machine room located in the back or on the roof of the store. This requires thousands of meters of pipe with case connections that have historically been designed for ease and rapidity of service rather than low leakage. This practice is changing for new supermarkets with more emphasis on reducing leakage. Heat rejection is usually done with air-cooled condensers because these are the least cost to install and maintain. Evaporative condensers can be used as well and will reduce condensing temperature and system energy consumption. However, they carry the burden of increased maintenance effort and cost. In either case, system controls are usually set to allow the condensing temperature to float with the outdoor ambient, usually to a minimum level of around 21°C (about the lowest condensing temperature for reciprocating compressors which are the most common type used in supermarkets).

The amount of refrigerant needed to charge this type of supermarket refrigeration system is very large - typically 1300- 2500 kg. The large amount of piping and pipe joints required can also result in large refrigerant losses – historically 30% or more of the total charge annually. New systems can achieve leak rates of around 15% or somewhat lower (Sand, et al, 1997).

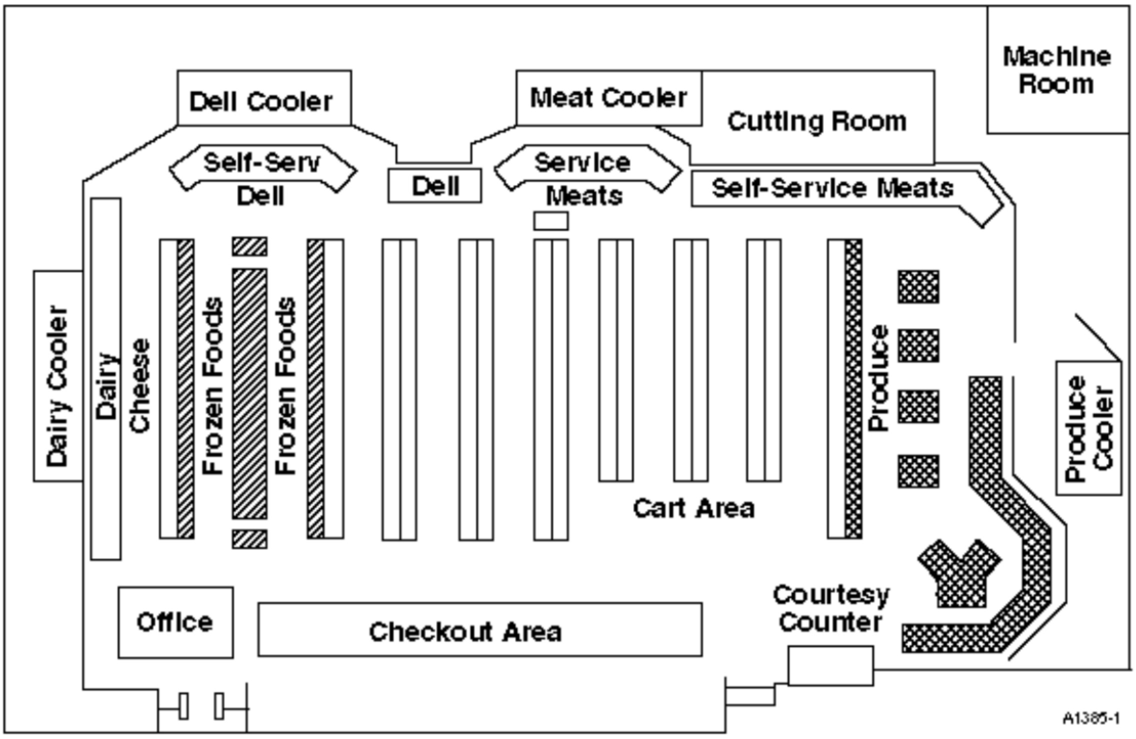

Figure 1 – Layout of a typical modern supermarket

Figure 2 shows the major elements of a multiplex refrigeration system. Multiple compressors operating at the same saturated suction temperature are mounted on a skid, or rack, and are piped with common suction and discharge refrigeration lines. Using multiple compressors in parallel provides a means of capacity control, since the compressors can be selected and cycled as needed to meet the refrigeration load.

With increased concern about the impact of refrigerant leakage on global warming, a number of new supermarket refrigeration system configurations requiring significantly less refrigerant charge are being considered. In order to help promote the development of advanced systems and expand the knowledge base for energy-efficient supermarket technology, the International Energy Agency (IEA) established IEA Annex 26 (Advanced Supermarket Refrigeration/Heat Recovery Systems) under the *IEA Implementing Agreement on Heat Pumping Technologies*. Annex 26 focuses on demonstrating and documenting the energy saving and environmental benefits of advanced systems design for food refrigeration and space heating and cooling for supermarkets. Advanced in this context means systems that use less energy, require less refrigerant and produce lower refrigerant emissions. Stated another way, the goal is to identify supermarket refrigeration and HVAC technology options that reduce the total equivalent warming impact (TEWI) of supermarkets and their potential impact on global warming. The Annex currently has five participating countries: Canada, Denmark, Sweden, the United Kingdom, and the United States.

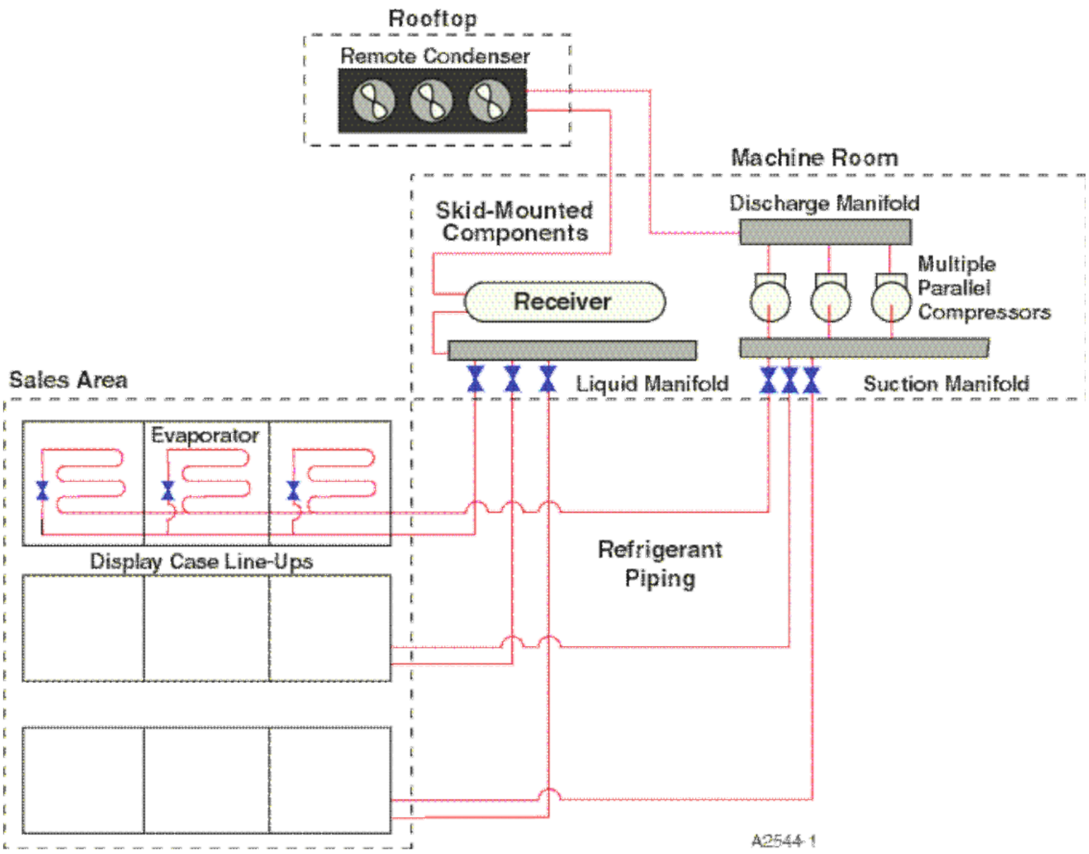

Figure 2 – Multiplex refrigeration system

The Annex participants are investigating several candidate system design approaches to determine their potential to reduce refrigerant usage and energy consumption. System types include the following:

distributed compressor systems – small compressor racks are located in close proximity to the food display cases they serve thus significantly shortening the connecting refrigerant line lengths;
secondary loop systems – a central chiller is used to refrigerate a secondary coolant (e.g. brine, ice slurry, or CO_2) that is pumped to the food display cases on the sales floor;
self-contained display cases – each food display case has its own refrigeration unit;
low-charge direct expansion – similar to conventional supermarket systems but with improved controls to limit charge.

Means to integrate store HVAC systems for space heating/cooling with the refrigeration system are being investigated as well. One approach is to use heat pumps to recover refrigeration waste heat and raise it to a sufficient level to provide for store heating needs.

A workshop on advanced supermarket refrigeration was held October 2-4, 2000 in Stockholm. Reports were made by Annex participants and other invited experts on the status of refrigeration research and development activities in the US and Europe. A proceedings is available from the IEA Heat Pump Centre that summarizes the results of the workshop (Lundqvist, ed, 2000).

This paper presents results of analyses of several low-charge refrigeration systems along with some preliminary results from system field tests.

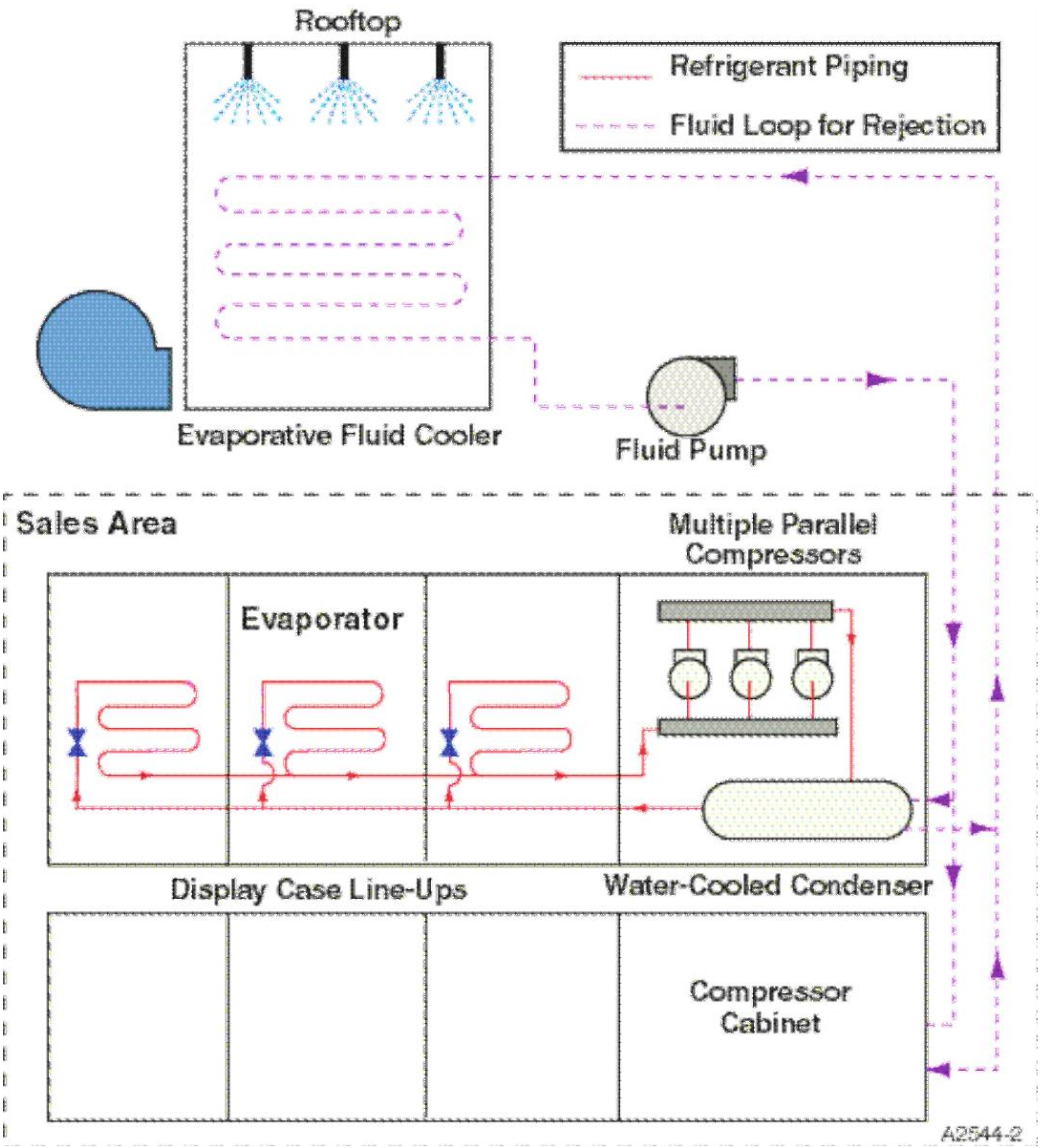

Figure 3 – Distributed refrigeration system

2. ADVANCED SYSTEM DESCRIPTIONS

Distributed compressor systems. Figure 3 illustrates typical system components. Multiple compressors are arranged in cabinets that are located near the loads they serve. Heat rejection from the compressors can be accomplished through the use of either air-cooled condensers located on the roof above the cabinets or by a glycol loop that connects the cabinets to a fluid cooler. To enable the cabinets to be located in or near the sales area, this refrigeration system employs scroll compressors because of their very low noise and vibration levels. Scroll compressors have no valves and in general are not quite as efficient as reciprocating units for refrigeration applications. However, this efficiency disadvantage is offset by the fact that the no-valve feature allows them to operate at lower condensing temperatures – down to about 15 ºC.

The refrigerant charge required for a distributed refrigeration system is on the order of 30% or 50% of that required for a conventional air-cooled multiplex system depending upon whether water- or air-cooled condensing is employed, respectively. When water-cooled condensers are employed a glycol loop is used to transmit the reject heat to a fluid cooler, usually located on the roof of the supermarket. The use of the glycol loop increases the energy consumption of the refrigeration process due to the pump energy needed and higher condensing temperature due to the added temperature rise of the fluid loop. Much of this energy penalty can be negated if an evaporative fluid cooler is employed where heat rejection can take place at close to the ambient wet-bulb temperature.

Secondary loop systems. These systems employ chillers located in a remote machine room (see Figure 1) to refrigerate a brine solution that is pumped to each display case or cold store room. Lowest energy consumption for secondary loop systems is achieved when the display case heat exchangers are designed specifically for the use of brine, so that the temperature difference between the brine and air is minimized. Brine selection is also of importance, because energy consumption for pumping is a large component of overall energy consumption. The use of brines with high heat capacity and low viscosity at low temperature is desirable. The number of brine loops employed will also impact energy consumption. Typically, 2 loop temperatures are used, such as -30 and -7 °C. If significant portions of the refrigeration load can be addressed by higher temperature loops, energy savings can be obtained. For example, refrigeration loads at -10 °C could be addressed by a loop at -18 °C, rather than including this portion of the load with the -30 °C loop. For the analysis given here, 4 loops are considered, operating at temperatures of -30, -18, -7, and -1 °C with a potassium formate brine solution in the two lower temperature loops and a propylene glycol solution in the higher temperature loops. It should be stated, however, that more loops means higher installed costs. Each loop requires its own controls and means of maintaining the loop temperature (separate chiller, etc.).

The central chiller systems are constructed similarly to multiplex racks, using multiple parallel compressors for capacity control. Use of high-efficiency compressors is highly desirable to help offset some of the added energy consumption associated with brine pumping. Because of the location of the evaporator on the chiller skid, the compressors for the secondary loop system are considered close-coupled to the evaporator. The pressure drop and return gas heat gain are minimized in this configuration. Both these factors help to reduce compressor energy consumption. These chiller systems can also be equipped with hot brine defrost where brine is heated by subcooling of the chiller refrigerant. Heat rejection can be accomplished with air-, water-, or evaporatively cooled condensers. Lowest condensing temperatures are achieved with evaporative condensers. The system refrigerant charge will be on the order of 15-25% of that required for conventional air-cooled multiplex systems with either air-cooled or evaporative condensers and about 7% of the multiplex charge when water-cooled condensers and a fluid loop are used. Like distributed refrigeration, the use of evaporative heat rejection for the fluid loop is recommended to reduce energy consumption.

Low-charge multiplex systems. Several refrigeration system manufacturers now offer control systems for condensers that limit the amount of refrigerant charge needed for the operation of multiplex refrigeration. The refrigerant liquid charge is limited to that needed to supply all display case evaporators. This control technique can reduce the charge needed by the refrigeration system by 1/3 or more. Some liquid charge control approaches can also provide some energy-saving potential by enabling the compressors to operate at lower condensing temperatures. The minimum condensing temperature values suggested are 4.5 and 15 °C for low and medium temperature refrigeration, respectively.

Self-contained refrigeration systems. In this type, each display case and storage room has its own compressor and condenser (usually water-cooled). A glycol loop is used to reject heat from the individual refrigeration units to the exterior of the store. For energy-efficient operation of a self-contained system, capacity control of the compressor is needed. In modeling this system compressor unloading for capacity control was modeled as a continuous process; and the compressor power was modeled using the standard relationship for power change with compressor unloading. For analysis the minimum condensing temperature was set at 4.5 and 15 °C for low and medium temperature refrigeration, respectively (Walker and Baxter, 2002).

3. ANALYSIS RESULTS

A 3720 m^2 supermarket based on the layout in Figure 1 was simulated and energy consumption estimates were made for a baseline air-cooled multiplex refrigeration system and the advanced, low charge systems (Walker and Baxter, 2002). Total refrigeration load was 328 kW (82 kW for frozen foods and 246 kW for fresh foods). The baseline system charge was 1360 kg or 4.15 kg/kW load. The results of this analysis for a Washington, DC location are given in Table 1. Both the distributed system and the secondary loop system with evaporative condensing achieved similar results with annual energy savings of 11.3% and 10.4%, respectively, compared to the baseline. The low-charge multiplex refrigeration system showed annual energy savings of 11.6% compared to the baseline system. No energy savings were estimated for the advanced, self-contained system.

Table 1 - Predicted Energy Consumption for Low-Charge Refrigeration Systems				
System	Heat Rejection	Annual Energy (kWh)	Energy Savings (kWh)	% Savings vs baseline
Multiplex (baseline)	Air-Cooled Condenser	976,800	-	-
Multiplex	Evap. Condenser	896,400	80,400	8.2
Low-Charge Multiplex	Evap. Condenser	863,600	113,100	11.6
Distributed	Water-Cooled Condenser, Evap Rejection	866,100	110,700	11.3
Secondary Loop	Evap. Condenser	875,200	101,600	10.4
Advanced Self-Contained	Water-Cooled Condenser, Evap Rejection	1,048,300	-	-
Secondary Loop	Water-Cooled Condenser, Evap Rejection	959,700	17,100	1.8
Results for supermarket at Washington, DC location				

Use of evaporative heat rejection (evaporative condenser or cooling tower) was the principal driver for energy savings for any system. The energy consumption of the multiplex baseline system was reduced by about 8.2% when an evaporative condenser was substituted for the air-cooled condenser. Energy consumption of the secondary loop system was less than that of the baseline multiplex system primarily because of the use of evaporative condensing. Secondary loop system energy savings can also be attributed to the close coupling of the compressors to the chiller evaporators, subcooling associated with the warm brine defrost scheme employed, and use of four brine loops to raise the effective average evaporator temperature of the system.

Three systems were modeled with water-cooled condensers and glycol loops for heat rejection. These systems had the lowest refrigerant charge and could be coupled with water-source heat pumps for heat reclaim for space heating. Of these three systems, the distributed system showed the lowest energy consumption.

An environmental assessment of these refrigeration systems was also made through a TEWI analysis for a 15-year life. Table 2 gives the results of this investigation. A range of leak rates is assumed for the multiplex systems to represent both historical and modern, low-leak design practices. The lowest TEWIs were achieved by the distributed system and the secondary loop systems with estimated CO_2 emission reductions compared to the baseline multiplex system (multiplex with air-cooled condensing) of 13 - 14 million kg, or about 57 - 60%. The low-charge multiplex system has estimated TEWI reductions of about 24% or 43% compared to the baseline system depending upon whether a 30% or 15% annual refrigerant loss rate is assumed. Replacing the air-cooled condenser with an evaporative condenser on the baseline system results in an estimated TEWI reduction of about 3% due to the energy savings from operation at lower condensing temperatures. The self-contained system analyzed had the lowest direct warming impact (from refrigerant losses) over the 15-year study period. However, its energy use (highest of the systems studied) caused its overall TEWI to be 4% to 12% higher than that of the distributed and secondary loop systems.

Table 2 - Total Equivalent Warming Impact (TEWI) for Supermarket Refrigeration								
System	Condensing	Charge, kg/kW	Primary Refrigerant	Leak (%)	Annual kWh	TEWI (million kg of CO_2)		
						Direct	Indirect[a]	Total
Multiplex	Air-Cooled (baseline)	4.15	R404A /R-22[b]	30 (15)	976,800	13.62 (6.81)	9.52 (9.52)	23.14 (16.33)
	Evaporative	4.15		30	896,400	13.62	8.74	22.36
Low-Charge Multiplex	Evaporative	2.77	R404A /R-22[b]	30	863,600	9.08	8.42	17.50
				15	863,600	4.54	8.42	12.96
Distributed	Water-Cooled, Evap	1.24	R404A	5	866,100	1.00	8.44	9.44
Secondary Loop	Evaporative	0.69	R507[c]	10	875,200	1.13	8.54	9.67
				5	875,200	0.56	8.54	9.10
	Water-Cooled, Evap	0.27	R507[c]	5	959,700	0.23	9.36	9.59
				2	959,700	0.09	9.36	9.45
Advanced Self-Contained	Water-Cooled, Evap	0.14	R404A	1	1,048,300	0.02	10.22	10.24
Results for Washington, DC location – 15 year service life								

[a]Conversion factor = 0.65 kg CO_2/kWh
[b]1/3 R404A (low temp.), GWP = 3260; 2/3 R22 (medium temp.), GWP = 1700
[c]R507, GWP = 3300

In general, further efforts to reduce total global warming impacts for the distributed and secondary loop systems would benefit more from reduction in energy usage (through efficiency increases or load reductions) than from further reduction in direct impact (from refrigerant losses). The same is true for the low-charge multiplex system and, to a lesser extent, for the conventional multiplex system providing annual refrigerant losses can be held to 15% or less.

4. SUPERMARKET HVAC ANALYSIS

The use of water-source heat pumps represents an excellent way to utilize refrigeration reject heat for space heating where water-cooled condensers and water/glycol loops are used for refrigeration system heat rejection. The heat pumps can be installed in the glycol/water loop and use the rejected heat to provide space heating. This method enables reclamation of a very large portion of the reject heat without requiring elevation of the condensing temperature and head pressure of the refrigeration system as happens with conventional heat reclaim approaches. Refrigeration system energy savings achieved by low head pressure operation can be realized along with the energy benefits seen through heat reclaim. An analysis was performed for a supermarket HVAC system where conventional roof top units, refrigeration heat reclaim, and water-source heat pumps were examined and compared. The lowest operating cost was achieved by the combination of distributed refrigeration and water-source heat pumps, which saved about 13% when compared to the baseline air-cooled multiplex refrigeration system with conventional rooftop HVAC units. Local utility rates for gas, electricity, and water (to account for evaporative tower make up water usage) in Washington, DC were used in this cost comparison.

5. SUMMARY OF PLANNED ANNEX WORK AND FIELD TEST RESULTS TO DATE

Canada. Three systems are under test including one conventional multiplex system. One advanced system approach uses a multiplex refrigeration system with extensive use of heat reclaim for space and water heating and uses ground water to supplement heat rejection. The second advanced approach also is a multiplex system which has several heat pumps integrated to provide space heating for the store and subcooling for the refrigeration system. Initial baseline tests in 1999-2000 showed that both advanced approaches achieved about 6% lower specific energy consumption (kWh/m^2/yr) compared to the baseline store (Minea et al. 2002a). Refinements to the test systems, including a more rapid defrost concept and liquid refrigerant pumping for head pressure control, are under evaluation. The defrost improvements have reduced defrost time by about 85% (Minea et al. 2002b)

In addition to the above, a technology showcase is planned to be installed in a Montreal area supermarket early in 2002. This technology showcase is expected to demonstrate the integration of several technologies to meet the supermarket's heating, ventilation, air conditioning and refrigeration (HVAC&R) requirements. Prefeasibility studies indicate that energy consumption can be reduced by 18% and refrigerant charge by 87% through integration of the HVAC and refrigeration functions and use of a secondary loop system approach. These measures together should reduce the TEWI by about 75% (Giguere, 2001).

Denmark. In a small Danish supermarket the old refrigeration plant has been replaced with a cascade plant. Propane is used as the high temperature refrigerant (-14/+30°C) while carbon dioxide is used at the low temperature level (-32/-11°C). Carbon dioxide is used directly to perform the cooling in the freezers while a brine circuit with propylene glycol is used in the coolers. Total energy consumption decreased by 10% with the new plant, however it must be noted that the old plant was worn out. Based on the results from the first demonstration plant a second propane/carbon dioxide demonstration plant has been built in a medium-size supermarket and just started operation in late 2001. The chosen supermarket is part of a chain of about 250 shops so it will be possible to compare the propane/carbon dioxide plant with a newer traditional plant with the same cooling capacity. It is estimated that the additional cost for a propane/carbon dioxide cascade plant for a medium sized Danish supermarket (30 kW freezing load and 60 kW cooling load) will amount to approximately 15% of the total installation (Knudsen, 2001).

Sweden. Sweden's work for the Annex is part of their national program Klimat 21 under a project "Energy Efficient Solutions for Supermarkets in Theory and Practice." Field tests of advanced systems are underway in three supermarkets (floor area ranging from 720 to 2700 m^2). Two use cascaded secondary loop system designs with R404A primary refrigerant and a potassium formate brine solution as the secondary refrigerant. The other has individual secondary loop refrigeration units in each display case that are all connected to a central building chiller for heat rejection. A significant result is that night coverings tested in one of the stores resulted in 10-20% lower system energy consumption with only 70% of the case coverings operative (Arias and Lundqvist, 2000).

United Kingdom. The UK has established a strong collaborative government and industry team to work on supermarket technologies. Four case studies are now underway. These include 1) an evaluation of the economic and environmental viability of combined cooling, heating, and power schemes for supermarkets, 2) a comparison of various secondary loop system concepts against standard direct expansion systems, 3) analytical and experimental investigation of the effect of various HVAC systems on case performance (including cold aisle issues), and 4) analytical and experimental investigation of three different defrost strategies (Shaw, 2001).

United States. Two systems are being field tested in operating supermarkets near Boston, MA – a distributed compressor refrigeration system and a baseline multiplex refrigeration system. The distributed system uses a glycol loop for heat rejection and includes water-source heat pumps that reclaim the reject heat for store heating. HVAC for the baseline store is provided by conventional rooftop air-conditioning units with gas heating. Test results from December 1999 through July 2000 indicated that the distributed system had higher average energy consumption than the baseline by about 14% (2760 kWh/d vs. 2410 kWh/d). There were three main reasons why the actual energy use has been higher than what was expected from the modeling study. First, the store operator chose to use a dry cooling tower rather than an evaporative tower to avoid the extra maintenance burden. Second, the water-cooled condensers in the compressor cabinets were undersized (14 °C approach temperature vs. the design value of 8 °C). Finally, operational problems with the heat rejection loop during January allowed the loop temperature to fall below the minimum value for the heat pumps causing a loss of heating in the store. As a temporary fix to maintain heating capability, the minimum loop temperature was raised by about 12 °C and maintained at this level through April. The combined impact of these problems caused the distributed refrigeration system condensing temperature to be 6 – 16 ºC higher than expected compared to the pretest analysis assumptions and about 8-10 ºC higher than that experienced by the multiplex baseline test system. The distributed system manufacturer has provided correctly sized condensers and the loop operation problem has been corrected, however the dry cooling tower remains. Both the modified distributed system and the baseline system will be monitored again over the 2001/2002 winter. Analysis of the water-source heat pump data indicated that the distributed system test store enjoyed an estimated space heating cost savings of about $10,000 compared to what it would have cost if conventional rooftop gas heating systems had been used (see Table 3). The prevailing local utility rates of $0.09/kWh and $0.265/(m^3 of natural gas) were used to estimate the heating cost savings. Substantial savings were seen for all months except for January. Very low loop temperatures were experienced during that period (as mentioned above) and the heat pumps operated with only the supplemental electric heat for much of the time. (Walker and Baxter, 2000).

Table 3 – Water-source heat pump field test results for 1999-2000 winter, Boston, MA, USA

Month	Heat Supplied (kWh)	Heat Pump Energy[1] (kWh)	Equivalent gas use (m^3)	Savings[2] ($)
December	157,900	26,784	17,420	2,200
January	157,900	39,878	16,220	706
February	187,950	22,480	18,050	2,760
March	148,180	21,854	15,200	2,064
April	154,450	23,184	15,350	1,980

[1] Energy for compressors and supplemental electric heaters; fans not included
[2] Calculated based on energy costs of $0.09/kWh and $0.265/m^3

6. CONCLUSIONS

A few major conclusions and observations are noted in this section from the analyses and testing programs discussed. Before proceeding, however, it must be noted that these conclusions are subject to the assumptions used in the analyses and the particular locations and installations of the field test systems. These specific results should not be considered to be generalizable to all store sizes and locations. However, they do provide a good relative indication of the energy savings and TEWI reduction potential of the low-charge refrigeration systems discussed in this paper.

Analyses carried out under the Annex 26 project and individual country programs have shown that both energy savings (over 10%) and TEWI reductions (up to 60%) are possible with low-charge refrigeration systems as compared to a baseline multiplex system with air-cooled condensers. Savings are possible with distributed compressor systems, secondary loop systems, and low-charge multiplex systems. Use of evaporative heat rejection approaches (condensers or cooling towers) to reduce condensing temperatures is a key to obtaining maximum energy savings. Evaporative condensers (or cooling towers) will impose greater maintenance efforts and costs, however. Proper design and implementation of advanced low-charge systems is essential if energy savings are to be realized. Early field testing of a distributed system in the U. S. showed greater energy usage than expected due to excessive condensing temperatures caused by use of a dry cooling tower, problems from heat rejection glycol cooling loop control inadequacies, and undersized refrigerant-to-water condensers. Field tests are being repeated with correct condenser sizes and revised heat rejection loop controls on the distributed system.

Initial demonstration of a new cascade system in a small Danish store showed 10% lower energy consumption compared to what the store had used with the old conventional refrigeration system. Use of night coverings to reduce display case load has been shown to result in at least 10% reduction in refrigeration system energy use in a Swedish demonstration store.

The supermarket refrigeration systems showing lowest estimated TEWI were the distributed system and the secondary loop systems considered in the analyses - about 57 - 60% reduction compared to the baseline multiplex system. In general further efforts to reduce total global warming impacts for all of the advanced low-charge systems examined here would benefit more from reduction in energy usage (through efficiency increases or load reductions) than from further reduction in direct impact (from refrigerant losses) providing annual refrigerant losses are held to 15% or less of the total system charge annually.

The use of water-source heat pumps with refrigeration systems employing glycol loops for heat rejection was estimated to produce about a 13% operating cost savings over the baseline refrigeration system with conventional HVAC in a 3720 m^2 store in a Washington, DC location.

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