SUMMARY OF ADVANCED SUPERMARKET R&D ACTIVITIES CONDUCTED UNDER INTERNATIONAL ENERGY AGENCY (IEA) ANNEX 26

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ABSTRACT

Present supermarket refrigeration systems require very large refrigerant charges for their operation and an individual store system 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. Integrating the refrigeration and HVAC functions in this manner can potentially reduce combined operating costs by over 10%.

Key Words: *supermarket refrigeration, heat recovery, heat pumps, secondary loops, CCHP.*

1 INTRODUCTION

Supermarkets are among the most energy-intensive 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. There is a wide range in size of supermarkets among the Annex 26 countries (Canada, Denmark, Sweden, United Kingdom, and United States). In Europe stores range in size from about 500 m^2 to 3000 m^2 or somewhat larger. Stores are typically larger in Canada and the US ranging from a minimum of about 1000 m^2 to over 10000 m^2. Plant capacities range from 30-60 kW for small markets to over 400 kW for the largest stores. Similarly, annual energy use ranges from about 100,000 kWh/y for the smaller stores to 1.5 million kWh/y or more for the largest.

Refrigeration is the largest component of supermarket energy use, accounting for half or more of the store total. Perishable products must be kept refrigerated during display and for storage. 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 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 (DX) 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 rapidity and ease 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 costly 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 dry bulb (or wet bulb) temperature, 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).

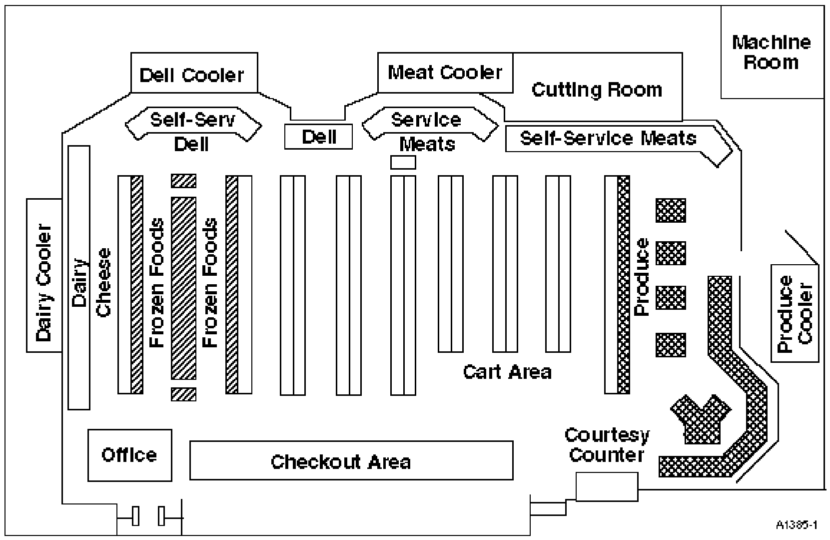

Fig. 1. Layout of a typical modern supermarket

The amount of refrigerant needed to charge multiplex DX systems is very large - typically 4-5 kg/kW of refrigeration capacity. The large amount of piping and number of pipe joints required can also result in large refrigerant losses – historically 30% or more of the total charge annually. New systems can achieve annual loss rates of around 15% or somewhat lower. The large refrigerant charge and high loss rate for multiplex DX systems results in high values of TEWI (total equivalent warming impact) with direct impact resulting from system refrigerant losses accounting for about half of the total as shown in Figure 2.

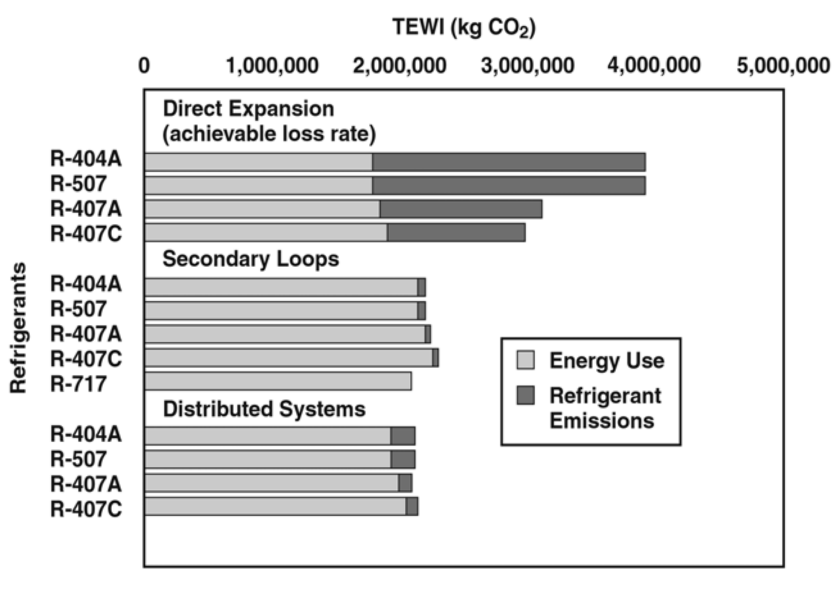

Fig. 2. Total equivalent warming impact (TEWI) for low temperature supermarket refrigeration in North America

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* (IEA Heat Pump Centre 2003a, 2003b). Annex 26 began in 1999 and concluded in 2003. The Annex work focused 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 was to identify supermarket refrigeration and HVAC technology options that reduce the TEWI of supermarkets by reducing both system energy use (increasing efficiency) and reducing total refrigerant charge.

The working program of the Annex involved analytical and experimental investigation of several candidate system design approaches to determine their potential to reduce refrigerant usage and energy consumption. Several advanced refrigeration system types were investigated and compared to a baseline composed of a direct expansion (DX), multiplexed parallel compressor system with a direct air-cooled condenser (the most prevalent refrigeration system used in supermarkets today). Advanced systems investigated included the following:

secondary loop systems – one or more central chillers are 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;
distributed compressor systems – small parallel compressor racks are located in close proximity to the food display cases they serve thus significantly shortening the connecting refrigerant line lengths;
low-charge direct expansion – similar to conventional multiplex refrigeration systems but with improved controls to limit charge.

Integration of store HVAC systems for space heating/cooling with the refrigeration system was 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. Another involves use of combined heating and power (CHP) or combined cooling, heating, and power (CCHP) systems to integrate the refrigeration, HVAC, and power services in stores. Other methods including direct recovery of refrigeration reject heat for space and water heating have also been examined.

2 ADVANCED SYSTEMS DISCUSSION

2.1 Secondary Loop Type Systems

Secondary loop refrigeration systems can take many forms, but they generally employ one or more chillers to refrigerate a secondary fluid that is then pumped to the display cases and storage rooms. Remote air-cooled or evaporative condensers can be used for heat rejection. Evaporative condensing will yield lower average condensing temperatures with lower fan energy than seen with air-cooled condensers, thus minimizing overall energy consumption especially in warmer climate areas. Primary refrigerant charge requirement can be reduced to about 10-15% of that needed for conventional direct expansion system. A variation is to use a secondary fluid on the heat rejection (condenser) side of the chiller as well as on the refrigeration (evaporator) side. This approach can reduce primary refrigerant requirements to less than 5% of direct expansion but would introduce an additional secondary heat exchanger thermodynamic energy penalty to the system and increase energy usage.

Secondary loop systems have features that tend to improve the efficiency of the primary system. These include close coupling of the compressors to the chiller evaporators, and the ability to subcool the primary refrigerant with the secondary fluid (brine) and use the warmed brine to defrost the case heat exchangers. For large stores secondary loop systems generally use at least two separate secondary fluid loops and chillers – one each for the low temperature (frozen food) cases and storage rooms and medium temperature (chilled food) cases and rooms. Using only two fluid loops for refrigeration, however means that all display cases and storage coolers must operate with these two temperatures. The use of multiple secondary fluid loops with temperatures more closely matching the case air temperature requirements can improve energy efficiency because it raises the effective average evaporator temperature of the system. It must be stated however, that each loop will require a separate chiller and controls and that will increase the system cost.

2.2 Distributed Compressor Refrigeration System

This system features several small compressor cabinets distributed throughout the store and close-coupled to the display case lineups or storage rooms they serve. Each compressor cabinet in a distributed system is similar to a multiplex DX rack only smaller. With this approach the long lengths of piping needed to connect the cases with large remote compressor racks are eliminated. The cabinets may be placed near case lineups on the sales floor or behind the cases around the perimeter of the store.

With this arrangement, the saturated suction temperature (SST) of each compressor cabinet can closely match the evaporator temperature of the display cases and walk-in coolers to which it is connected. This is not always possible with conventional multiplex systems, since a single rack will often provide refrigeration to display cases with three or four different evaporator temperatures. The better temperature matching seen with distributed refrigeration can benefit the energy consumption of the overall system.

The refrigerant charge requirement for the distributed system is much less than for multiplex systems due to the shortening of the suction and liquid lines to the display cases. If a secondary fluid loop is used for heat rejection then the refrigerant heat rejection piping to a remote condenser and its associated charge is eliminated as well. With a secondary loop for heat rejection, the refrigerant charge required for a distributed system would be about 30-35% of that required for multiplex systems. If separate rooftop condensers are used for each cabinet, the total charge requirement will be about 50-60% that of multiplex systems. A secondary heat rejection loop will result in higher condensing temperatures and energy consumption than if direct roof top condensers are used.

2.3 Low Charge Multiplex Systems

Several approaches have been taken by refrigeration system manufacturers to reduce the refrigerant charge required by traditional multiplex system compressor racks. These approaches reduce the overall system refrigerant charge but retain the long connecting lines between compressors and display cases. Total charge required for this system is expected to be about 2/3 or less than that required for the conventional baseline multiplex system. In addition, some approaches feature controls that allow the system compressors to operate at lower condensing temperatures than would normally be the case and thereby can provide some operating energy savings as well.

3 HVAC INTEGRATION APPROACHES

The large amount of heat rejected by the refrigeration system in a typical supermarket offers an attractive resource for use in store space heating. Integration approaches examined during the course of this Annex have included straightforward heat reclaim, use of heat pumps integrated with the refrigeration system, and use of combine heat and power (CHP) or combined cooling, heating, and power (CCHP) systems.

The use of heat pumps represents an excellent way to utilize refrigeration reject heat for space heating. Individual Annex participants have examined two different heat pump integration approaches. One involves direct integration of the heat pump evaporator(s) and refrigeration system condenser(s). The second utilizes water-source heat pumps (WSHP) 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. Either method enables reclamation of a very large portion of the reject heat without requiring elevation of the condensing temperature of the refrigeration system as can happen 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.

The use of WSHPs in conjunction with water-loop heat rejection for the refrigeration system was examined by the US. An analysis was performed for a supermarket HVAC system where conventional rooftop air-conditioner/gas heating units and water-source heat pumps were examined and compared. The combination of a water-cooled distributed compressor refrigeration system with water-source heat pumps was predicted to save about 10-20% in overall operating (refrigeration plus HVAC energy) costs depending on local climate and utility rates when compared to the baseline air-cooled multiplex DX refrigeration system with conventional rooftop HVAC units.

CHP/CCHP system concepts were studied in detail by the UK team. They concluded that CCHP has an improved load match compared to CHP, when used with absorption chilling for building cooling. Integral cascade vapor compression systems within each display case integrated with the absorption system provide food refrigeration. Estimated primary energy savings are around 15%, and the estimated TEWI reduction is of more than 50% compared with conventional supermarket systems.

4 COUNTRY SUMMARIES

The five participating countries in Annex 26 have carried out a significant amount of research on supermarket refrigeration and heat recovery systems – an estimated $5 million US total effort. A few major conclusions and observations are noted in this section from the analyses and testing programs conducted. 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 generalized 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.

4.1 Canada

Hydro Quebec’s laboratory (LTE) field-tested two advanced systems and a baseline multiplex DX system. One advanced approach used a multiplex DX system with heat reclaim for space and water heating and ground water to supplement heat rejection. The other used integrated heat pumps to provide space heating for the store and subcooling for the refrigeration system. In winter, the discharge gas from the refrigeration compressors goes first through three plate heat exchangers that serve to desuperheat and precondense the gas. The three heat exchangers also serve as evaporators for rooftop heat pumps that supply space heating to the store. Using heat pumps for heat recovery places no minimum limit on refrigeration system condensing pressure, as is the case for traditional heat recovery approaches. A fourth rooftop heat pump is integrated with the liquid line exiting the air-cooled condenser via a fourth plate heat exchanger. This heat pump subcools the refrigerant leaving the condenser and uses the recovered heat for store space heating. 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.

CETC-Varennes conducted lab studies of CO_2 as secondary refrigerant. They also partnered with Loblaws (Canadian supermarket chain) to install a refrigeration showcase in a new 9000 m^2 store. Planning for this project began during the Annex and the showcase store began operation in April 2004. The store features secondary loop refrigeration systems which are integrated to the space heating system via the secondary coolant on the condenser side (Pajani et al 2004).

4.2 Denmark

A propane/carbon dioxide demonstration plant installed in a medium-size supermarket was field tested. 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. Results indicated that energy consumption in the test store was similar to that of other new stores in the same chain of markets with conventional systems. The additional cost for a propane/carbon dioxide cascade plant for this size store was estimated at approximately 15% of the total installation. A second test store (190 kW chilled food load, 60 kW frozen food load) with a cascade system using R404A as the high temperature refrigerant and R744 (carbon dioxide) for the lower stage was monitored also. The CO_2 is used to cool both frozen food and chilled food cases, thus the amount of R404A required was only about 120 kg or about 10% of what a conventional DX system would require resulting in initial refrigerant cost savings of about $37,000US due to high Danish taxes on HFCs. The total system cost was about 10% more than a conventional DX but showed 15-20% lower energy use than similar stores with R404A DX systems. The store used recovered heat from the refrigeration system for heating and required no back up during the test period.

4.3 Sweden

Sweden's work for the Annex is part of their national program Eff-Sys under a project "Energy Efficient Solutions for Supermarkets in Theory and Practice." They have developed a computer model (Cybermart) for system predesign and have conducted field measurements in four supermarkets to validate the model. Sweden's analyses indicate that well designed advanced secondary loop systems do not compromise energy efficiency compared to conventional DX systems. Major conclusions from Sweden's work include the following.

- Standard secondary loop systems with subcooling of the low temperature loop primary refrigerant by the medium temperature brine loop have efficiency advantages over cascade systems.
- Night covering of display cases reduces energy consumption by 10-20%.
- Practical experience with heat recovery to date show that only about 40-70% of stores' heating needs are supplied by refrigeration heat recovery, primarily due to very low refrigeration loads during winter and unoptimized control systems.
- Air-conditioning is needed in Swedish stores even if the cooling season is very short to avoid food quality problems. When the store ambient exceeds 25 °C food in display cases will exceed code minimum temperatures and shelf life is halved.

4.4 United Kingdom

Four research activities were conducted. The first was an evaluation of combined heat and power (CHP), and combined cooling, heating, and power (CCHP) schemes for supermarkets. CCHP has an improved load match compared to CHP, when used with absorption chilling. Cascade vapor compression systems integrated with the absorption system provide case refrigeration. Primary energy savings are around 15%, and there is a TEWI reduction of more than 50%. A second study involved comparison of various secondary systems with standard DX systems. Results from that study indicated that secondary loop systems use about 30% more energy mostly due to secondary pumping power. TEWI for secondary systems was estimated to be 8% lower than a DX baseline system, assuming the reference case had a 15%

annual refrigerant leakage rate and a 15 year service life. Capital costs were estimated to be about 20% higher for the secondary approach. The third study was an investigation of the effect of various store conditions on case performance. Environmental chamber tests of low and medium temperature case systems show that an increase in ambient temperature from 19 to 22 °C increases system energy use by 20%. Increasing RH from 35 to 50% at an ambient of 22 °C increased the medium temperature case energy use by 15%. Large savings were observed when the voltage was dropped from 240V to 220V, with no negative impact on product temperature. Finally analytical and experimental investigations of defrost methods and alternative control strategies were carried out. Studies looking at the frequency and duration of defrost cycles showed that the current cycles are suited to relatively warm internal temperatures and high relative humidities (22°C and 60% RH), and for different internal conditions, a lower frequency would be sufficient. For electric defrost, optimized cycles and controls could reduce energy use by 25-50%, and better termination controls on completion of defrosting would reduce energy use still further.

4.5 United States

A 3720 m^2 supermarket was simulated and TEWI and energy consumption estimates were made for a baseline air-cooled multiplex refrigeration system and advanced systems. Total refrigeration load was 328 kW with a refrigerant charge of 4.15 kg/kW load. The distributed compressor, low-charge multiplex, and secondary loop systems (with four independent secondary loops) all achieved estimated annual energy savings of about 11%. Use of evaporative heat rejection was the principal driver for these energy savings - baseline system energy consumption was 8.2% lower with an evaporative condenser. The lowest TEWIs were achieved by the distributed system and the secondary loop systems with CO_2 emission reductions of about 13 - 14 million kg, or 57 - 60%. The low-charge multiplex system had estimated TEWI reductions of about 24% or 43% depending upon the refrigerant loss assumption. An analysis of an integrated water source heat pump and distributed compressor refrigeration system showed about 13% operating cost savings compared to a baseline air-cooled multiplex refrigeration system with conventional rooftop HVAC units.

5 SUMMARY COMMENTS

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 the most prevalent type baseline -- a multiplex DX system with air-cooled condensers. Savings are possible with distributed compressor systems, secondary loop systems, and low-charge multiplex systems. The secondary loop system option was the most thoroughly investigated advanced low-charge alternative in this Annex (all participants studied this option to some extent). Energy consumption comparisons with the baseline ranged from up to 30% greater energy use to about 10% savings. Use of evaporative heat rejection approaches (condensers or cooling towers) to reduce condensing temperatures is a key to obtaining maximum energy savings for all of the systems studied. 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.

In general further efforts to reduce total global warming impacts (TEWI) 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).

Recovery of refrigeration system rejected heat was shown capable of providing from about 40% to all of space and water heat needs for the test stores examined in this Annex. The amount of waste heat that is effectively applied to the space and water heat requirements at a given site will depend upon the size of the coincident refrigeration load and the refrigeration/HVAC control system’s ability to effectively manage the heat recovery process. The integration of heat pumps with refrigeration systems is an excellent means for recovering refrigeration waste heat and reducing overall store energy use. Heat-pump-based heat recovery does not require the refrigeration system condensing temperature to be maintained artificially high to facilitate heat recovery. Use of CCHP systems in supermarkets is a potentially effective means to integrate refrigeration and HVAC functions as well.

Available cost studies show installed cost premiums for secondary loop systems range from 0% to about 35% while distributed compressor systems show about a 15% premium. The low-charge multiplex approach is estimated to cost no more than current multiplex systems. It should be noted that the actual installed cost of any supermarket refrigeration system will be highly dependent upon many factors, not the least of which are the complex relationships between supermarket companies and equipment suppliers. These factors include negotiated purchasing arrangements, inclusion of display cases with system purchase, special system features, and unique installation requirements (site specific). If/when any of the advanced systems studied begin to obtain increased market share, the price differential with the current baseline can be expected to decrease somewhat due to the pressures of these market forces.

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ACKNOWLEDGEMENTS

The author gratefully acknowledges the support and contributions of the lead investigators from each Annex 26 participant: V. Minea and D. Giguère of Canada; Prof. H. J. H. Knudsen of Denmark, Prof. P. Lundqvist and J. Arias of Sweden, and A. Crompton and J. Palmer of the United Kingdom. Thanks are also expressed to US contributors S. Fischer and D. Walker. The U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Building Technologies Program sponsored U. S. activities for IEA Annex 26 under contract DE-AC05-00OR22725 with UT-Battelle, LLC.