Energy comparisons between CO_2 cascade systems and state of the art R404A systems

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Abstract

The focus on the global warming and the political determination to phase out the use of the HFC was clearly stated by minister for the environment Svend Auken at the IIR meeting in Aarhus September 1996 when he said: "It is therefore my sincere hope that in ten years time, not a single fridge, freezer or cooling plant is being built in Denmark that requires HFC's or other greenhouse effect gases.[1]" Taxes linked to the GWP value and phase out plans have lead to intense investigations in alternative solutions. Amongst these systems are also cascade systems for supermarkets with CO_2 as working fluid for both medium and low temperature applications.

In 2002 two of these cascade systems with CO_2 and R404A were installed. The displays cabinets and cooling/freezing rooms are cooled directly by CO_2 in the low temperature part of the cascade plant, while the high temperature part of the cascade plant is using R404A. Initial monitoring of the absorbed power and the observed employed compressors lead to the belief that there was an energy reduction, but it was difficult to quantify. The problem is that two supermarkets are not are identical. Even if they were identical in lay-out they would not use the same amount of energy due to the influence of the turnover.

The Danish EPA has sponsored a research project with the purpose to find a method to make the data collected comparable and to put numbers on the energy reductions observed. This presentation describes the methods used to compare state of the art R404A technology systems and two CO_2/R404A cascade systems.

1. Introduction

Newly developed cascade systems have been installed in two supermarkets in the Copenhagen area. The original intension was to built totally HFC-free refrigeration systems but due to the placement of the refrigeration plants the use of flammable and/ or toxic refrigerant like propane and ammonia was not an option. For this reason the high temperature part of the cascade system therefore use HFC R404A. The amount of R404A has been reduced to approximately 10% of the amount in a conventional supermarket refrigeration system.

The reason to eliminate HFC's as refrigerants is the very high direct Global Warming Potential (GWP) but the indirect GWP from the use of the refrigerant has also to be taking into account. The Total Equivalent Warming Impact (TEWI) includes the direct and indirect contribution to global warming. It is therefore necessary to compare the energy consumption of the new and the conventional supermarket refrigeration system. To perform such a comparison, measurements have been made on two conventional and two cascade systems in supermarkets in the area of Copenhagen. Choosing all the supermarkets to be in the Copenhagen area insures the same external environmentally conditions for the refrigeration plants and therefore minimize the influence of the environment on the measure energy consumption.

2. Principal lay-out of the test plants

2.1 Conventional plants

The plants named ISO-2 and ISO-4 are conventional built plants with parallel systems for low and high temperature (LT and HT) and air-cooled condensers at the roof. ISO-2 has piston compressors and ISO-4 has scroll compressors. ISO-4 is equipped with mechanical sub-cooler and heat recovery. The sub-cooler has been out of work during the measuring period. Figure 1 shows the principal lay-out.

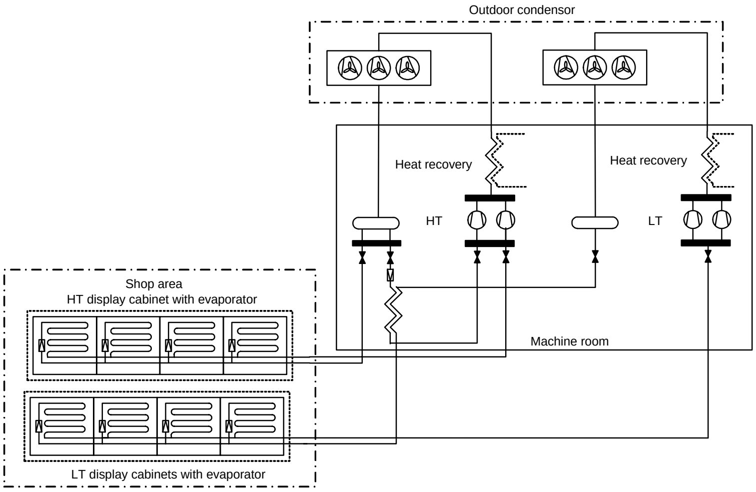

Figure 1. Conventional lay-out. ISO-2 and ISO-4.

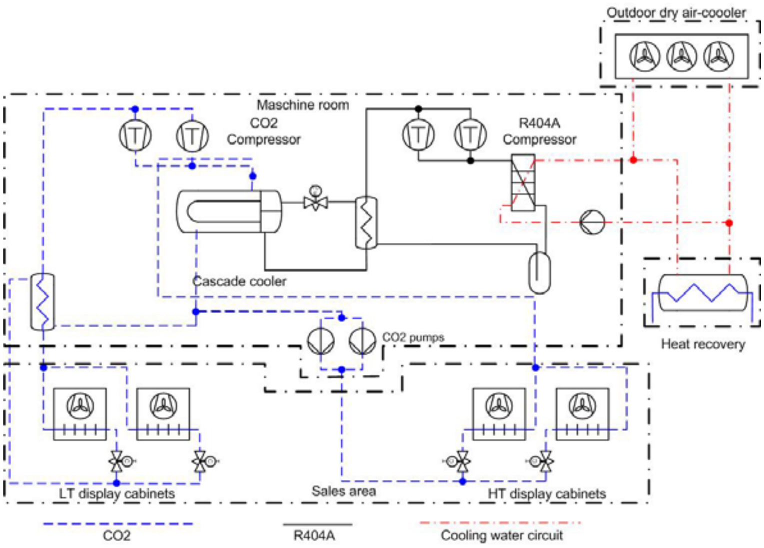

Figure 2. Cascade plant. ISO-1 and ISO-3

2.2 Cascade plants

The plants named ISO-1 and ISO-3 are the new cascade plants. Carbon Dioxide (CO_2) is use in both the HT and LT evaporators. The LT evaporators are dry expansion evaporators and the vapour generated is compressed to the pressure in the HT circuit by the CO_2 compressors. The HT evaporators are flooded evaporators with pump circulation. The CO2 vapour is condensed in the cascade cooler by evaporating R404A. R404A is compressed to the condensing pressure by R404A compressors. The R404A condenser is part of a water system, which transfers the condenser heat to the dry coolers mounted on the roof. All compressors are piston compressors. ISO-1 is equipped with heat recovery. Figure 2 shows the principal lay-out.

2.3 Principal lay-out of the supermarkets

The display cabinets for all four supermarkets are in principle the same and they are arranged in the same way in the shops. Figure 3 shows the principal arrangement of the display cabinets.

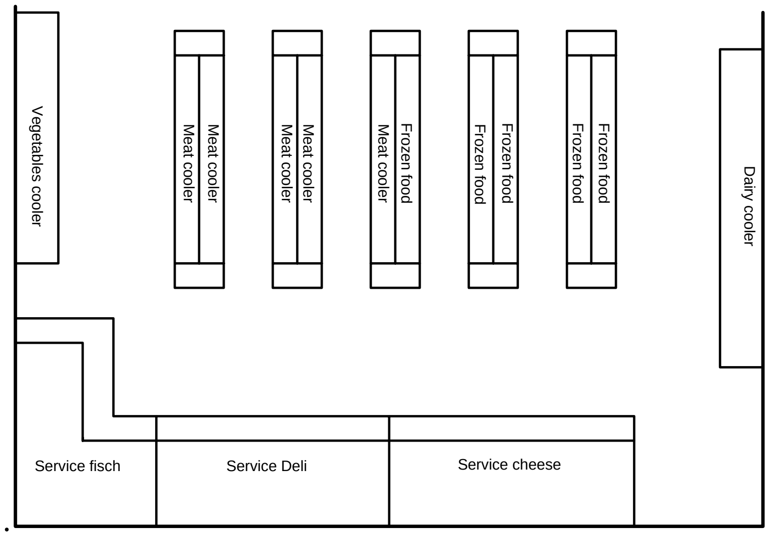

Figure 3. Arrangement of display cabinets in the supermarkets.

2.4 Size of cooling plants

The size of the cooling plants is stated in Table 1.

	Frozen food	Meat cooler	Vegetable cooler	Service disk	Island coler	HT rooms	LT rooms
	Circum-ference	Circum-ference	Length	Length	Circum-ference	Volume	Volume
	m	m	m	m	m	m^3	m^3
ISO-1	56.8	42.1	50.0	12.5		375.0	104.5
ISO-2	43.2	55.7	17.5	11.3	20.7	257.3	57.7
ISO-3	58.0	40.2	36.3	10.0		340.5	128.3
ISO-4	45.8	63.7	35.6	15.0	20.7	407.6	94.3

Table 1. Specification of the supermarket

As can been seen from Table 1 the four cooling plants have different size both with respect to the total size and with respect to the cooling categories (coolers, freezers, room size). All evaporators are equipped with pulse modulating expansion valves.

3. Measuring programme

For all four supermarkets the following properties are measured. Power consumption, used compressor and condenser capacity, suction and discharge temperature and pressure, opening degree of the expansion valves and for the dry expansion evaporators the superheat at evaporator exit and the air temperature in all the display cabinets. Outside temperature and the temperature and humidity in the supermarket are also measured.

4. Data analysis

4.1 Used data

Data are collected each second minute. Due to the large amount of data the values used in the analysis are hourly averaged values.

4.2 Cooling and power consumption

Based on the information delivered by the compressor manufacturers expression for the volumetric and isentropic efficiency has been worked out. The efficiency has been expressed as functions of the pressure ratio and the condensing temperature:

$$\eta_v = f_v\left({P_c}/{P_0}, T_c \right); \qquad \eta_{is} = f_{is}\left({P_c}/{P_0}, T_c \right)$$

With the developed expression the cooling capacity is within 1% and the power consumption is within 2% of the manufacturers data.

Based on measured pressure and temperature together with the used compressor capacity the cooling capacity and the power consumption is estimated. The estimated power consumption is compared with the measure electric power consumption to validate the accuracy of the used model.

The Coefficient of Performance (COP) and Carnot efficiency is also calculated. Due to the influence of heat recovery on the condenser temperature a COP corrected to 30°C condenser temperature is calculated based on the compressor models stated above.

4.3 Calculation of comparable energy consumption

Due to the different size of the supermarkets the measured energy consumption has to be corrected to the energy consumption for a supermarket of the equal size. Comparable energy consumption is calculated using the measured COP with a reference-cooling load. For ISO-1 and ISO-3 the energy consumption of the circulation pump has to be added. Two methods have been used to calculate the reference-cooling load. The first method specifies the circumference/length of the display cabinets together with the volume of the HT and LT rooms (equivalent to use a multiplier defined as the ratio between the circumference of the display cabinets in the reference supermarket and in the current supermarket). The second method uses a specified load profile for HT and LT. The load profile for the four supermarkets has been made dimensionless dividing the measured load (HT, LT) with the maximum measured load in the measuring period 1/8 – 31/12 2003. The dimensionless load profile for the four supermarkets is nearly equal. An example is given for the HT profile for measuring period 1/9 – 7/9 2003 in Figure 4. The same picture is seen for the whole measuring period. The dimensionless profile for ISO-2 has been used in the calculation together with specified maximum HT load of 110 kW and maximum LT load of 40 kW.

5. Comparison of energy consumption

5.1 Measured and calculated energy consumption.

The measured energy consumption for ISO-2 and ISO-4 cannot be directly compared with the calculated energy consumption because the measured energy consumption includes the consumption to rail heaters, fans and defrosting. A correction has been performed based on the installed electric power and the measured on time. For ISO-4 one of the effect transmitters went out of order very early, but in February 2004 it has being working. For ISO-2 the deviation between the calculated energy consumption and the corrected measured energy consumption is less then 11%

while ISO-4 in the beginning of February gives a deviation less then 10% but at the end of February the deviations has increased to 35%. A comparison done later indicated that this effect transmitter is unstable. The measured energy consumption for ISO-1 and ISO-3 can be directly compared to the calculated energy consumption by adding the energy consumption for the circulation pump to calculated energy consumption for the compressors. For ISO-1 the deviation between the calculated and measured energy consumption is less than 20%, For ISO-3 there seems to be a measuring error because the measured power is much higher then the installed power. This error has not been solved yet.

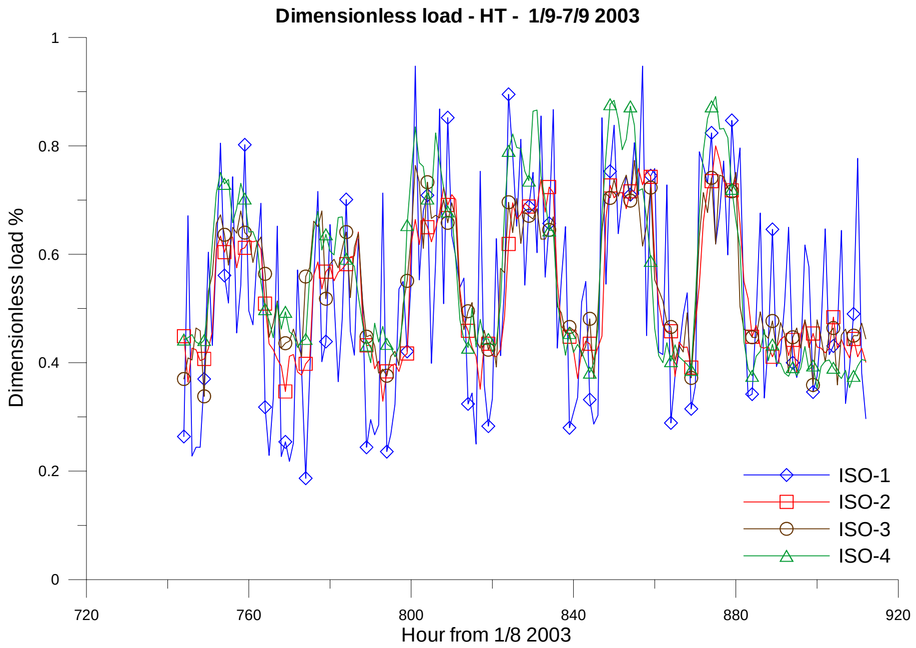

Figure 4. Dimensionless load HT-profile

5.2 Mean COP and Carnot efficiency.

For the period 1/8 to 31/12 2003 the mean COP and Carnot efficiency based on evaporation and condensation temperature without including the pumping power have been calculated. The result is given in Table 2.

	ISO-1	ISO-2	ISO-3	ISO-4
COP_{HT}	3,49	2,53	4,20	2,55
$COP_{HT,kor}$	3,42	3,12	3,41	2,84
COP_{LT}		1,10		1,10
$COP_{LT,kor}$		1,30		1,30
$COP_{LT,tot}$	1,87		1,81	
$Eta_{Carnot,HT}$	0,49	0,52	0,53	0,47
$Eta_{Carnot;LT}$	0,48	0,42	0,45	0,33
$Eta_{Carnot,LT,tot}$	0.46		0,39	

Table 2. Mean COP and Carnot efficiency.

In Table 2 index kor indicates, that the value is corrected to 30°C condensation temperature. Index tot indicates the value for LT working as a two-stage-plant with the measured COP for HT-stage.
Table 2 shows that the cascade plants has higher COP than the conventional plants. The Carnot efficiency is approximately the same in ISO-1, ISO-2 and ISO-3 while ISO-4 has a lower Carnot

efficiency. The lower COP for ISO-4 is believed to be due to the chosen compressor type, where the efficiency is very depending of the pressure ratio due to the built-in volume ratio. The compressors have not worked at pressure ratio corresponding to the built-in volume.

5.3 Energy consumption from mean COP

For the period 1/8 to 31/12 2003 the energy consumption has been calculated for the specified load profile and using mean COP. The results are shown in Table 3.

Accumulated consumption:			
ISO-1: Etotal (corrected)	94555 kWh	of this the pump uses	9440 kWh
Etotal (measured)	93572 kWh	of this the pump uses	9440 kWh
ISO-2: Etotal (corrected)	93492 kWh		
Etotal (measured)	113799 kWh		
ISO-3: Etotal (corrected)	94290 kWh	of this the pump uses	7812 kWh
Etotal (measured)	85160 kWh	of this the pump uses	7812 kWh
ISO-4: Etotal (corrected)	111158 kWh		
Etotal (measured)	127195 kWh		

Table 3. Energy consumption based on load profile and mean COP for the period 1/8-31/12 2003

As seen from Table 3 ISO-1, ISO-2 and ISO-3 has the same corrected energy consumption while ISO-4 has 20% higher energy consumption. The difference between measured and corrected energy consumption is due to the difference between the actual condensation temperature and 30°C condensation temperature. Figure 5 shows the measured condensation and evaporation temperature for HT for the four supermarkets for the whole measuring period. Figure 5 shows the new plants work with higher evaporation temperature and lower condensation temperature. For the evaporations temperature this can partly be ascribed to the flooded operation and partly to the better heat transfer properties of CO_2 compared to R404A. The same picture is seen for the LT cycle but the difference in evaporation temperature is smaller than for the HT cycle. For the condensation temperature it is remarkable that even ISO-1, which has worked with heat recovery, has lower condensation temperature than ISO-2 and ISO-4.

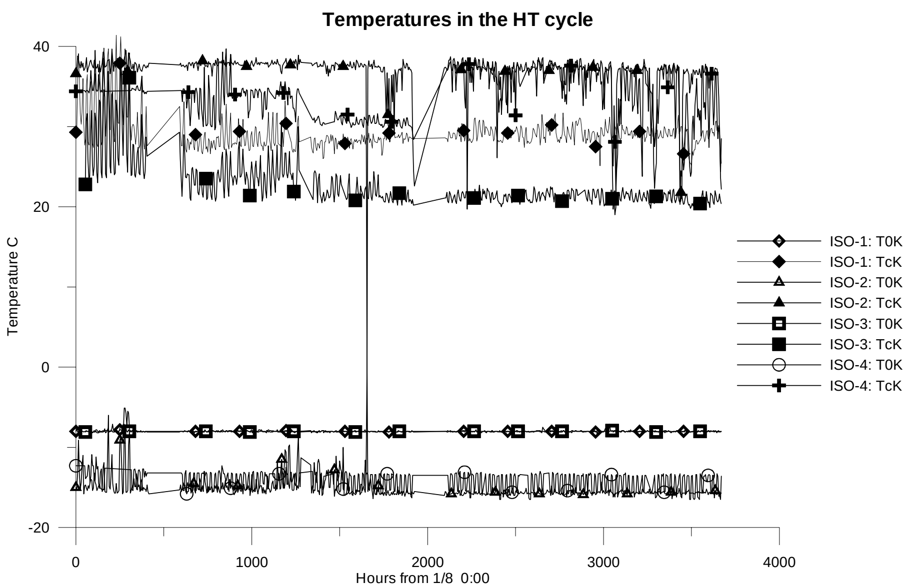

Figure 5. Evaporation/condensation temperature in the HT cycle.

5.4 Energy consumption based on reference supermarket

5.4.1 Calculated energy consumption by means of "multiplier"

The energy consumption calculated as the "multiplier" times the measured energy consumption appeared not to give a correct value for the comparable energy consumption because the cooling load calculated simultaneously is different. For the same supermarket the cooling load should be the same and this method is therefore rejected.

5.4.1 Calculated energy consumption by means of load profile

Using load profiles ensures equal cooling capacity and the calculated energy consumption, corrected to the same condensing temperature and including pumping power, can therefore be compared directly. The used load profile for HT and LT is shown in Figure 6 for the first week in September 2003, where the cooling load is high. Figure 7 gives for the same period the sum of power to HT and LT compressors and for the plants with circulation pumps also the pumping power (hourly mean values).

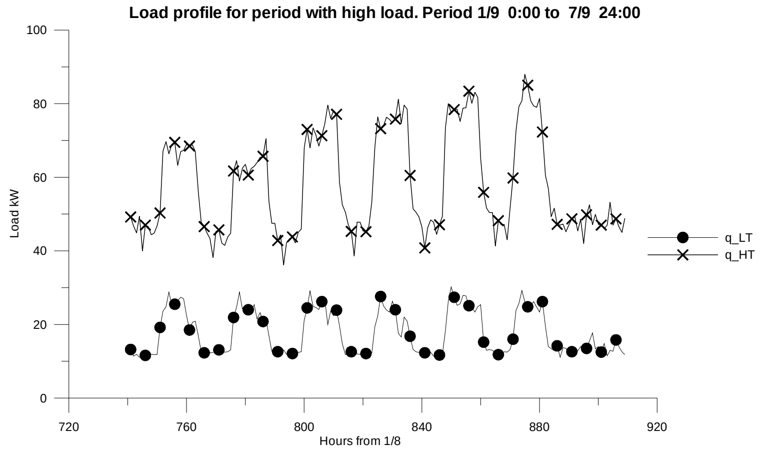

Figure 6. Load profile for period with high load.

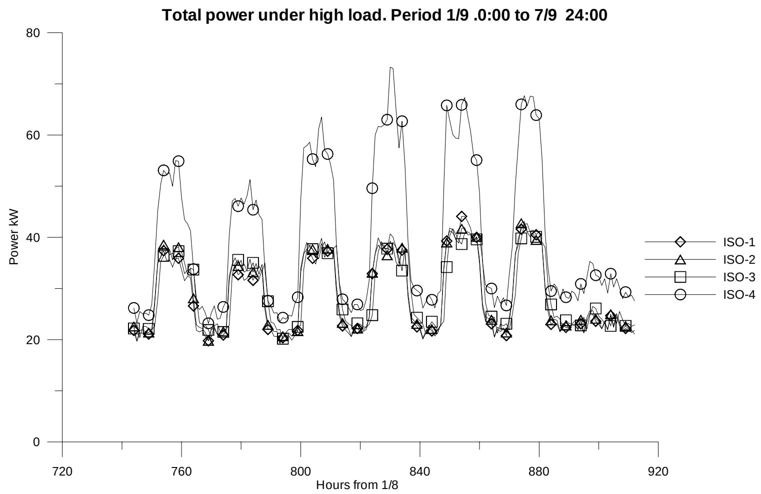

Figure 7. Total power consumption for period with high load.

It can be seen from this figure, that ISO-1, ISO-2 and ISO-3 has the same power consumption while ISO-4 has much higher power consumption. The result is the same for low cooling load. It shall be emphasized, that all supermarkets has the same external conditions as seen from Figure 8.
The turnover in the supermarkets has not been taken into account directly, but using COP based on measured values and standard load eliminates correction for difference in turnover. The relative turnover for the four supermarkets is between 1 and 1.25

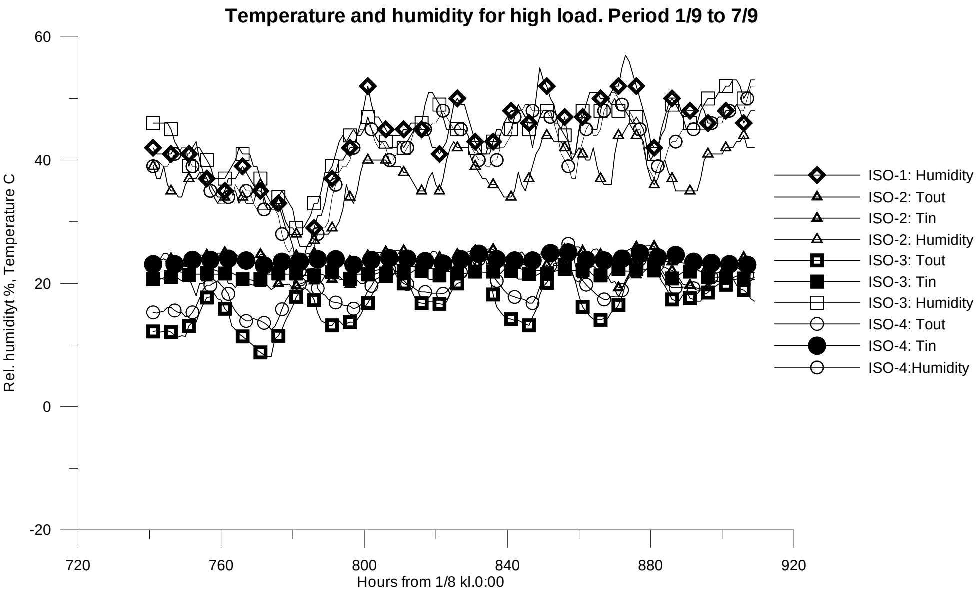

Figure 8. Environmental conditions for high load period.

6. Comparing initial cost

According to information from the installer and the producer of the cascade plant the initial costs for the cascade plant is approximately 10% higher than the initial costs for the conventional plant without taking into account the tax on R404A. If one takes into account the Danish tax on R404A (328 DKR ≈ 44 EUR) the initial costs for the two types of plants will be approximately equal.
The cost for the cascade plant will probably be reduced in the future due to development of standard components as valves and pumps.

7. Conclusion

Based on the result from the measuring period it can be concluded, that the new cascade system has the same energy consumption as a well-dimensioned conventional plant.
The energy consumption for the cascade plant can be reduced implementing a control strategy for the circulation pump. As used now the pumps are running at full capacity no matter the cooling loads.

8. Reference

1: Official opening of the conference; Applications for Natural Refrigerants, Aarhus Sept 1996, IIR proceeding 1996-3

Acknowledgement
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The full report (in Danish, but English version in preparation) can been found on EPA home page www.mst.dk