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Energy Optimisation Potential through Improved Onsite Analysing Methods in Refrigeration

by

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ABSTRACT

This thesis work investigates the potential for energy saving by regular performance analysing of air-conditioning, heat pump and refrigeration systems. The performance analysing method discussed in this report is done by following the “Internal method” where the system parameters are measured on the refrigerant circuit.

A database consisting of performance analyses of 164 refrigeration systems covering the Heat Pump, Air-conditioning and Commercial sectors has been created. The performance analysing of these 164 systems has been done with the help of ClimaCheck™ and ETM 2000 Performance analysing tools which uses the internal method of measurement. Also the performance analysing of 3 case studies covering each sector has been done.

The results from the database establish that 87% of the systems analysed are found to function with faults. The database also establishes that these systems on an average are found to function with a variation of -9.7% in COP and -8.6% in their capacity from the nominal performances.

In terms of achieved energy saving from the analysed performance inspections, the database results when extrapolated on a European level show that 45.44TWh of electrical energy /16.02 million tonnes of CO_2 equiv. can be saved if this type of performance analyses are introduced. This is a very large number in terms of electricity production and is approximately equal to the electricity generation of Denmark or Portugal for the year 2003 and is also equal to the generation of electricity from renewable sources for Germany or Italy (for 2003) or the total wind power generation (for 2003) for EU25.

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1 INTRODUCTION

The long debated issue of climate change has together with increasing energy prices been the driving force behind today's focus on energy consumption in society. The global energy sector has made a considerable progress in exploiting renewable energy sources but much work is to be done in view of the fact that fossil fuels still dominate the global energy mix. The issue of climate change has in no way spared the refrigeration sector and has forced it to improve the efficiency over the past decades since the refrigeration sector plays a major and increasing role in the global energy consumption and the climate change. The improvement in efficiency of refrigeration systems over the decades can be illustrated by the increase in mean COP for commercial refrigeration installations from 2.5 in 1960's to 3.8 in 2002 for a temperature lift of 30K (1).

Even though much work has been done in the refrigeration with regard to energy efficiency, there is still a large potential for energy savings if these systems are better designed and the operation optimized. Often the refrigeration systems do not function the way they are intended. As the focus is on keeping the desired temperature, the unnecessary high energy consumption is often not identified as a problem. The efficiency of refrigeration systems can be determined only by proper commissioning and regular maintenance and performance inspections of the systems.

This thesis work strives to analyse the potential for energy saving by regular performance analysing of the refrigeration process. A database has been created which consists of results from performance analysing of 164 systems covering the Air-conditioning, Heat pumps and the commercial refrigeration sector. These systems has been analysed for their deviation in performance from their design performance for the given operating conditions. A number of case studies from above sectors are reported in more detail in the later part of the report. The performance analysing of the systems covered in the database has been done over the years with the help of ETM 1500, ETM 2000 and ClimaCheck performance analysing "tools". The performance analysing of the systems covered in the case studies have been done with the help of ClimaCheck performance analyser.

2 ENERGY CONSUMPTION IN THE SECTORS

The global energy consumption by the refrigeration and air-conditioning sector is by no means a negligible figure as the growth in refrigeration sector is directly associated with the growth in standard of living of people and the associated change of consumption habits as well as increased demands on comfort. This is an important reason for the difference in the growth of refrigeration applications between the developing and the developed countries. The global electricity consumption by the refrigeration systems has been estimated to 15% (1). But there exists a vast difference in this value between the developing and the developed countries. The energy consumption by the refrigeration sector in some of the developed countries is well above the 15 %(1) average value and in some of the least developed and developing countries it is much less than this value. A striking example to establish this difference can be noted by comparing the production of domestic refrigerators in the year 1996; only 33% were produced for the developing countries in spite of being home to 80% of global population(1). Also in the year 1999 the refrigerated storage capacity for developed countries was 220 litres / inhabitant whereas for developing countries it was 8 litres / inhabitant (1).

In today's scenario the growth rate of refrigeration is very high in the developing countries such as China and India when compared to that of the developed countries. As these developing countries have started to witness high economic growth, a boom in the refrigeration sector can be expected to occur in the coming decade. As most of the developing countries experience a tropical climate, the application of Air-conditioning will most likely see a huge increase in the fore coming years. Also in developing countries 31%(1) of the total volume of food consumed is perishable and only one fifth of this is being refrigerated now, hence there will also be a significant energy increase in refrigerating and preservation of perishable goods. In terms of monetary value globally, the annual investment in the refrigeration sector is around US$200 billion (1), which equals one third of Automobile sector's annual sales.

Refrigeration sector is mainly dominated by the use of Vapour Compression systems which uses electricity as the main source of energy. It has been reported that this trend would be dominating for at least two more decades even with the emergence of new technologies (1). But the impact on the energy consumption from new technologies in the market will happen much slower as many vapour compression refrigeration systems will be functional after 25 years. Today the vapour compression technology is still more energy efficient in most applications than the alternative technologies.

The following are the most promising alternate technologies (besides reducing or eliminating the demand for "active cooling" which is not covered in this report) in which key research has been done over the years;

- *Absorption and Adsorption Technology,*
- *Solar Refrigeration,*
- *Desiccant Cooling.*
- *Magnetic Refrigeration.*

Absorption and adsorption has been mainly used today in areas where restraining the demands on electric distribution has been a priority. They are heat driven cycles and can successfully compete with vapour compression technology in places where the cost of heat is much lesser than electricity. In particular these processes can be an effective way to make “waste heat” useful for both heating and cooling and increase the efficiency in Combined Heat Power (CHP) used to provide heating, cooling and electrical power. The major drawback of this technology is that they are less energy efficient and involves higher investments when compared with the vapour compression technology. A classic example of the lower energy efficiency of Absorption and adsorption cycles than vapour compression cycles has been reported by D W Hudsons (9). It compares and reports that for an ammonia refrigeration cycle with a temperature lift of 55°C between the evaporator and condenser, the $COP_{vaporcompression}$ is almost 4.5(9) times higher than that of $COP_{absorption}$.

Solar Refrigeration can be used in developing countries since most of them experience a tropical climate. The major hindrance for the market development of solar refrigeration is the high investment cost involved and slow technical development. Desiccant cooling systems has a potential market in the regions with hot and dry climate. But many production and technical issues have to be addressed in order to make the alternative technologies more competitive versus vapour compression technology in the majority of applications. Generalising, alternate technologies are today found to be competitive with vapour compression only in certain specific applications and many technical and economical issues have to be addressed before the use can be expected to increase drastically.

The high level of energy consumption by the refrigeration sector has made it an important contributor to the global warming through emission of green house gases from power generation but also through the direct effect of many refrigerants. The implementation of several international protocols over the last two decades has made the refrigeration sector to implement environmental and energy conservative measures which have produced some positive results. The Montreal Protocol (18), which has been the backbone in making the refrigeration sector shift from the usage of ozone depleting substances as refrigerants also resulted in a restructuring of the servicing sector and an increased focus on competency in this industry that is beneficial also for the efforts to improve energy efficiency. This shift to non Ozone Depleting Substances has been successfully achieved in the developed countries and is about to be achieved by the developing countries according to the time frame set by the Montreal Protocol (total phase out before 2010). The next challenge for the industry is to adapt to the intentions in the Kyoto Protocol (19). This protocol focus is to reduce the emission of green house gases. As approximately 20% of the refrigeration sector influence on global warming is due to the direct emission of refrigerants and 80% of the influence on global warming is due to the CO_2 emissions originating in the production of energy used by refrigeration plants (10). Production of electricity required to operate the refrigeration systems and also the direct use of fuel in mobile Air-conditioning and refrigerated transport applications are the key responsible for the indirect emissions.

In this report, the energy consumption of the refrigeration sector has been explained by classifying it into three major categories namely Air-conditioning, Commercial refrigeration and Heat Pump sectors. The estimated number of refrigerating systems operating world wide has been presented in the table 1.

Commercial and Industrial Refrigeration	**Air-conditioning**	**Heat Pumps** **(including reversible Air-conditioning)**
Commercial Supermarkets 0.117million units Condensing Units 2.8 million units Stand alone display cabinets 10 million units Miscellaneous 13,25 million units	**Air-conditioning (air-cooled)** Duct free packaged & split systems 89 million units Ducted split systems 55 million units Commercial unitary Systems 16 million units	**Residential** **110 million units**
Food Industry Bulk Milk coolers 5 million units Industrial refrigeration 300 million m^3		**Commercial & Institutional applications** **15 million units**
Transport Marine Containers 0.41 million units Reefer ships 1,088 ships Refrigerated rail cars 0.08 million units Road transport 1 million units Merchant Marine 30,000 ships Buses and coaches 0.32 million units Liquefied gas tankers 71 units	**Air-conditioning (water chillers)** **8.56 million units** **Mobile Air-conditioning** (Pass. and Com. Vehicles) **380 million units**	**Industrial** **0.03 million units**

Table 1: World wide Refrigerating systems in use (1)

The energy consumption of the Air-conditioning sector in Europe has been on a rapid increase for the last decade. It has been reported that in the year 2005, around 1500Mm^2 of area was cooled in Europe and is expected to rise to 1974Mm^2 by the year 2010 (11). Most of the Air-conditioning systems presently used in Europe will become nearly 15 years old by the year 2010 and will hence need a renewal. This will give room to establish energy efficiency measures on 800 million m^2 of area in Europe by the year 2010 (11). The following figure shows the predicted growth in cooled area in Europe for different cooling systems up to the year 2020.

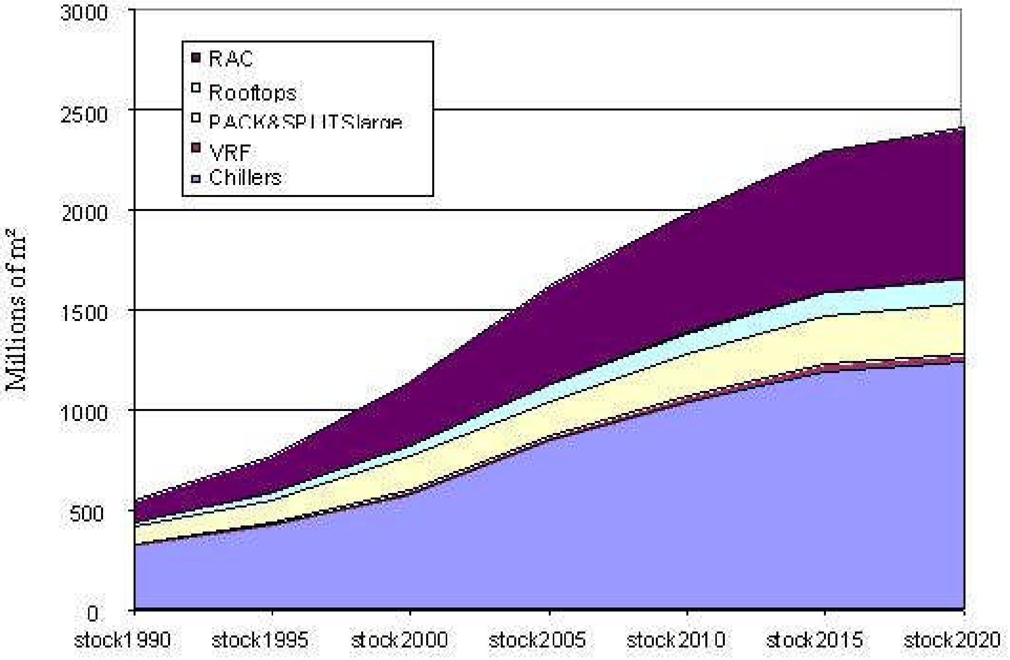


Figure1: Cooled area in Europe (11)

Commercial Refrigeration also plays a significant role in the global energy consumption. There are approximately 7700 Hypermarkets (sales area more than 2500m^2) and 59000 Supermarkets (sales area below 2500m^2) in Europe (12). The numbers of Hypermarkets and Supermarkets for the European countries are shown in the figures below (figures 2 & 3).

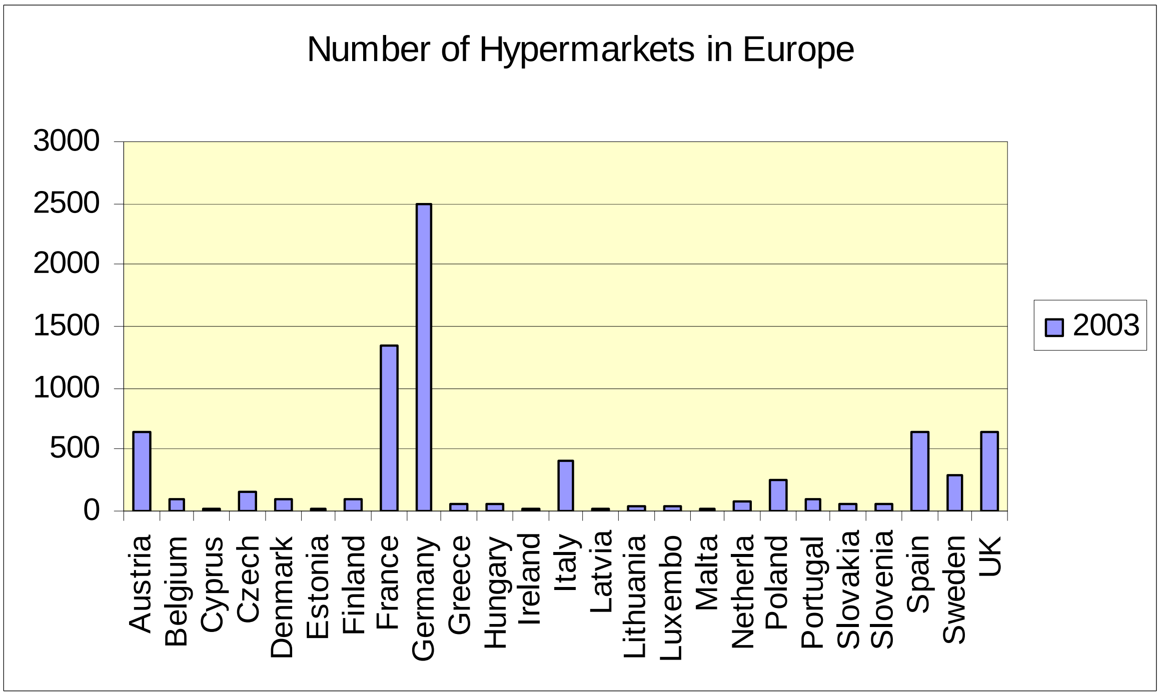


Figure2: Number of Hypermarkets in Europe ***(12)***

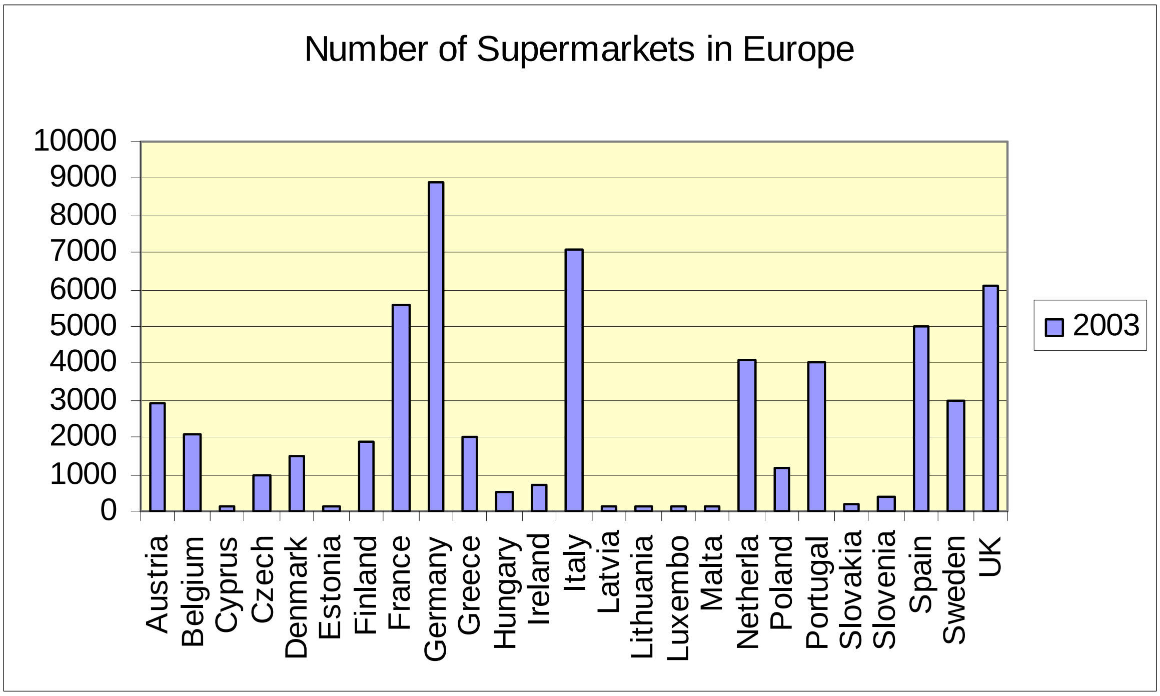


Figure3: Number of Supermarkets in Europe ***(12)***

3 ENERGY EFFICIENCY OF REFRIGERATION PROCESS

The refrigeration cycle like many other thermodynamic cycles is influenced by number of losses due to its irreversibility. It is impossible to run a machine with moving parts without friction and without temperature differences in heat exchangers resulting in losses, but there is significant potential to minimise the energy consumption by reducing the losses. Many of the measures to reduce the losses can be done cost effectively.

The main components of a Vapour compression system are the heat exchangers, compressor and the expansion device. A Vapour Compression cycle is dominated mainly by the following losses,

- Losses due to temperature differences
- Throttling loss
- Loss in the compressor and motor
- Losses in the Auxiliaries (pumps, fans etc.)

The temperature lift of the system plays a major role in determining the energy performance of the system. The condensing temperature should be kept as low as possible and the evaporation temperature should be kept as high as possible depending upon the type of application to have the optimal energy performance of the system. There must be a temperature difference between the refrigerant in the heat exchangers and the secondary cooling/heating media in order to make the heat transfer occur between them. This temperature difference should be kept as small as possible thereby increasing the energy performance of the system. The sizing of the heat exchangers is of major importance for the energy efficiency.

Throttling loss and the losses in the compressor increase the energy consumption of the system. The throttling loss can be reduced if the liquid refrigerant is sub-cooled to the highest possible level before reaching the throttling device. With economizers the throttling losses can be reduced considerably. But the economiser systems are only used in a few percent of the installations as the investment cost is often not considered justified by the efficiency improvements. The potential for improvements depend on the pressure ratio and sub-cooling achieved without economiser.

The losses in the compressor have been of major research interest in the refrigeration field and several substantial improvements have been made over the decades. Volumetric efficiency of the compressor, internal pressure drop and the mechanical losses together with the performance of the electric motor are the main factors which define the performance of the compressor.

The other important loss which occurs in a vapour compression cycle is due to auxiliary components such as fans and pumps. Even though the energy consumed by the fans and pumps are relatively small when compared with the energy input to the compressor, bad design or malfunctioning of these components lead to increased use of electricity directly and/or non-optimal working conditions in the system which results in the increase of energy consumption of the system.

The losses, resulting from poor design and maintenance, occurring in a system are often noticed only when the system fails to heat/cool the required volume. But large number of system continues to heat/cool the required space also with non-optimal working conditions but with increased energy consumption. A system will continue to deliver its heating/cooling load even if the evaporation takes place at lower temperature than the designed one, thus working in non optimal conditions leading to higher energy consumption.

4 ENERGY EFFICIENCY REGULATIONS

This chapter highlights some regulations and certifications relevant to the energy efficiency of refrigeration and air-conditioning systems. The scope of these regulations and the methods of implementation and the merits and demerits are also discussed.

4.1 Energy Performance of Building Directive (EPBD)

The Energy Performance of Building Directive was passed by the European Parliament on January 4, 2003 and comes into force from January 4, 2006. This directive regulates the energy efficiency of buildings in Europe by stating the methods to achieve it in several articles. Of those articles, article 9 is focused directly on inspections to ensure the energy-efficiency of air-conditioning systems. In order to review the directive, article 9 and some of the necessary definitions are listed below taken as excerpt from Energy Performance of Building Directive (2),

> *"With regard to reducing energy consumption and limiting carbon dioxide emissions, Member states shall lay down the necessary measures to establish a regular inspection of air-conditioning systems of an effective rated output of more than 12kW.*
>
> *The inspection shall include an assessment of the air-conditioning efficiency and the sizing compared to the cooling requirements of the building. Appropriate advice shall be provided to the users on possible improvement or replacement of the air-conditioning system on alternative solutions. "*
>
> **Definition in EPBD:** *"An air-conditioning system is a combination of all components required to provide a form of air treatment in which temperature is controlled or can be lowered, possibly in combination with the control of ventilation, humidity and air cleanliness."*

Article 9 of Energy Performance of Building Directive emphasises the need for regular inspection of Air-conditioning systems with a capacity higher than 12kW (2). It requires an independent inspector to assess the efficiency of the system and suggest "possible improvement or replacement of the air-conditioning system and on alternative solutions". It also requires the inspector to compare the sizing of the installed capacity compared to the buildings cooling requirements.

The directive has left room for the member states of the European Union to state the way of conducting these inspections and also the frequency of inspections. The frequency and details of inspections would normally be dependent on the capacity of the air-conditioning unit.

The 12kW limit defined by the regulation is the effective rated output of the system as specified by the manufacturer under continuous operating conditions Dupont et.al (4) has explained four different ways to interpret the12kW limit. The four ways to interpret the 12kw limit from Energy Performance of Building Directive article 9 according to Dupont are listed below with explanation of the first two as they are considered to be more relevant to this report.,

- defined as the cooling load of the whole building in consideration
- defined as the cooling capacity of individual systems in use in the building
- defined for each temperature controlled zone
- defined per owner in a given building

The first way would require an inspection to be made on the Air -conditioning systems of the building if the total cooling load of the building exceeds the 12kW limit. This condition would apply for the systems even if their individual cooling capacity is much less than the 12kW limit. This will increase the time and cost required for the inspections since it might involve quite many numbers of small systems and also the energy saving potential in individual systems might be low.

The second way would require an inspection only if the individual cooling capacities of the systems is greater than the 12kW limit. This would reduce the time required for the inspections and also increase the energy saving potential on each inspected system. One of the major disadvantages is that, this would make the building owner invest in many small systems rather than making an evaluation of the best system from energy efficiency perspective.

4.2 Eurovent Certification

Eurovent is the association representing the European air-conditioning, ventilation, heating and refrigeration manufacturers. Eurovent certification of a product guarantees that the product will have a specified performance in accordance to the conditions established in a well defined test. Well specified methods for testing decrease the risk of “overrated” performances from the manufacturer.

The following are the list of products which have been certified by the Eurovent association (6),

- Comfort Air-conditioners up to 100kW
- Close Control Air-conditioners
- Liquid chilling packages
- Air-coolers for Refrigeration
- Refrigerated Display cabinets
- Air cooled condensers
- Dry coolers
- Cooling Towers
- Air Handling Units
- Cooling and Heating coils
- Air to Air Plate Heat Exchangers
- Air to Air Rotary Exchangers
- Fan Coil Units

Manufacturers can choose to let these products be tested and given a Eurovent certification that they comply with the specifications as stated by the manufacturer. It is not uncommon to see companies going for Eurovent certification only for their top range of products. Since a certain section of the customers focus mainly on the initial cost of the product there is a large market for lower cost equipment where a certain level of compromise is made with regard to energy efficiency. The lack of awareness and focus on long term cost of operation can be stated as one of the hindrances of more widespread implementation of Eurovent certification.

5 INSPECTIONS

The methods for inspecting the refrigeration systems have not yet been clearly stated by any regulation. There is a standard under development prEN15240 “Ventilation for buildings - Energy performance of buildings - Guidelines for inspection of air-conditioning systems“. But this guideline for inspection of Air-conditioning systems in its current wording which should serve as the guide line for article 9 of EPBD fails to establish any specific inspecting procedure for the actual refrigeration unit. The CEN standard does not address the specific parameters to be measured in order to determine the performance of the system. It is the view of the author that the CEN standard for inspection of Air-conditioning systems is not enough to assess the performance of refrigeration plant. The following inspection methodology is one such stated by the CEN standard which questions its quality. “Compared with the ambient temperature in the plant room (or indoors or outdoors), one side of the refrigeration circuit should become cold and the other warm while the compressor is working. These temperature differences should be apparent when flow and return water pipe work or refrigerant pipes to and from the refrigerant plant are touched or, better still; the temperatures measured using one or two surface temperature probes. If, while the refrigeration plant is operating, the flow and return appear to be at the same temperature, or warmer than the surroundings, then it is likely that the equipment has lost its refrigerant charge." (4) But this condition stated as one of the inspection methodology by CEN does not hold good. A refrigerating system that has lost its refrigerant charge will not have the same temperatures at the discharge and suction side of the compressor on the contrary the discharge will increase as the pressure decrease and suction temperature increases. In fact it is according to the energy laws not possible for the discharge and suction side of compressor to have the same temperatures, (except for very temporarily) as the compressor will overheat if there is no gas flow or no increase of enthalpy to the pumped gas. If applied to the liquid and suction line of the refrigerant system the sub cooled liquid can be of a temperature not very different from the suction gas in some applications. Even applied on the tubes in a secondary system temperature differences of a few degrees are difficult or impossible to judge by hand and even if measured it does not rely give any indication of the efficiency of the system or make it possible to draw conclusions on the refrigerant charge of the system. In short the information is not sufficient for any meaningful evaluation. The performance of a refrigeration system should be analysed based on measuring some of the basic parameters such as temperatures, pressures and power input in the refrigeration circuit. The performance of the plant can be defined by these measured parameters (chapter 6) and compared with the nominal data normally provided by the manufacturer or with expected performance of this type of systems.

There is also a European standard EN378 which relates to “safety and environmental requirements in the design, manufacture, construction, installation, operation, maintenance, repair and disposal of refrigerating systems and appliances in respect to the local and global environments, but not to the final destruction of the refrigerants” (15). Part 4 of EN378 relates to operation, maintenance, repair and recovery of the refrigeration systems. It lays out some basic information regarding documentation of records for refrigeration systems and operational instructions. It also stresses that regular inspection and preventive maintenance should be carried out on all refrigeration systems especially with systems more than 3 kilograms of charge. But the standard does not clarify on the method of inspection.

6 METHODS FOR PERFORMANCE INSPECTIONS

There are two possibilities to establish the performance of a refrigeration process, the traditional way is by measuring “externally” on the air/liquid cooled or heated by the unit while the analyses in this report is based on measurements from an innovative measuring method based on measurement “internally” in the refrigerant circuit.

6.1 External method

The traditional method for performance analysing is through measurements on the secondary side of evaporator/condenser of flow and temperature differences (for air also humidity).

The major restrictive factors in this method are:

- *The cost and difficulty to apply and achieve good accuracy on flow measurements (i.e. to calibrate at relevant flows and temperatures in a field installation).*
- *The sensitivity of errors in temperature measurements caused by the often small ΔT on the secondary side.*
- *The difficulty in establishing accurate humidity in air systems and physical properties in brine systems.*

Documentation shows that it is possible to achieve results with uncertainty less than 2 % (3) for measuring specialists when performing inspections of large systems with access to the best available equipment and methods. But this largely depends upon the delicate calibration and accuracy of the flow meter and temperature sensors as well as the stability of the system in study. As temperature errors of 0.5 K on the ΔT normally will result in errors of in the order of magnitude of 10% and brine can increase the inaccuracy with 5-10% the result of a typical field measurement have an uncertainty between 10-20%.

6.2 Internal method

This method has been used for performance inspections of the systems analysed in the data base and case study of this report. This method is based on the measurements of temperature and pressures in the refrigerant circuit. The enthalpies of the refrigerant in the key points can then be calculated and the main performance parameters such as COP and Capacity can be established. The most distinguished advantage of this method is that it not only pinpoints the deviation of the system from expected performance but also provides information on reason for the deviation. The performance based on the internal method tends to be more accurate as they are generally much less sensitive to measurement errors and have only an uncertainty around 5% (3). A schematic sketch of mounting the temperature and pressure sensors in an internal measurement method is shown in figure 4. The accuracy of the internal method under field conditions is often in practice higher than for the external method but the main advantage is that it gives more information at a lower cost. The lower sensitivity for measurement errors is a main advantage as it reduces the risk of errors.

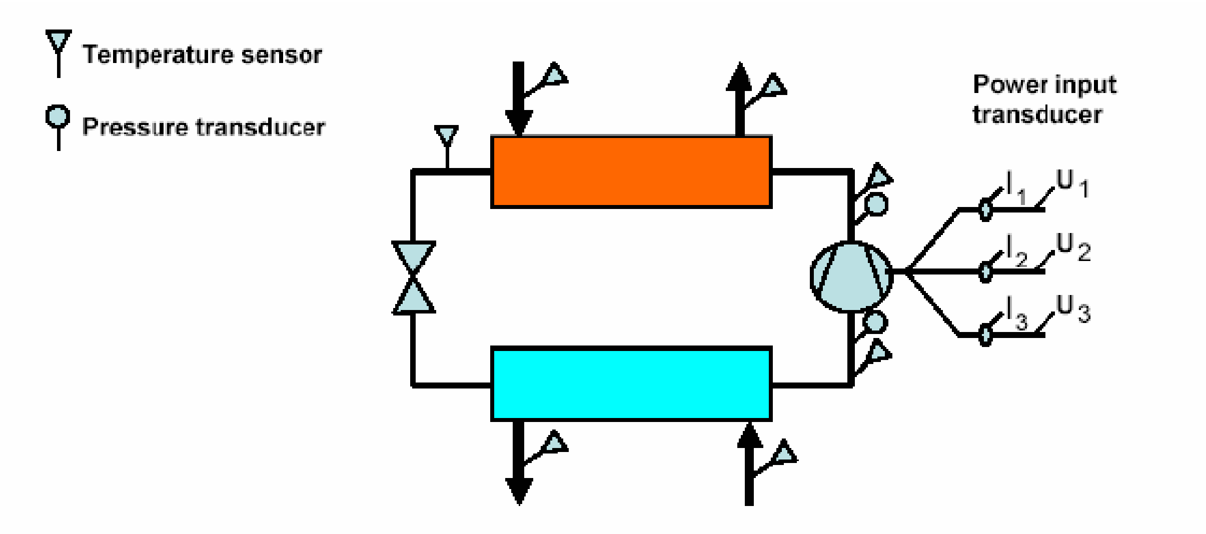


Figure 4: Location of sensors and transducers on the refrigeration circuit in the internal method (7)

ClimaCheck (and the older version ETM 2000) of Performance Analysing tools use the above described internal method for performance analysing of refrigeration systems. The readings taken by the various sensors and transducers mounted on the system (figure 7) are then calculated. The results can be illustrated in a Pressure-Enthalpy diagram (see figure 6) of the respective refrigerant. The necessary parameters needed to define the performance of the system are then calculated by an Energy balance over the compressor by considering it as a Black Box as shown in the figure 5.

The accuracy of the measurements recommended by ClimaCheck Sweden AB is:

Pressures	± 1%
Temperatures	± 0.5 K
Power Input	± 2%

This allows for a total measurement accuracy including temperature errors caused by using external temperature sensors to achieve the accuracy stated above.

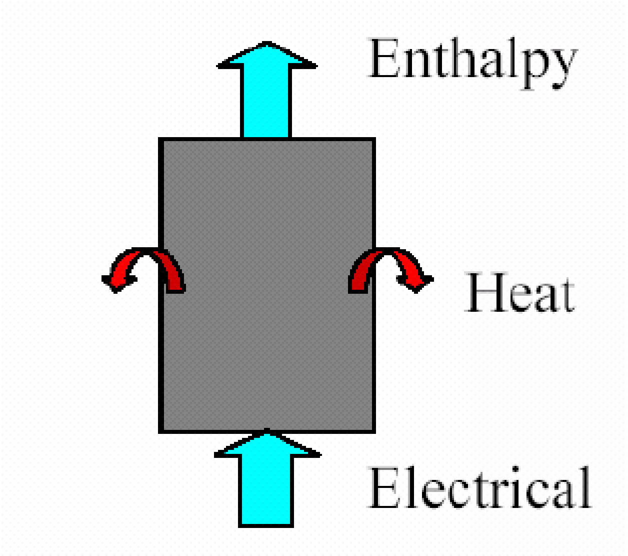


Figure5: Black Box Analysis on the Compressor

The necessary parameters can be calculated by the following equation,
Mass flow = (Electrical Input – Heat Losses) / (Enthalpy difference between inlet and outlet of compressor).

The heat losses from the compressor in above equation are assumed to be around 7% of the electrical input, as previous studies have established that the heat losses for hermetic and semi hermetic compressors lie in the range of 3 to 10% (20). This assumption is mostly precise since 50% increase or decrease in this value would result only in 3 to 4% error in the measurements according to the heat rejection rates established by Asercom (21).

The calculated values in the equation are then presented as shown in the figure 8. The stability and performance of the system can be more clearly understood when the graph, plotting the various parameters with respect to time is studied (figure 8).

6.3 Stability of measurements

The stability of the measured system is always an issue for field measurements regardless of method used. For the external method the requirement for stable operation is significantly higher than with the internal method as the sensitivity to a small change is larger. The delay in response is increased because the secondary system responds after the refrigerant process. In particular for chillers with a significant mass of secondary fluid in heat exchangers and system the response time to a change becomes significant. By plotting all changes over time it is possible to judge the influence of fluctuations. Fluctuations in operation conditions will naturally increase the uncertainty of any performance analysing method due to lack of precise operating condition definition, and the measuring accuracy is also affected.

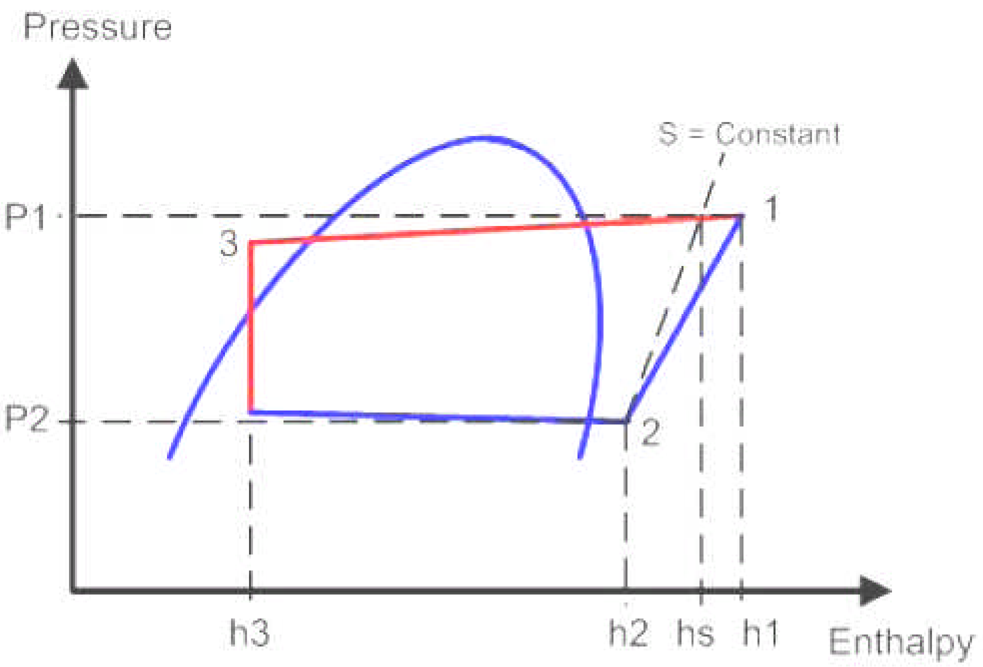
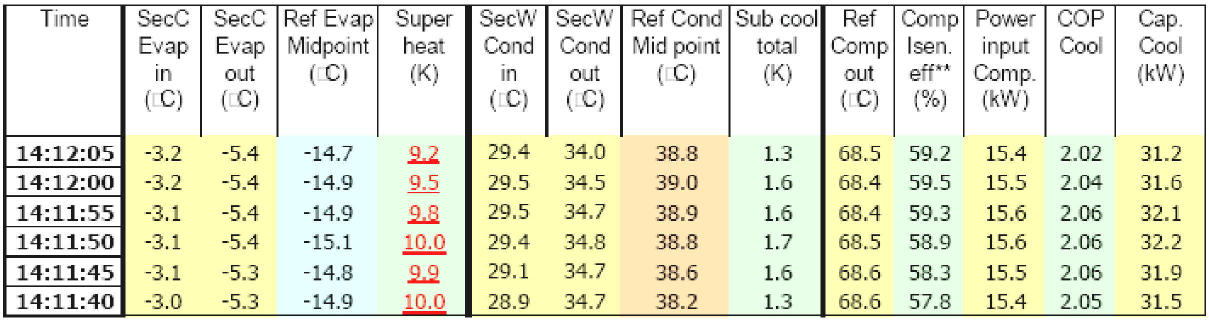


Figure6: Pressure-Enthalpy diagram of a standard Refrigeration Cycle



Time	SecC Evap in (□C)	SecC Evap out (□C)	Ref Evap Midpoint (□C)	Super heat (K)	SecW Cond in (□C)	SecW Cond out (□C)	Ref Cond Mid point (□C)	Sub cool total (K)	Ref Comp out (□C)	Comp Isen. eff** (%)	Power input Comp. (kW)	COP Cool	Cap. Cool (kW)
14:12:05	-3.2	-5.4	-14.7	9.2	29.4	34.0	38.8	1.3	68.5	59.2	15.4	2.02	31.2
14:12:00	-3.2	-5.4	-14.9	9.5	29.5	34.5	39.0	1.6	68.4	59.5	15.5	2.04	31.6
14:11:55	-3.1	-5.4	-14.9	9.8	29.5	34.7	38.9	1.6	68.4	59.3	15.6	2.06	32.1
14:11:50	-3.1	-5.4	-15.1	10.0	29.4	34.8	38.8	1.7	68.5	58.9	15.6	2.06	32.2
14:11:45	-3.1	-5.3	-14.8	9.9	29.1	34.7	38.6	1.6	68.6	58.3	15.5	2.06	31.9
14:11:40	-3.0	-5.3	-14.9	10.0	28.9	34.7	38.2	1.3	68.6	57.8	15.4	2.05	31.5

Figure7: Figure with selection of calculated data

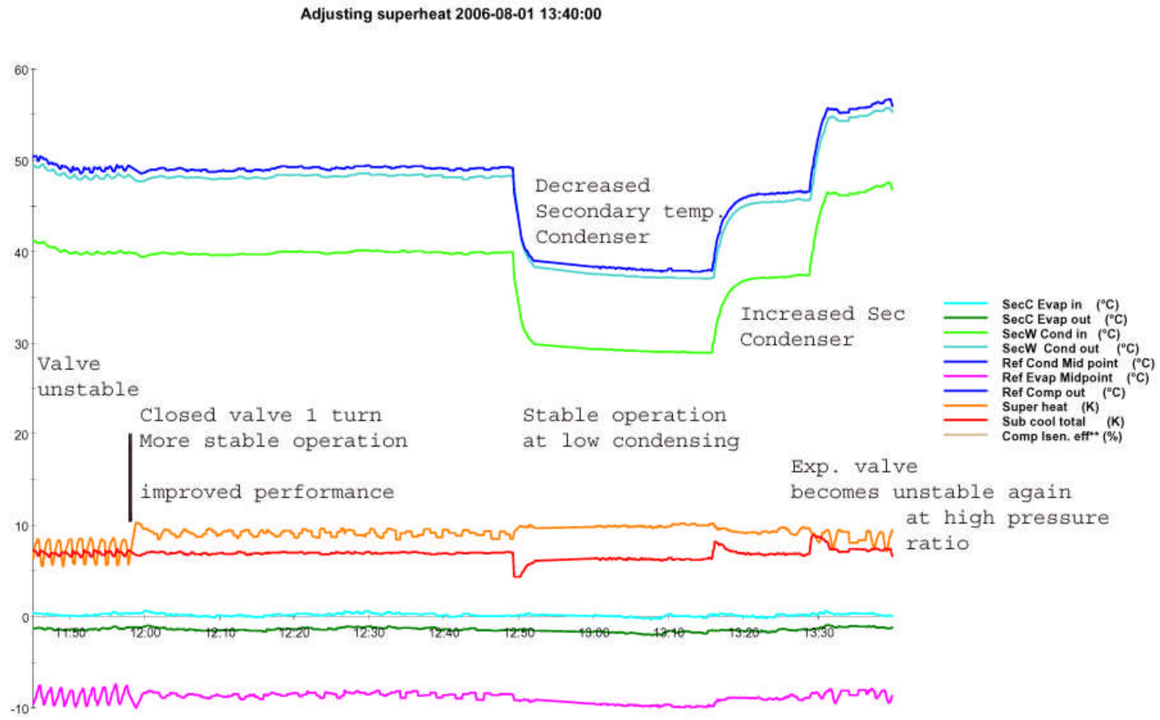


Figure8: Graph displaying the importance of documenting behaviour at different conditions. Adjustment of expansion valve followed by, Stable superheat and evaporation at low condensing but remains unstable at high condensing.

7 ENVIRONMENTAL IMPACT

This chapter concentrates in explaining the environmental impact of the refrigeration systems. The environmental impact of refrigeration systems can be established by the following approaches namely, Life Cycle Climate Performance (LCCP) and Total Equivalent Warming Impact (TEWI) (8). The TEWI approach includes the direct emission of CO_2 due to refrigerant leakage and refrigerant losses at the end of the system's life and the indirect emissions of CO_2 associated with the energy consumed by the plant. The LCCP approach takes into account the effect of production of refrigerant in the system in addition to the direct impact of leakage and indirect impact of energy consumption.

The TEWI of a refrigeration system can be calculated by the following relation (8),

$TEWI = (M_{losses} * N + M_{ref} * (1-\kappa)) * GWP_{ref} + RC * E * N$ (Jaime Arias, 2005)

where,
M_{losses} is the refrigerant leakage
N is the life time of the refrigeration system
M_{ref} is the refrigerant charge
κ is the recycling factor
GWP_{ref} is the Global Warming Potential of the refrigerant
RC is regional conversion factor, depends on the energy mix of individual countries
E is the annual energy consumption of the equipment

Table 2 shows the Global Warming Impact of the Refrigeration sector in million tonnes of CO_2 equivalent for European Union (1998).

Global Warming Emission, M tonnes CO_2 equivalent.

	Direct HFC Emissions	Indirect CO_2 Emissions	Total Global Warming Impact	% of Global Warming impact related to energy use
Super Market Refrigeration	9	23	32.0	72
Mobile Air-conditioning	8.9	14	22.9	61
Industrial Refrigeration	3.4	25	28.4	88
Air-conditioning, DX systems	2.6	10	12.6	79
Small Commercial Refrigeration	1.8	12	13.8	87
Domestic Refrigeration	0.8	30	30.8	97
Transport Refrigeration	0.7	6	6.7	90
Air-conditioning, Chillers	0.7	12	12.7	94
Other Small Hermetic	0.3	12	12.3	98
Total Emissions	**28.2**	**144**	**172.2**	**84**

Table 2: Global Warming Emissions of the Refrigeration sector in million Tonnes of CO_2 equivalent for European Union (1998) (14).

8 ENERGY OPTIMISATION

This chapter focuses on the various possible ways of energy optimisation during different stages of a refrigeration system. A special focus is also given on the energy optimisation by Performance Inspections at commissioning and regular inspection of refrigeration systems.

This thesis work is related to optimising the term “E” (annual energy consumption) in the above stated equation of TEWI. The energy optimisation of a refrigeration system as a whole can be done during the following stages,

- Design
- Commissioning
- Maintenance

Component selection which is done during the design stage has a substantial amount of influence on the energy efficiency of the system. Other factors such as the plant tightness of the system also should be considered as they affect the amount of refrigerant and how close to optimum the system will work over time.

During commissioning of the refrigeration plant good installation techniques should be followed to ensure that the refrigerant is contained in the system. Refrigerant charge optimisation is an important factor to be observed during commissioning, but it remains as a condition that many systems fail to achieve. Also during the commissioning phase the plant should be checked whether the system operates at optimum conditions and if the performance claimed by the manufacturer is achieved under the stated operating conditions. The plant should be installed in such a way that the system is easily accessible for future maintenance and inspections.

Maintenance of the plant on regular intervals helps in minimizing problems occurring in the plant. Improper maintenance will lead to increased failure rates such as compressor breakdown which is very important from the economic point of view. One of the major advantages of regular high quality maintenance is that the system can be tuned to perform in an optimal way thereby resulting in significant energy saving. Proper and regular maintenance also can result in early detection of problems that reduces the repair cost. Refrigerant leak monitoring can be improved by regular maintenance where detection of changes in the system can be detected were small or “hidden” leaks in the system often are missed when technicians search for leaks which results in substantial amount of indirect energy savings.

Inspection on a refrigeration plant should according to European Performance of Building Directive be carried out by qualified and independent inspectors whereas maintenance is carried out by the service contractor of the plant. Inspection of Refrigeration plant on a regular interval can ensure that the plant’s maintenance is carried out at regular intervals. Qualified and independent inspections can create awareness among the end-users which will make them more motivated to do energy efficiency improvements in the plant. Recommendations by an independent inspector can also be expected to be taken more seriously by the equipment owner than a contractor recommendation as the later will benefit from the extra short term work. It has been reported (chapter 5) that during documented inspections the systems often have been found to function in a non optimal way in spite of that the contractor previously checking the plant and stating that it is ready for inspection. This raises a question if the commissioning and maintenance work that is performed on refrigeration plants today is of the quality justified by the cost of energy and repairs as well as the environmental impact from direct and indirect effect on the climate. Normally the inspected plants have been checked by a contractor prior to the inspections. An increased frequency of qualified third party inspections of the refrigeration plant will improve the quality of the maintenance done on the plant thereby improving the energy performance of many systems.

9 STATISTICAL ANALYSES (DATABASE)

The database created consists of analysis of 164 systems covering Heat pumps, Commercial and Air-conditioning sectors. These analyses have been done from the performance reports prepared by ETM Kylteknik AB on various systems in Sweden.

9.1 Performance Reports

The Performance Inspection reports explain the current performance of the system by measuring their performance with the ETM Analyser. The ETM analyser uses the internal method of measuring the system as explained in section 6.2. The measured and calculated parameters are then compared with the nominal data of the refrigerant plant as specified by the manufacturer under the same working conditions. In some cases where there is a lack of system manufacturer's data, calculations are done with component data (e.g. compressor and heat exchanger manufacturer's software) and then they are compared with the measured values. These performance reports summarises the performance of the system also pointing out the problems in the system and suitable solution to them.

These measurements have been made under any one of the following circumstances,

- Capacity checks at commissioning of the system
- Capacity checks at the end of warranty period of the system
- Capacity checks (in connection with) overhauls, re-designs and retrofits.

9.2 Database

The database was created in MS-Excel. The amount of variation in the performance of the system was calculated from the nominal and measured data stated in the Inspection reports. Whenever possible the systems are operated at nominal capacity as specified in contract. At times when this has not been possible due to ambient or load conditions the measured data has been compared with nominal data adjusted to the relevant conditions. The "nominal data" for measured conditions that differ from in contract specified data have when possible been taken directly from system manufacturer data. When system manufacturers have not been able to give adjusted "nominal data", recalculations have been done in compressor and heat exchanger software.

In general the experience is that the cause of identified deviations from "nominal data" can also be identified in the analyses which suggest that the method for adjusting nominal data is of acceptable accuracy.

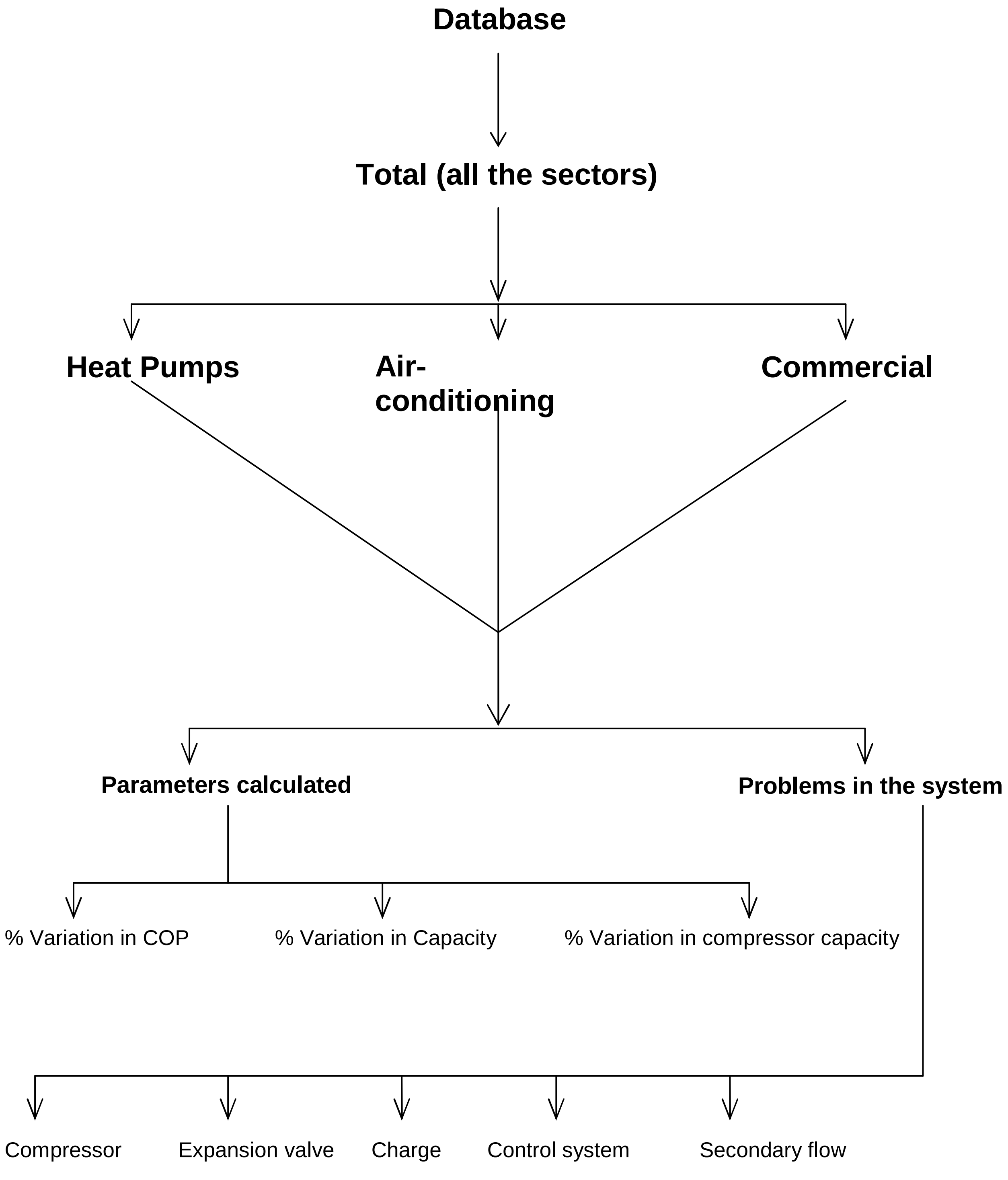


Figure9: Structure of the database

The structure of the database has been represented in the figure 9. The database consists of two major sections namely, calculation of parameters and the problem identification. The calculations and the problem identification have been done for the total database and also for the respective sectors. In the problem identification section, only the problems which will have a substantial amount of influence on the energy consumption of the system are taken into account.

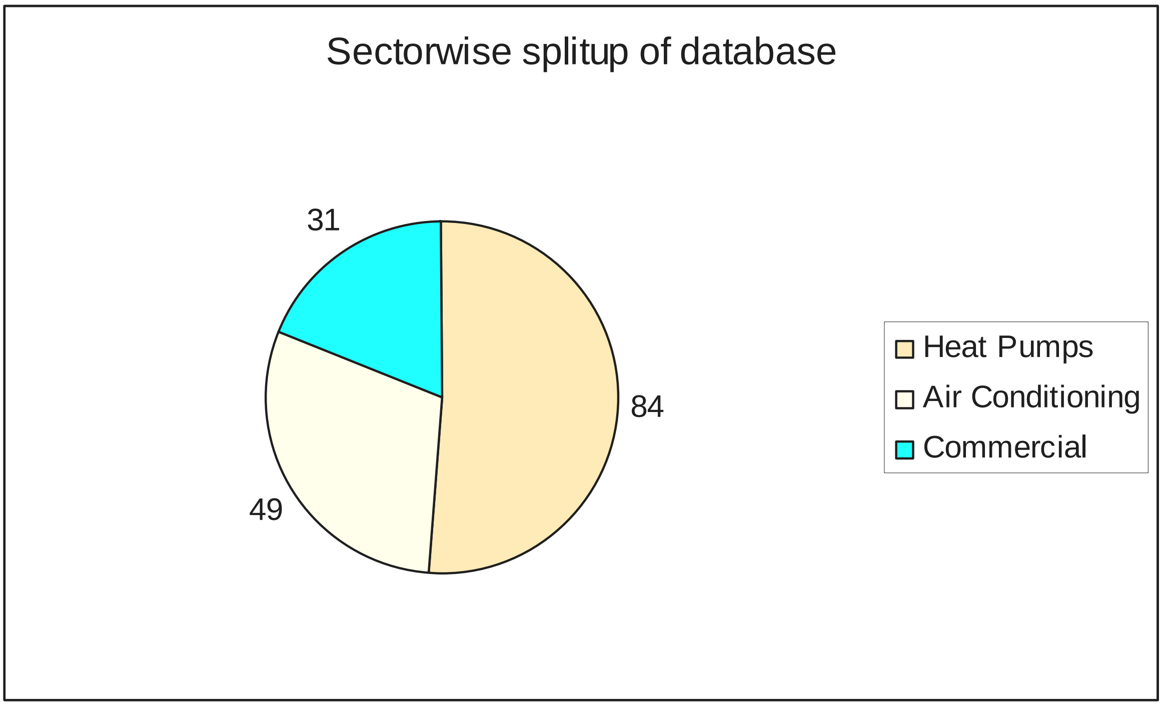


Figure10: Sector wise split up of database

The database has a large number of Heat Pumps (84), as they are used in large numbers in Sweden, a country with high heating demand and the focus on energy efficiency is stronger than in the commercial and air-conditioning sectors. The number of Air-conditioning systems analysed is 49 followed by 31 in the Commercial sector. The sector wise split up of the database has been represented in the figure 10. The Heat Pumps analysed in the database does not include the split units.

Number of Systems	164	
Number of Systems with faults	144 (87%)	
Calculated Parameters (Average)		
Variation in COP	-9.7%	
Variation in Capacity	-8.6%	
Variation in Compressor power input	1.3%	
Type of problem		
	Number of systems	**In % of total faults**
Compressor	3	2%
Expansion valve	51	36%
Charge	78	54%
Control System	4	3%
Secondary flow	7	19%

Table 3: Results from the database for all the sectors

Table 3 shows the summary of results of the total database. The results shown in the table are for all the 164 systems covering the sectors of Heat pumps, Air-conditioning and Commercial. These results indicate that most of the refrigerating systems analysed in this thesis work do not perform as specified. Around 87% of the systems have been found to work with some kind of faults. These faults are key reasons for the deviation in performance of the systems. These faults have been noticed only when the measurements have been done on the system.

As the inspections are announced in advance the contractors have been well aware that an inspection of the system is going to take place and in most cases check the systems in advance. But the results shown establish that the systems in-spite of this consume more energy than they should. As the customers and the service companies focus mainly on maintaining the desired temperatures, high energy consumption of these systems are often left unnoticed. The results show the need for regular inspection of the systems as most of faults are found only when measurements are done on the system.

The following graphs have been plotted in order to explain the variation of the calculated parameters with the variation in capacity of the systems (i.e.) how much the parameters vary between the systems with high and low capacity,

- % Variation in COP (vs.) Nominal Capacity kW
- % Variation in Capacity (vs.) Nominal Capacity kW
- % Variation in Compressor power input(vs.) Nominal Capacity kW

The average variation of COP is -9.6%. It is seen from the figure 11 that most of the systems lie in the range of 0 to -20%. It is also evident that the variation in COP is smaller for large systems than the small systems. The maximum and minimum variation in COP is -35% and 7% respectively. There are totally 20 (12%) systems which function with close to 0% variation in COP.

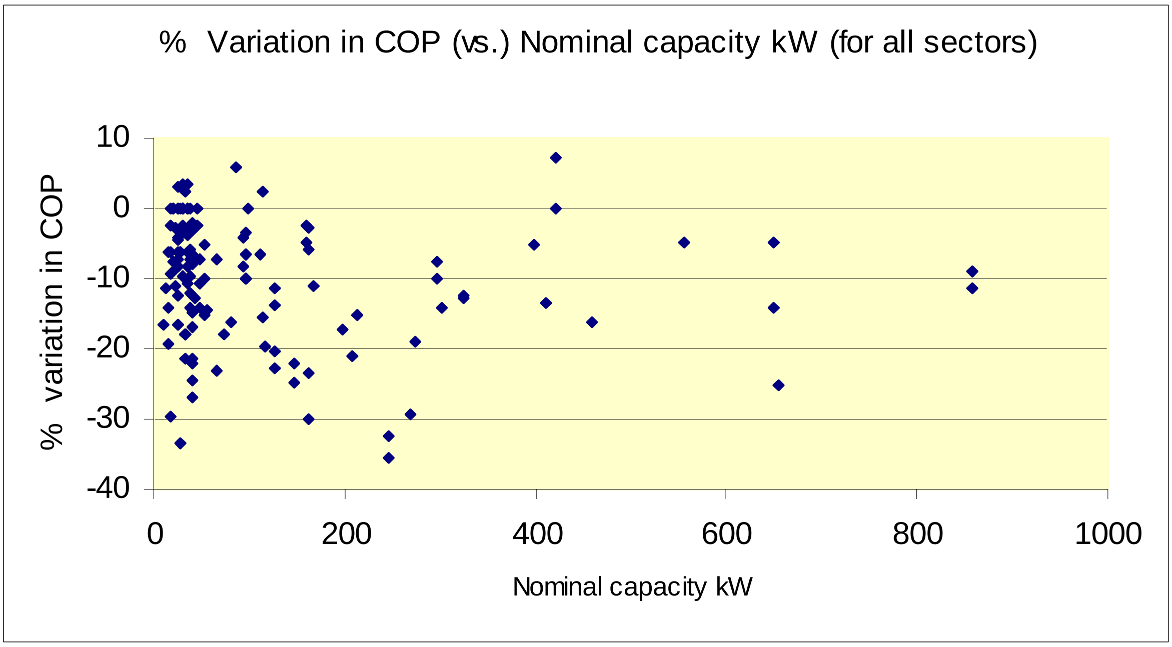


Figure11: %Variation in COP (vs.) Nominal Capacity kW (for all sectors)

The variation in capacity is mostly spread over the range of 5 to -20%. Following the trend of COP variation, large systems have less variation than their smaller counterparts with the exception of one system as shown in the figure 12. The average variation in capacity is -8.6%, the maximum and minimum variation is -67% and 16.9% respectively.

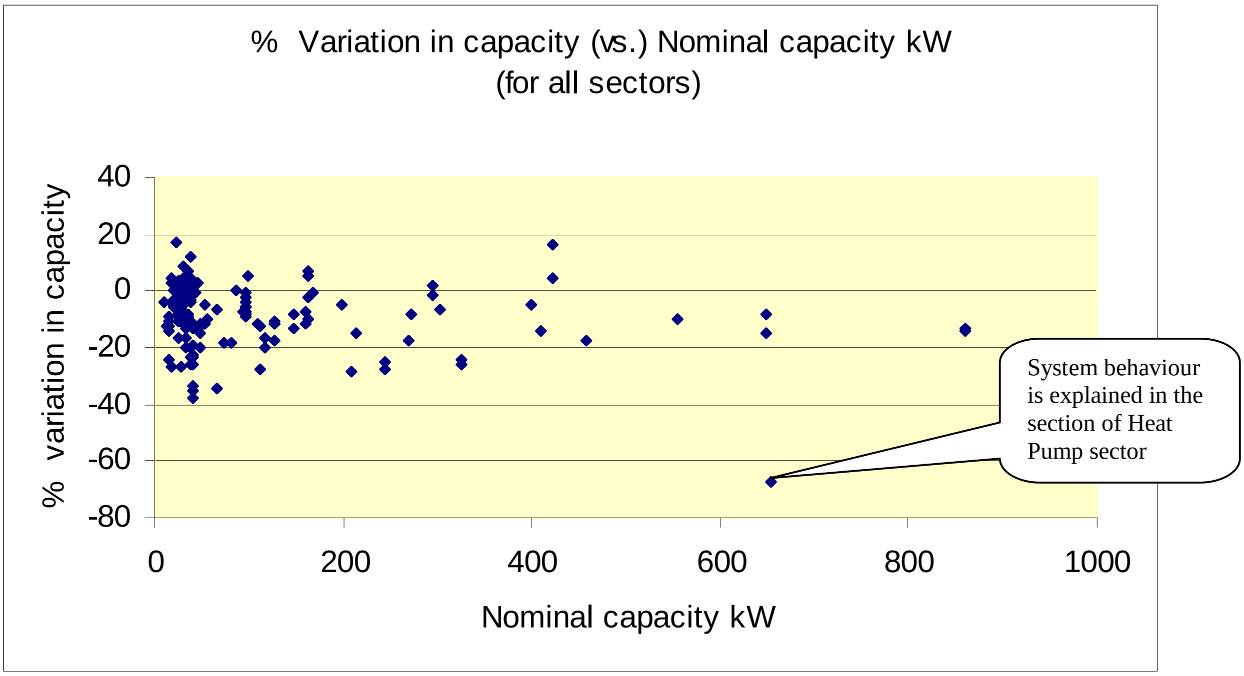


Figure12: %Variation in capacity (vs.) Nominal Capacity kW (for all sectors)

The average variation in Compressor power input is 1.3%. This is a much lower when compared with the COP and Capacity variations. Figure 13 shows that most of the systems are scattered around 0%. The variation is smaller for large systems than the smaller systems.

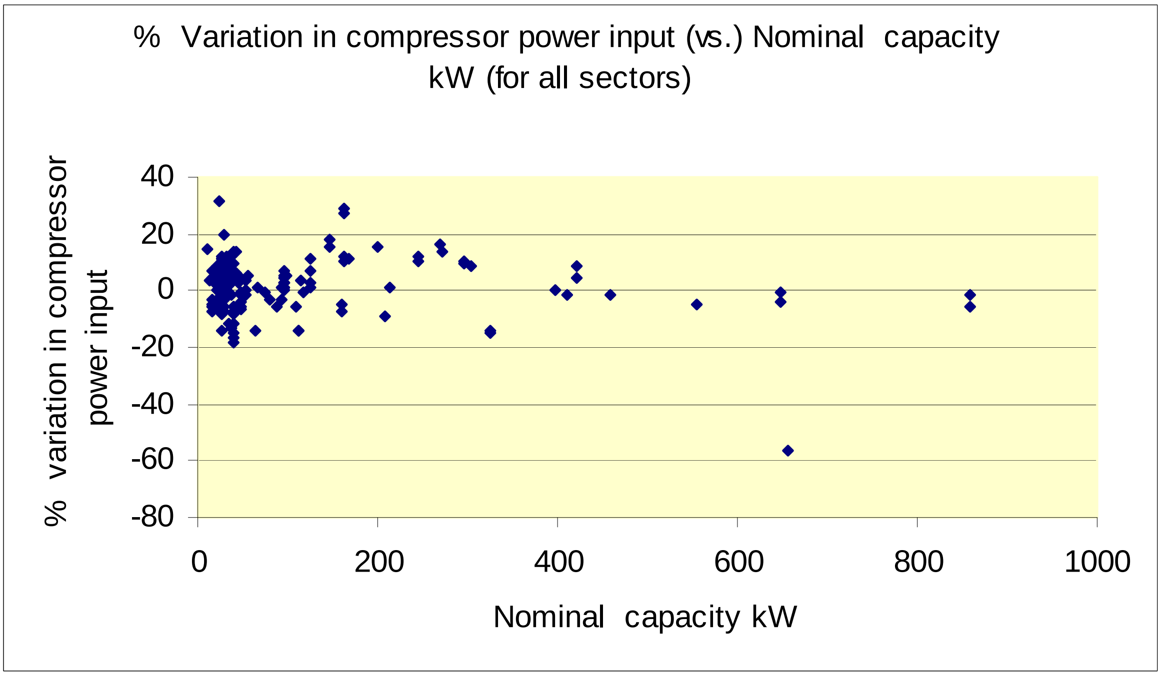


Figure13: %Variation in Compressor power input (vs.) Nominal Capacity kW (for all sectors)

A general conclusion can be drawn from the above three figures. It can be concluded that the larger capacity systems function better (i.e. with small variations in performance) when compared to small capacity systems. At the same time there are significant deviation and the cost of decreased performance and failures are much higher than the small systems.

Results shown in table 3 establish that around 87% of the systems analysed have been found to function with some kind of faults. It can also be noted that some systems have been found to function with more than one type of fault.

Figure 14 explains the number of systems operating with a particular kind of fault. Charge problems have been found to be dominating with 78 (43%) systems followed by expansion valve problems with 51 (31%) systems. 27 (16%) systems have been found to function with problems in the secondary flow. 20 (12%) systems were found to function without any kind of problem. Also 20 (12%) systems function with more than one kind of fault.

These faults affect the performance of the system by altering the basic parameters of the system such as the Condensing/Evaporating temperatures, superheat/subcool and the capacity of the system. In most of the systems reported in the database, the faults mostly increase the temperature lift of the system (T_{cond} - T_{evp}) thereby resulting in performance deviation.

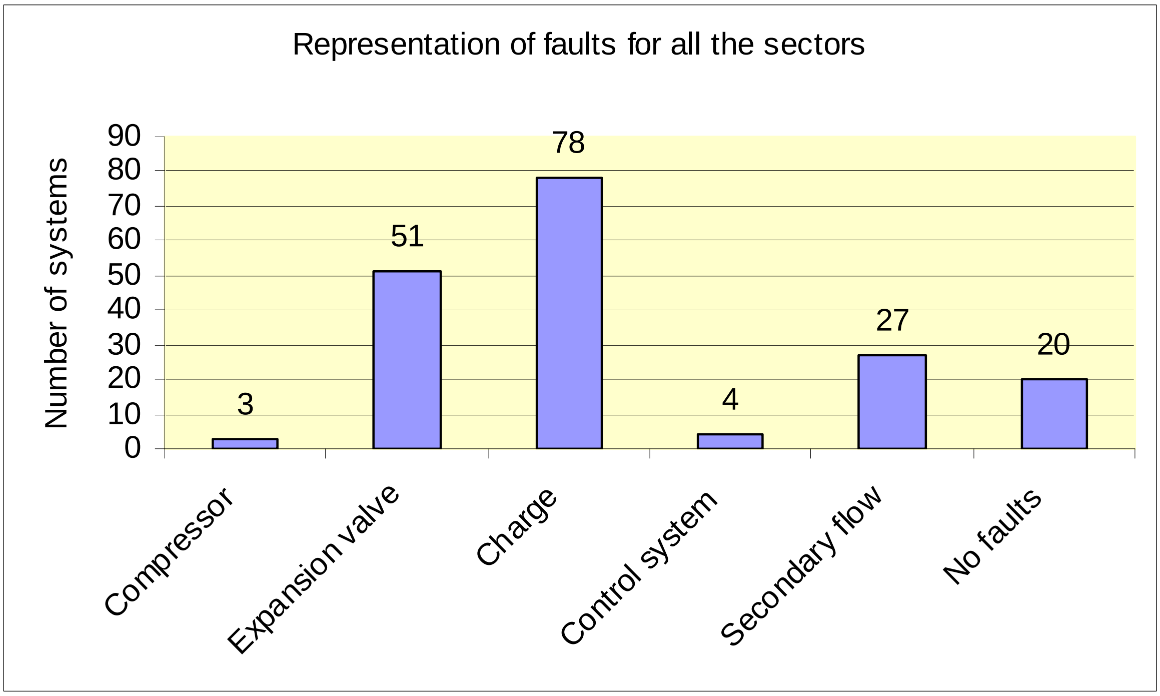


Figure14: Representation of faults for all the sectors

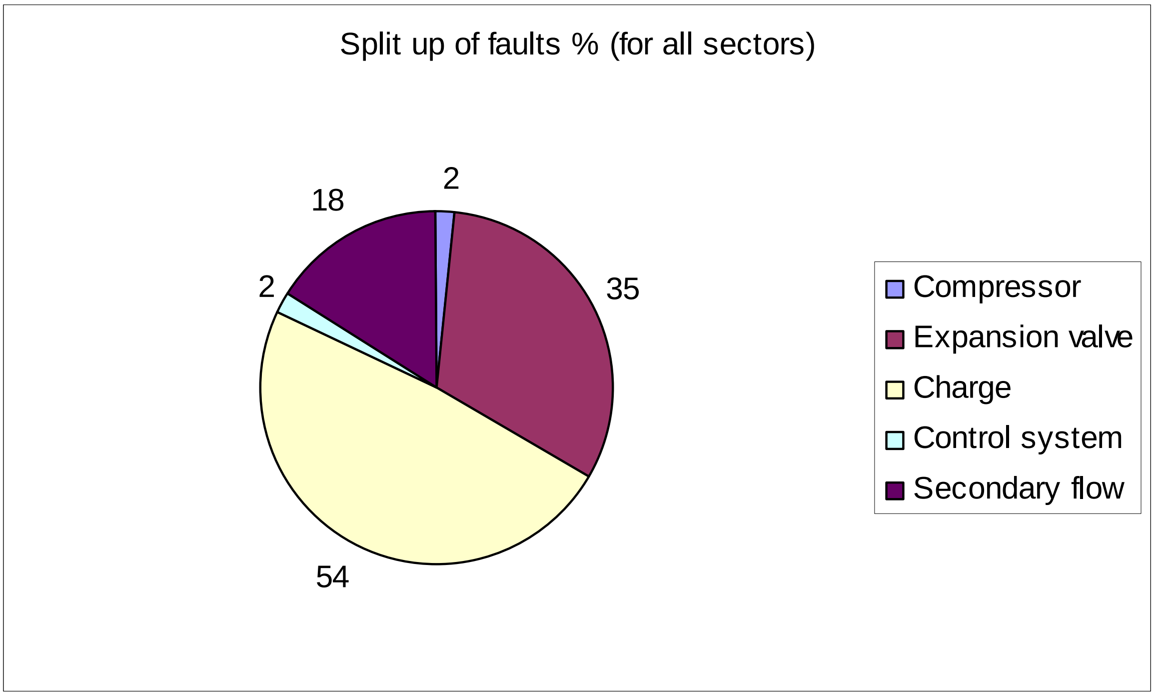


Figure15: Split up of faults in % (out of total number of faults for all the sectors)

9.2.1 Heat Pumps

Out of the total 84 Heat pumps analysed 77 (91%) systems have been found to function with faults.

Table 4 summarises the results for the Heat pump sector. The capacity of the systems analysed range from 9 to 655kW. The systems have been regrouped according to their capacity in order to understand the occurrence of faults and variation in the parameters with the variation in capacity.

The systems with capacity up to 20kW are mostly the domestic heat pumps which are factory built with high COP as the main criteria. Results from the table 4 reveal that the average variation in COP (-8.5%) of the heat pump sector is a little better than the results of the database (-9.7%) as a whole. The variation in COP of the heat pump sector is also lower when compared with the Air-conditioning (-11.5%) and Commercial (-10.2%). This low variation in COP than the other sectors could possibly explained by the fact that the installation of heat pumps is mostly justified by their COP in comparison with the other heating sources. The variation in capacity of the heat pump sector (-10%) is a little higher than that of the total database (-8.6%). The variation in capacity of the heat pump sector is a little higher than the Air-conditioning (-9.1%) sector and much higher than the Commercial (-4.3%) sector. The variation in Compressor power input for the heat pumps is -1.7% which is lower when compared with 1.3% of the total base. The results show that the measured power input of the systems is lesser than the nominal power input. This is mainly because this average is affected by other faults in the system such as that a lower evaporation decreases the Power input. Basically a decrease of power input would be positive but as it is normally caused by decrease of evaporation and thus decrease in COP it cannot be regarded as an indication that the system performs well.

	0 to 655kW	0 to 20kW	21 to 100kW	101 to 655kW
Number of Systems	84	8	70	6
Number of Systems with faults	77 (91%)	6 (75%)	65 (92%)	6 (100%)
Calculated Parameters				
Variation in COP	-8.5%	-14.2%	-7.4%	-13.1%
Variation in Capacity	-10%	-14.2%	-8.1%	-26.6%
Variation in Compressor power input	-1.7%	0.8%	-0.7%	-16.4%
Type of problem				
Compressor	1 (1.4%)	0 (0%)	0 (0%)	1 (16.7%)
Expansion valve	38 (49.4%)	0 (0%)	38 (58.5%)	0 (0%)
Charge	34 (44.2%)	0 (0%)	31 (47.7%)	3 (50%)
Control System	4 (5.2%)	0 (0%)	2 (3.1%)	2 (33.4%)
Secondary flow	16 (20.8%)	6 (100%)	10 (15.4%)	0 (0%)

Table 4: Results for the Heat Pump Sector.

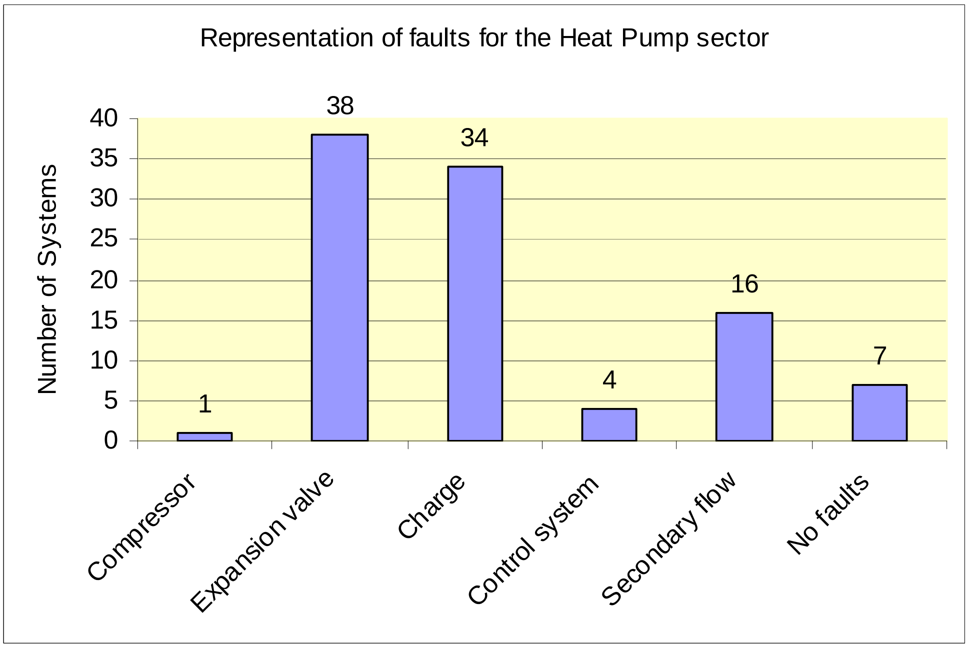


Figure16: Representation of faults for the Heat Pump Sector

The most dominating type of problem for the Heat pump sector is the problems with the adjustment of the Expansion valve followed by the Charge problems which dominates the database on the whole. Also 16 systems have been found to operate with more than one kind of fault. It should be mentioned that an insufficient charge often will cause a “fault” in the expansion valves function due to that it can not handle the “flash-gas”.

The variation in COP and Capacity for domestic heat pumps (0 to 20kW) are relatively higher than the general results of the heat pump sector. It can be noted that the frequency of faults with the secondary flow are high in the small heat pumps. The explanation to this can be that this is seldom checked by the contractor at the same time that they often have internal pumps that are sensitive for pressure drops in the external system. Another factor is that when these types of systems are connected in parallel the risk of unbalanced flows is often neglected. It can also be noted that these factory built domestic heat pumps perform with lesser faults than the medium size systems.

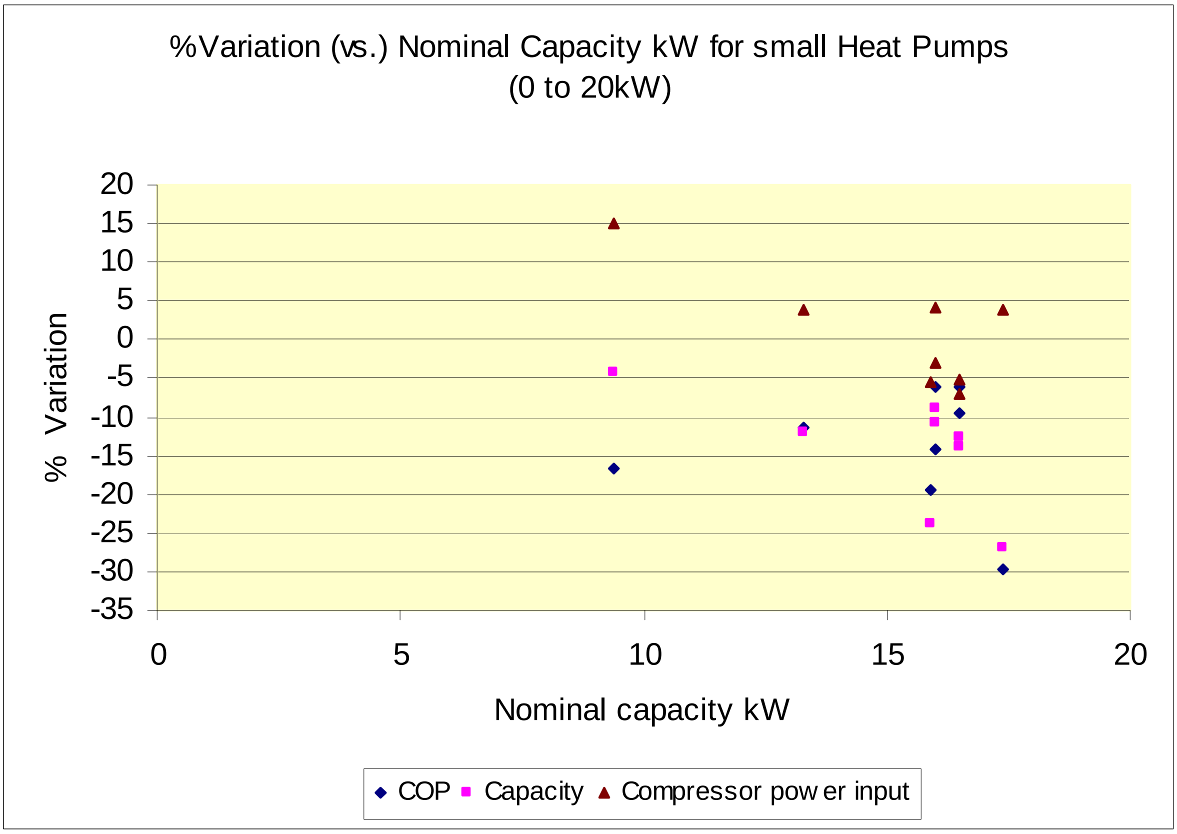


Figure17:% Variation (vs.) Nominal Capacity kW for small heat pumps (0 to 20kW)

The heat pumps which lie in the capacity range of 21 to 100kW more or less exhibit the same trend of the total heat pump sector. The systems with large capacity (101 to 655kW) exhibit quite a different trend in comparison with the heat pump sector as a whole. They exhibit a much higher variation in the parameters in comparison with the whole heat pump sector. Charge problems are the dominating kind of faults and the variation in capacity (-26%) is significantly higher than the average value of the heat pump sector (-10%). The variations have been plotted in the following figure 18.

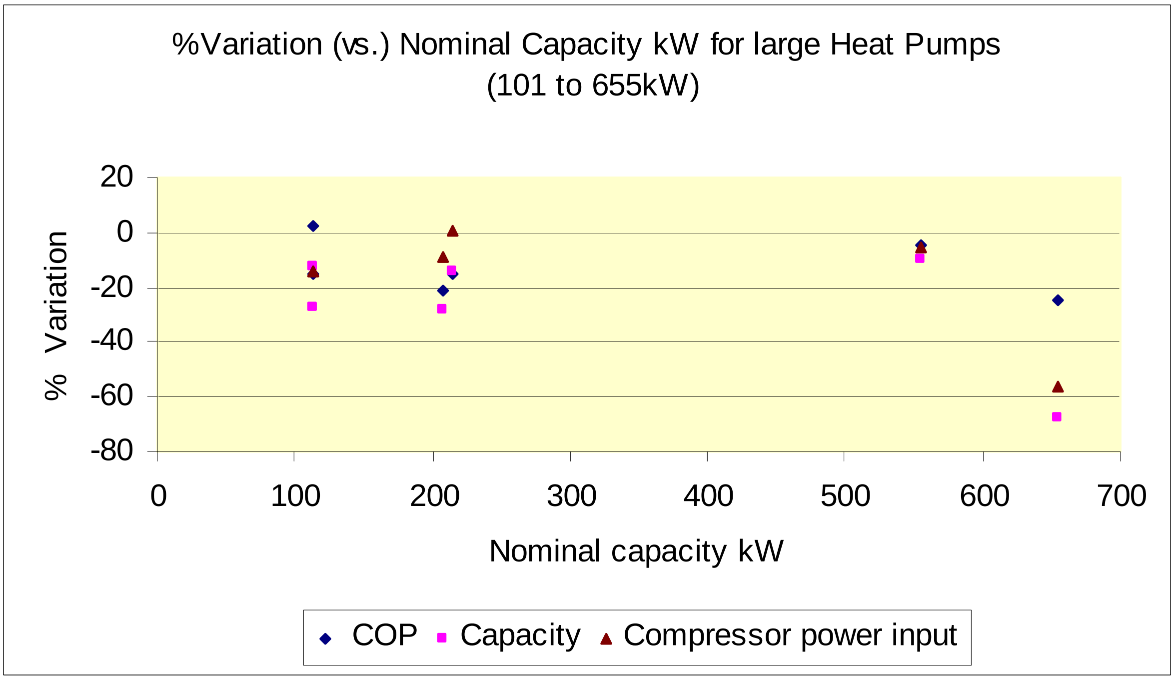


Figure18: % Variation (vs.) Nominal Capacity kW for large heat pumps (101 to 655kW)

It can be noted from the above graphs that one particular heat pump with the capacity of 655kW is found to function with high degree of variation in its performance. As the performance variation for this system is quite different from the other systems reported in the database, the reason is explained. When the measurement was done on the system it was functioning only with partial load. This was due to the fact that the system had low secondary flows over the evaporator and the condenser: This caused the system to quickly reach its set points for exiting water temperatures on evaporator or condenser. The controls then start to reduce the capacity. This resulted in that compressors operated at part load and frequently turned ON/OFF. Since the system was running most of the time with partial load on the compressors, it had high discharge temperature, caused by lower compressor efficiency at part load, which decrease the COP even further. These were the prime reasons for the system to function with extremely low COP and Capacity.

9.2.2 Air-conditioning

In the Air-conditioning sector, out of the 49 systems analysed 44 (90%) systems have been found to function with faults.

The capacity of the systems analysed range from 17 to 860kW. The systems have been regrouped according to their capacity in order to understand the occurrence of faults and variation in the parameters with the variation in capacity.

Results established from the calculations have been summarised in the table 5. The average variation in COP (-11.7%) of the Air-conditioning sector is higher than the results of the database (-9.7%) as a whole. The variation in COP of the Air-conditioning is the highest when compared with the other two sectors which have been analysed. Since meeting the cooling demand is the prime motive with which the Air-conditioning systems are built, COP is not given much importance which can be one of the reasons for the high variation in COP. The variation in capacity of the Air-conditioning sector (-9.1%) can be said to be in agreement with the results of the total database.

	0 to 900kW	**0 to 100kW**	**100 to 900kW**
Number of Systems	49	26	23
Number of Systems with faults	44 (90%)	26 (100%)	18 (78%)
Calculated Parameters			
Variation in COP	-11.5%	-9.7%	-13.5%
Variation in Capacity	-9.1%	-6.5%	-12.1%
Variation in Compressor power input	-2.7%	-3.5%	1.81%
Type of problem			
Compressor	0 (0 %)	0 (0 %)	0 (0 %)
Expansion valve	13 (30 %)	1 (4 %)	12 (66.67%)
Charge	31 (70.5%)	22 (84.7%)	9 (50 %)
Control System	0 (0 %)	0 (0 %)	0 (0 %)
Secondary flow	5 (11.4%)	4 (15.4%)	1 (5.6%)

Table5: Results for the Air-conditioning sector.

The most dominating type of fault in the Air-conditioning sector is the problems related to charge which is followed by the problems with the expansion valve. It can also be noted that there has been no faults reported with the compressors and with the Control system. It has also been found that 4 systems have been operating with more than one fault. This does not necessarily mean that there are no such faults but the focus for the performance inspections has not been to monitor over a longer period which is required to detect problems and optimise control strategies. Only control problems that occur during the relatively short performance inspections are obviously possible to detect.

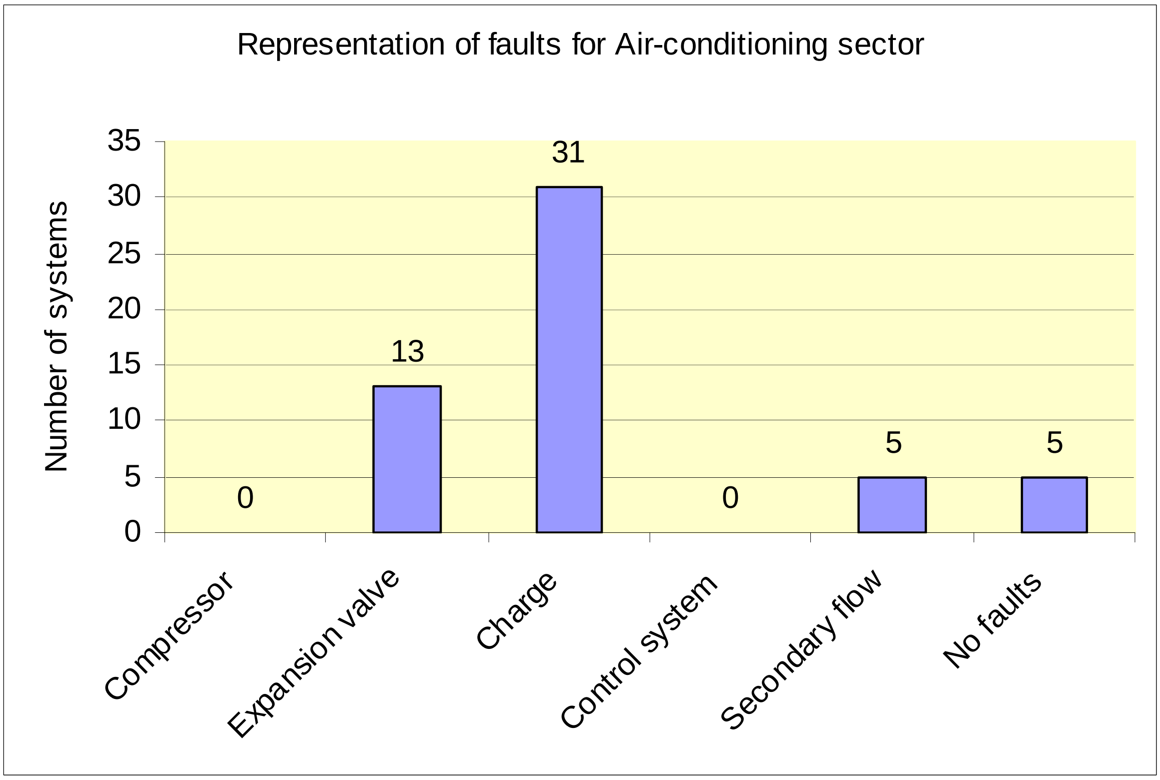


Figure19: Representation of faults for the Air-conditioning sector

It can also be noted that the systems which has capacity less than 100kW are said to be function with lesser variation in performance than the systems with higher capacities (above 100kW). These results are evident from the above table 5 and also by studying the figures which exhibit their characteristics.

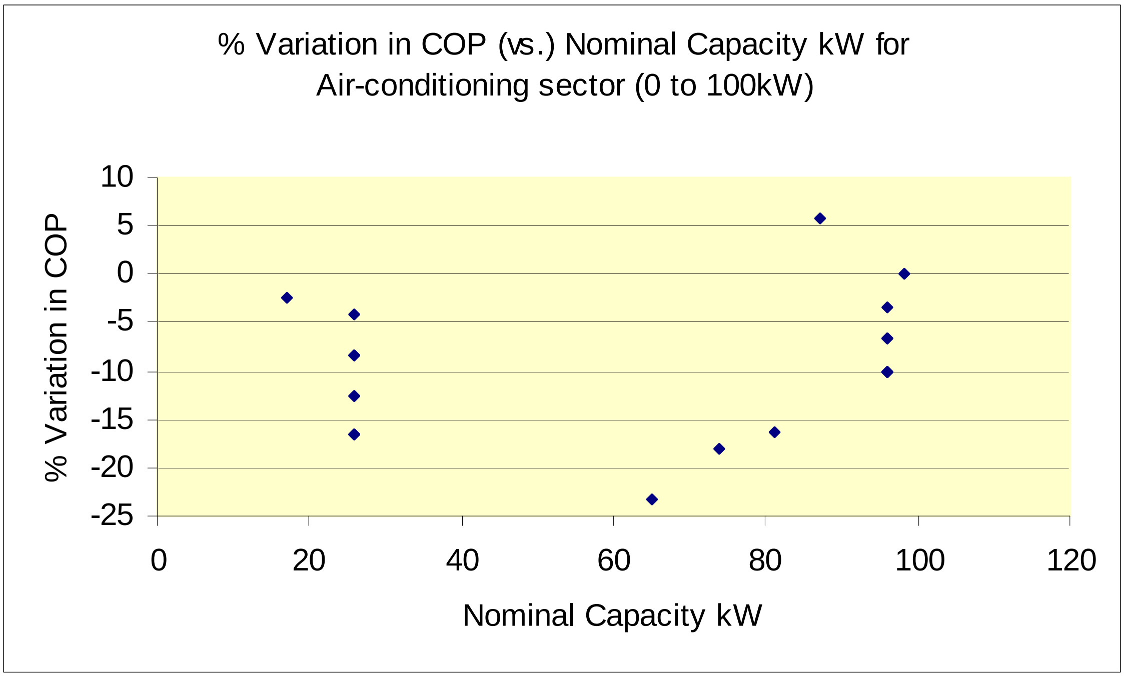


Figure20: % Variation in COP (vs.) Nominal Capacity kW (0 to 100kW)

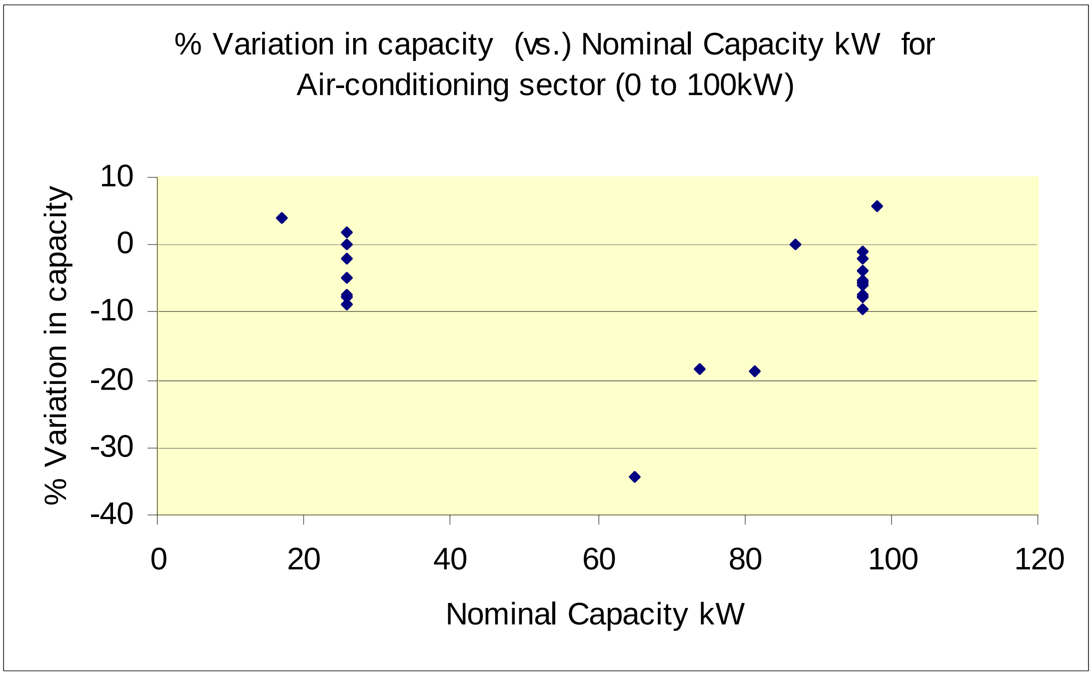


Figure21: % Variation in Capacity (vs.) Nominal Capacity kW (0 to 100kW)

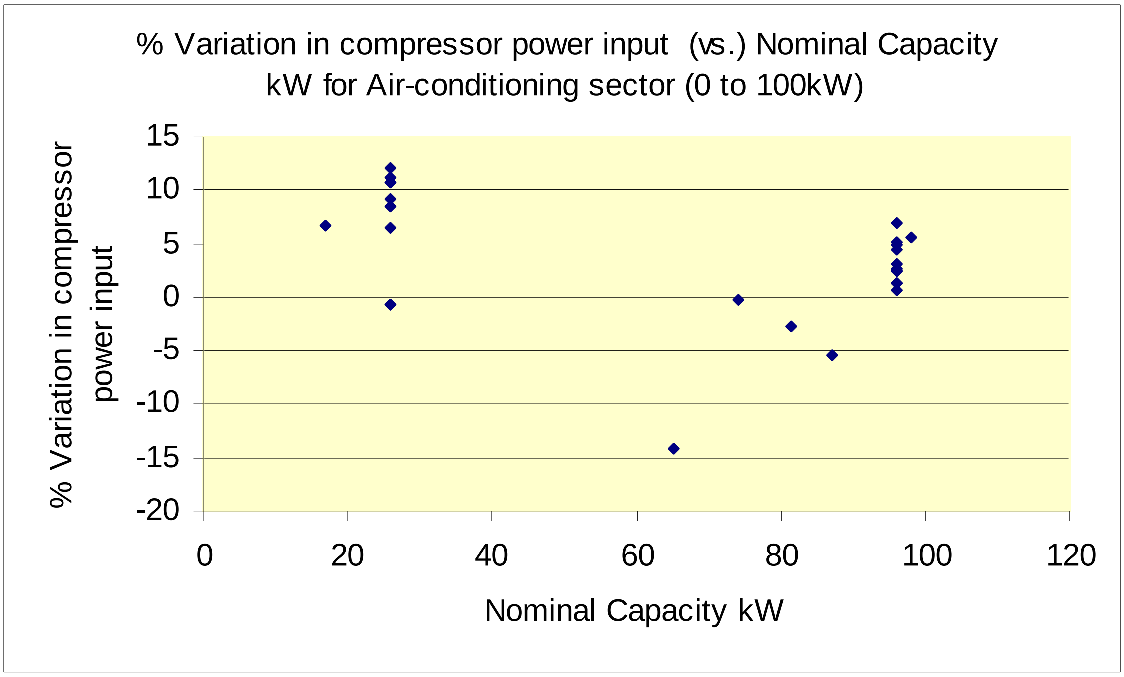


Figure22: % Variation in Compressor power input (vs.) Nominal Capacity kW (0 to 100kW)

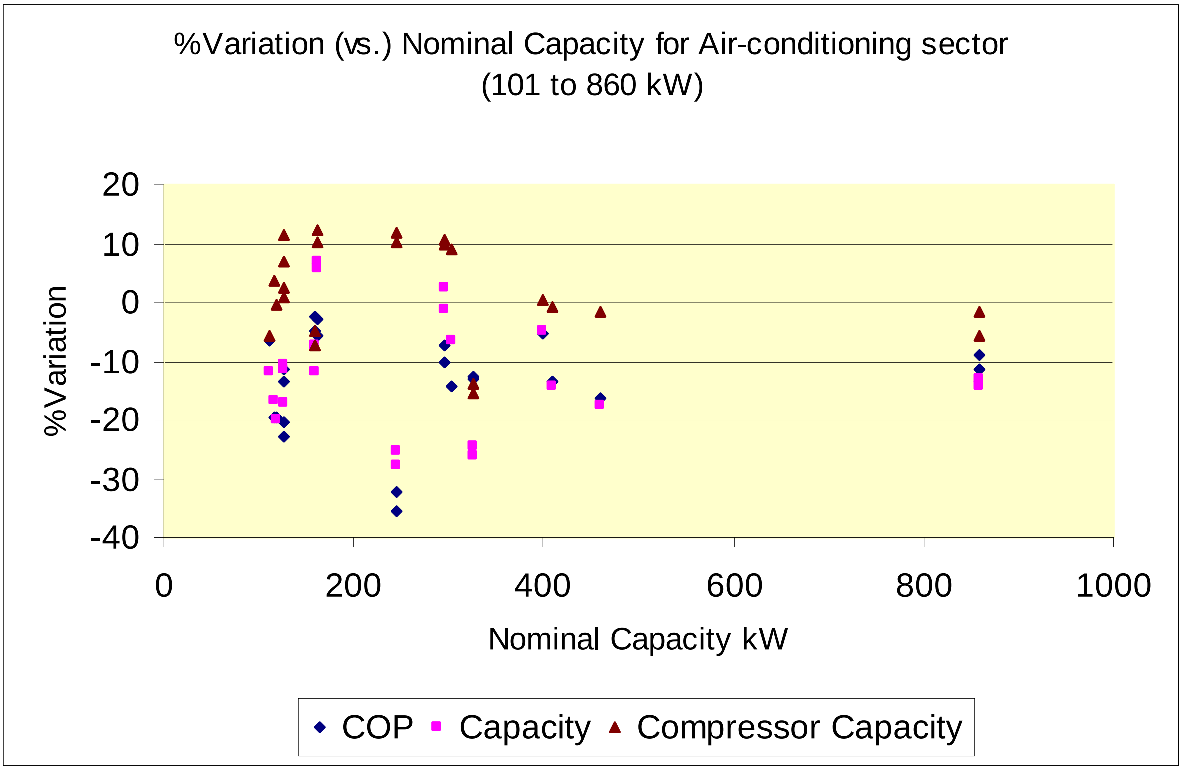


Figure23: % Variation (vs.) Nominal Capacity kW (101 to 860kW)

9.2.3 Commercial

Out of the 31 systems analysed in the Air-conditioning sector 23 (74%) systems function with some kind of fault.

The capacity of the systems analysed range from 18 to 650kW. Commercial sector mostly consists of measurements made on the systems in supermarkets.

The results of the commercial sector have been summarised in the table 6. The average variation in COP (-10.7%) of the Commercial sector is higher than the results of the database (-9.7%) as a whole. The variation in capacity (-4.3%) is significantly lower than the whole database (-8.6%) and is also very low when compared with the other two sectors. But the variation in compressor power input is just the opposite with higher variation than the other two sectors. The average variation in compressor power input is 7.2% which is significantly higher than the values of Heat pumps (-1.7%) and the Air-conditioning (-2.7%) sectors

	0 to 500kW	0 to 100kW	100 to 500kW
Number of Systems	31	19	12
Number of Systems with faults	23 (74%)	13 (69%)	10 (83%)
Calculated Parameters			
Variation in COP	-10.1%	-6.6%	-15.8%
Variation in Capacity	-4.3%	-3.4%	-5.6%
Variation in Compressor capacity	7.22%	3.61%	13%
Type of problem			
Compressor	2 (8.7%)	0 (0%)	2 (16.7%)
Expansion valve	0 (0%)	0 (0%)	0 (0%)
Charge	13 (56.5%)	11 (84.6%)	2 (16.7%)
Control System	2 (8.7%)	0 (0%)	2 (16.7%)
Secondary flow	6 (26.1%)	2 (15.4%)	4 (33.4%)

Table6: Results for the Commercial sector.

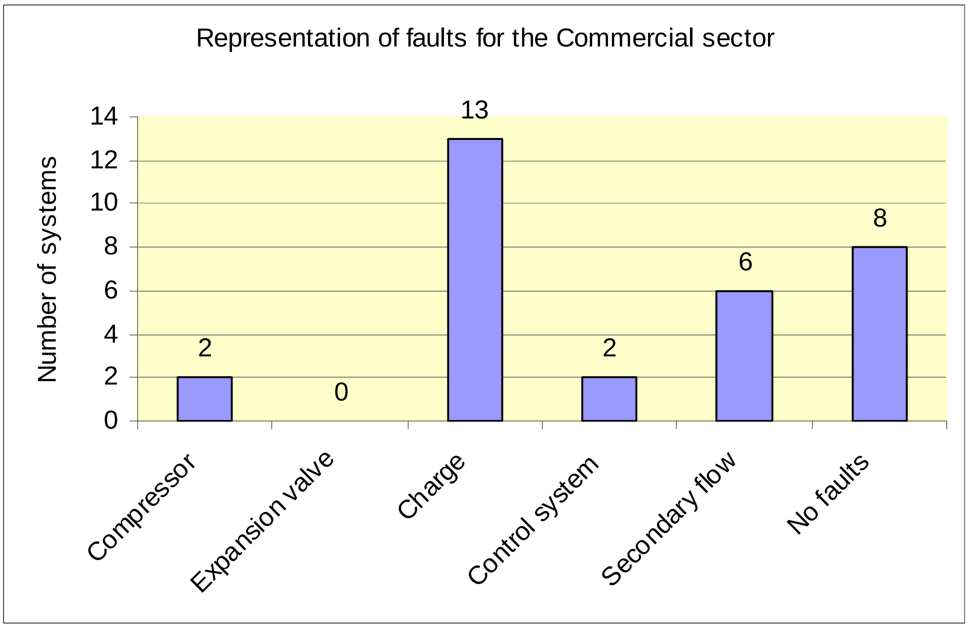


Figure24: Representation of faults for the Commercial sector.

The systems in the commercial sector have been found to function with fewer faults when compared to the other two sectors. Charge problems dominate the sector followed by the problems with secondary flow. No faults have been found with the expansion valves. This is not necessarily an indication that expansion valves in the commercial sector function better than in other sectors. The explanation is that in direct expansion system that are common in the commercial sector there are many expansion valves in one system and long suction lines. In this situation a problem with an expansion valve will only be detectable at the individual display case. No systems have been reported to function with more than one type of fault.

The results also show that the systems with high capacities function with more variation from the nominal performance than small systems. These large systems are mostly large and complex cooling and freezing units installed in supermarkets. The following figures give out more details about the characteristics of the commercial sector with the variation in capacity.

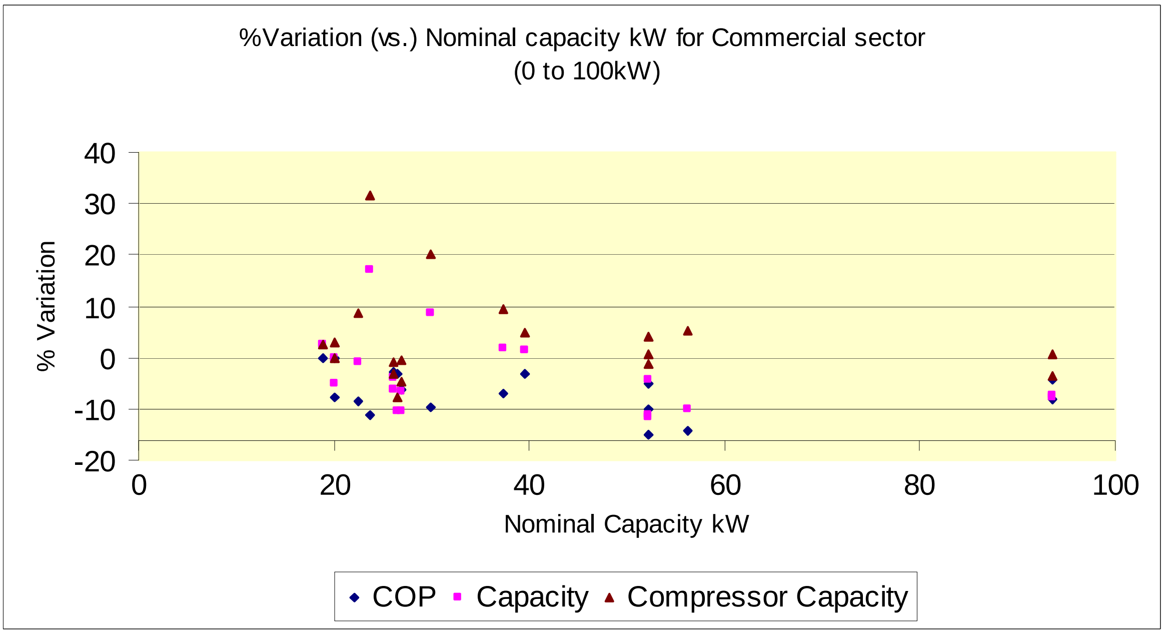


Figure25: % Variation (vs.) Nominal Capacity kW (0 to 100 kW)

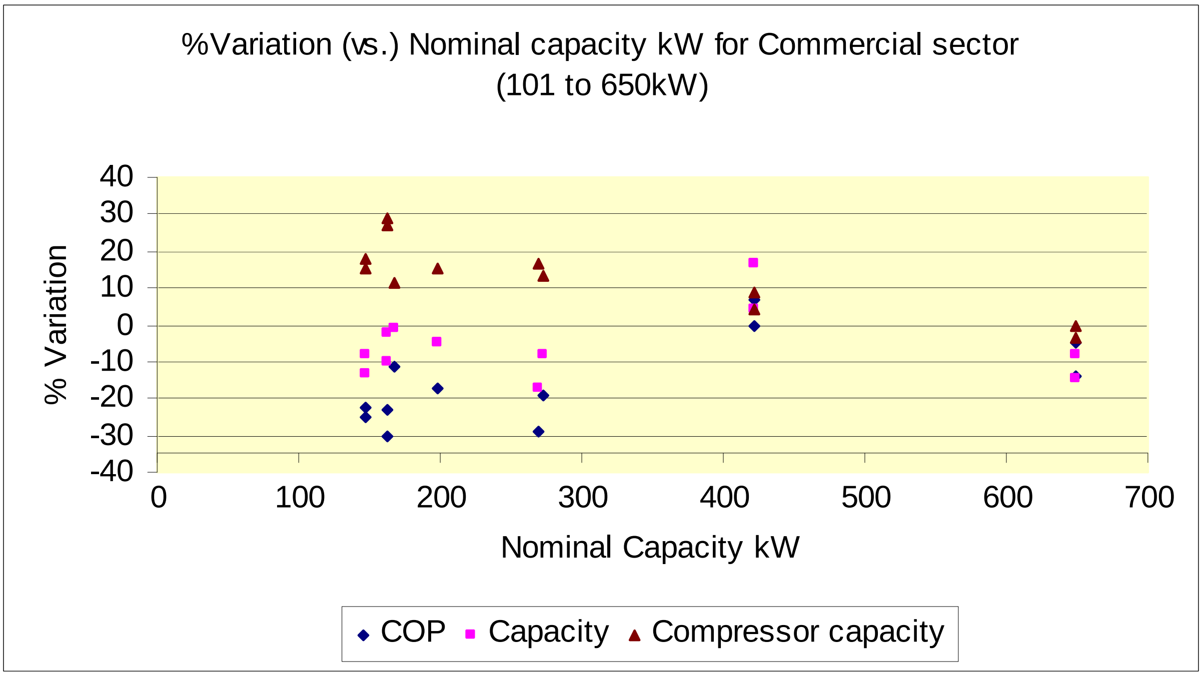


Figure26: % Variation (vs.) Nominal Capacity kW (101 to 650 kW)

10 CASE STUDIES

The Case studies for the three sectors describe the findings from three performance inspections done with participation of the author. The measurements where done with the ClimaCheck performance Analyser Tool. ClimaCheck Performance Analyser uses the Internal Method to measure and performance analyse the system. The setup of ClimaCheck along with the mounting of sensors is shown in the figure 27.

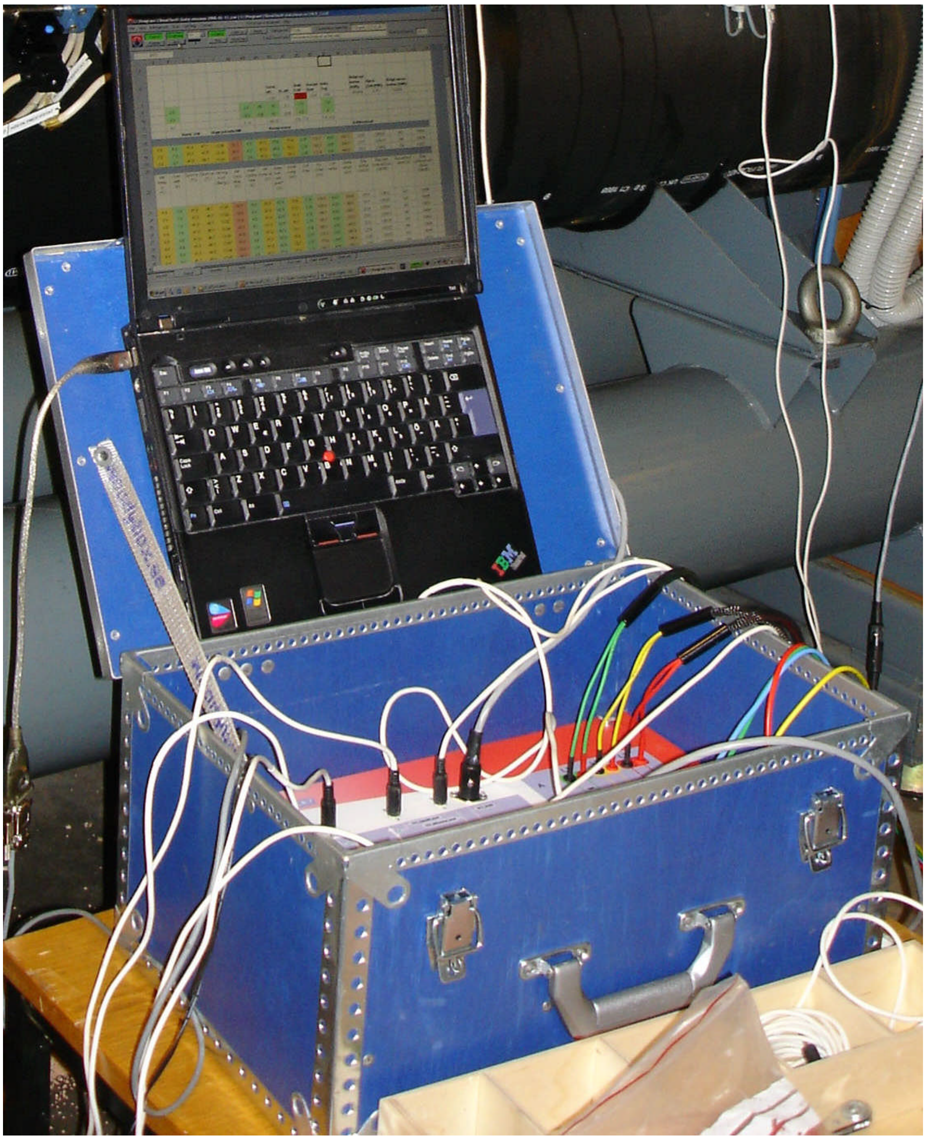


Figure27: Setup of ClimaCheck Performance Analyser

The sensors and transducers are connected to the Refrigeration system as explained in chapter 6. The measurements from ClimaCheck are then logged on to a computer which has ClimaCheck software on it. The measurements are then analysed to draw conclusions.

10.1 Heat Pump

The case study for this sector was done by performance analysing a domestic Heat Pump located in the city of Stockholm. This system is maintained by ETM Kylteknik as a part of Annual Maintenance contract, which paved way to perform the measurements on the system.

The system is a ground source (bedrock) heat pump and the design is that of a basic refrigeration system as shown in the figure 28. The nominal capacity of the system is 21kW. The heat pump covers the base load and an auxiliary oil boiler heating system is used to share the load during peak demand.

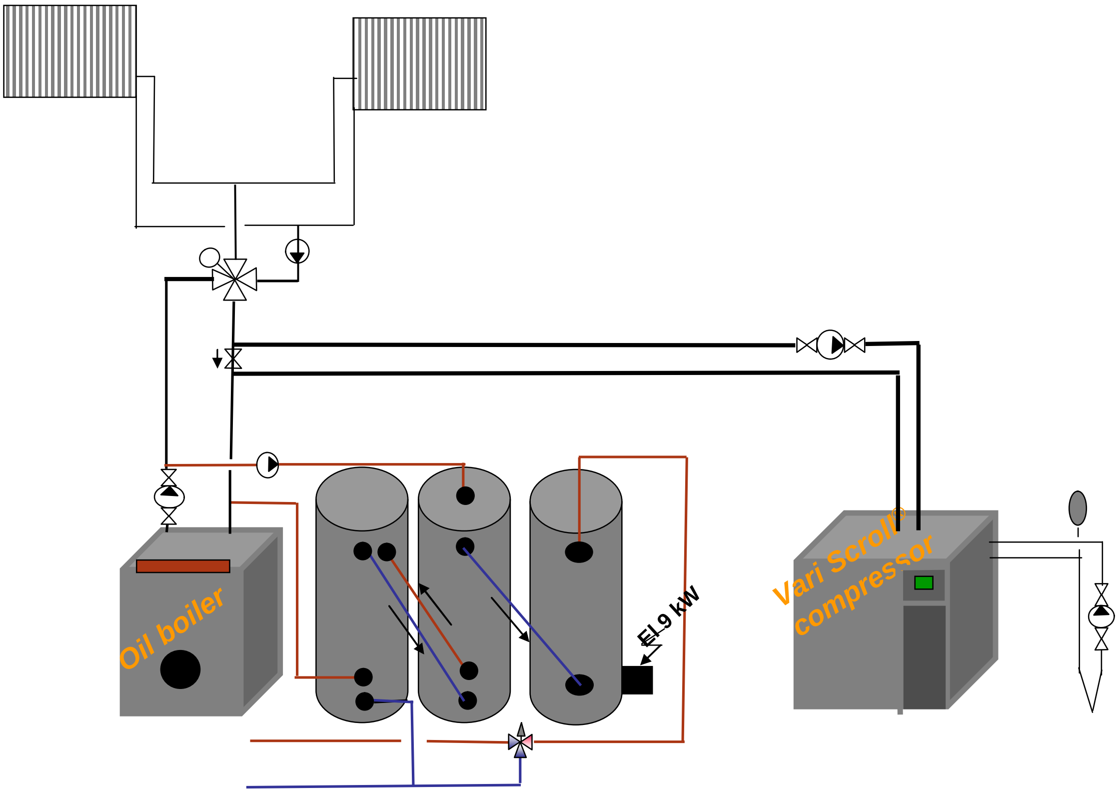


Figure28: Schematic Sketch of the frequency controlled “VariScroll$^{\circledR}$” Heat Pump system in Stockholm.

The measurements made on the system revealed that the system was functioning with a COP deviation of -5% (i.e. the compressor was consuming 5% more electricity than the nominal data). The power input could be affected by the losses in the frequency controller and also the secondary effects from the non-ideal wave most frequency controllers produce (obviously also the measuring accuracy of approximately 2% should be taken into account). In addition the graphs from the Performance Analyser showed that the superheat of the system was constantly fluctuating. The thermostatic Expansion valve used in the system was “hunting” slightly resulting in fluctuation in evaporation, sub cool and superheat. The figure 29 shows the fluctuation of the system parameters due to hunting of the expansion valve with a clear impact on the evaporation temperature.

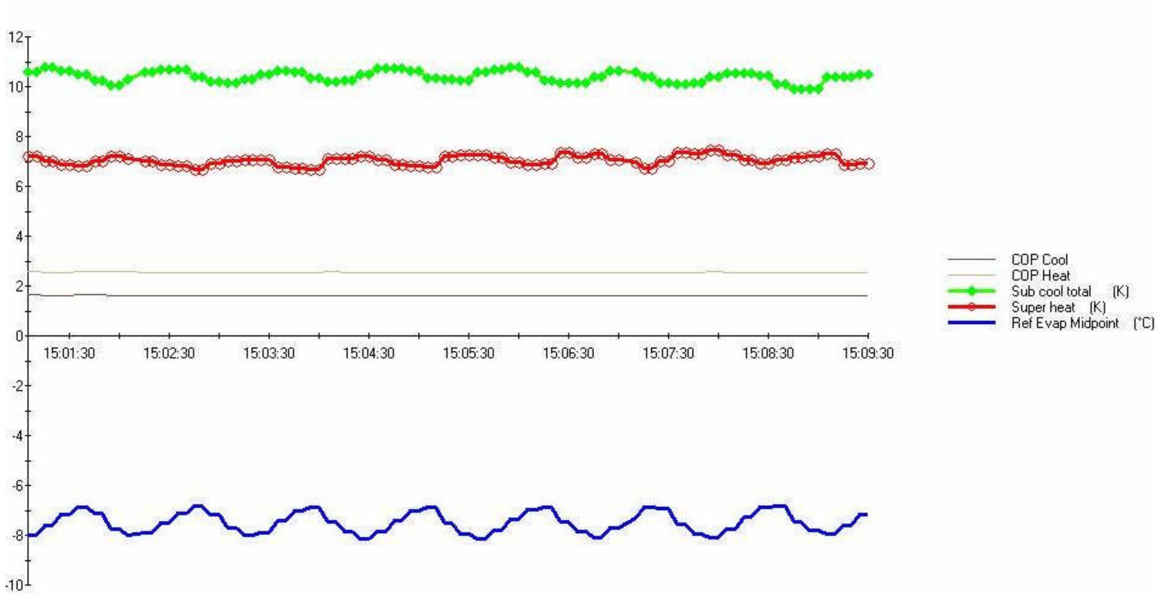


Figure29: Variation of Superheat and Subcool due to hunting of Expansion valve.

10.2 Air-Conditioning

The case study for the Air-conditioning sector was done on the system at a mail terminal in Årsta a Stockholm suburb as a follow up of performance of the system after one of its compressor failed in 2003. This system is a quite new installation with the installation year dated to 1999. But the system possesses a history of problems at an early stage. The total cooling capacity of the system is 1.8MW. It is a system with eight screw compressor with economiser circuits. It also has heat recovery installed on four circuits which cover part of the heating load of the terminal, additional heat comes from the District Heating System.

In the year 2003, a compressor failure on one of the circuits was reported. This was followed by another compressor breakdown in a relatively short period of time. On analysing the system with ETM analysing tool it was found that the systems with heat recovery was considerably overcharged for some common operating conditions. The circuit incorporated a liquid level control system but when this was full refrigerant liquid would block the condensing surface resulting in an increase of condensing pressure. The overcharged system would quickly reach extreme high pressures and often cut out on the high pressure safety switch. The high pressures together with many start and stop resulted in excessive wear explaining the compressor failures. That the heat recovery was not functioning as intended due to the overcharged circuits made the user pay high bills both to the utility company and the district heating company. But after the system was analysed with ETM Analyser in 2003 and then during 2004 the compressors replaced together with that remaining problems were fixed, the heat recovery started function thereby sharing the heating needs of the building along with district heating. This resulted in dramatic decrease in the electricity and district heating bills for the user.

The Heating Energy Consumption of the mail terminal over different years is shown in figure 30. The figure does not include the heat consumption for the month of December for all the years due to lack of data. The figure shows a gradual decrease in heat energy consumption of the building from 2003 to 2005. This can be explained by the fact that the two compressors and the problems in the system were rectified gradually over the period. The heat energy consumption of the building decreased by 900MWh from the year 2003 to 2005. The mail terminal buys district heat at the price of 750 SEK/MWh (81 Euro/MWh) (16) from their provider and the decrease in heat consumption resulted in saving of 67 500SEK (7260 Euro) over the period.

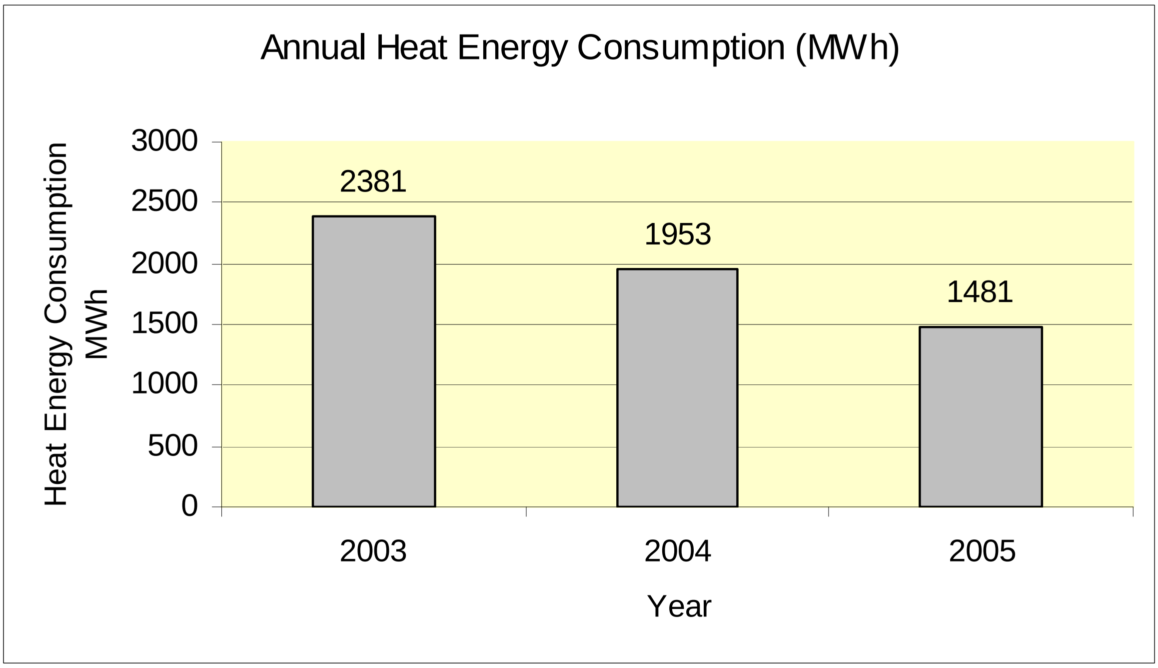


Figure30: Annual Heat Energy Consumption for Posten Årsta

The schematic layout of the system along with the mounting of sensors and transducers during the measurement is shown in the figure 31. The markings with yellow colour on the refrigerant circuit in the figure reveal the mounting of temperature sensors and blue and red show pressure transducers. There are eight temperature sensors, three pressure transducers and analog sensors mounted on the system.

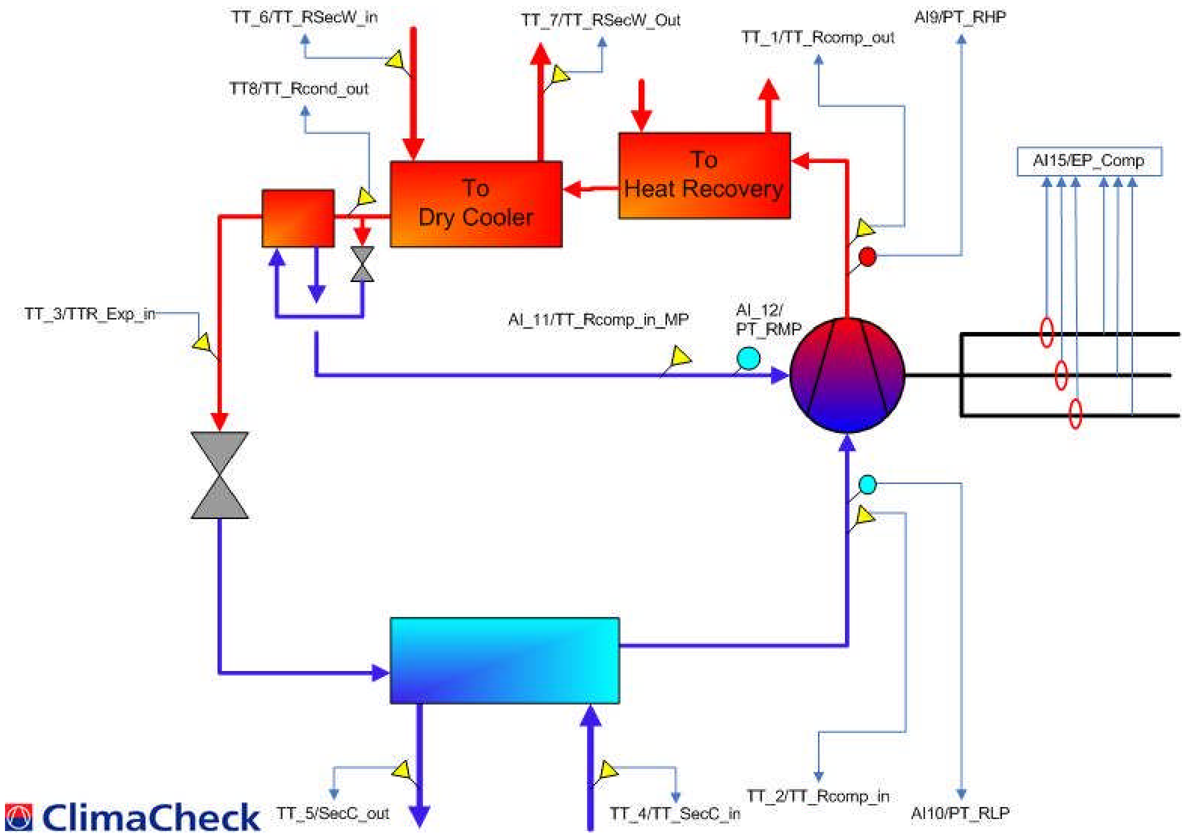
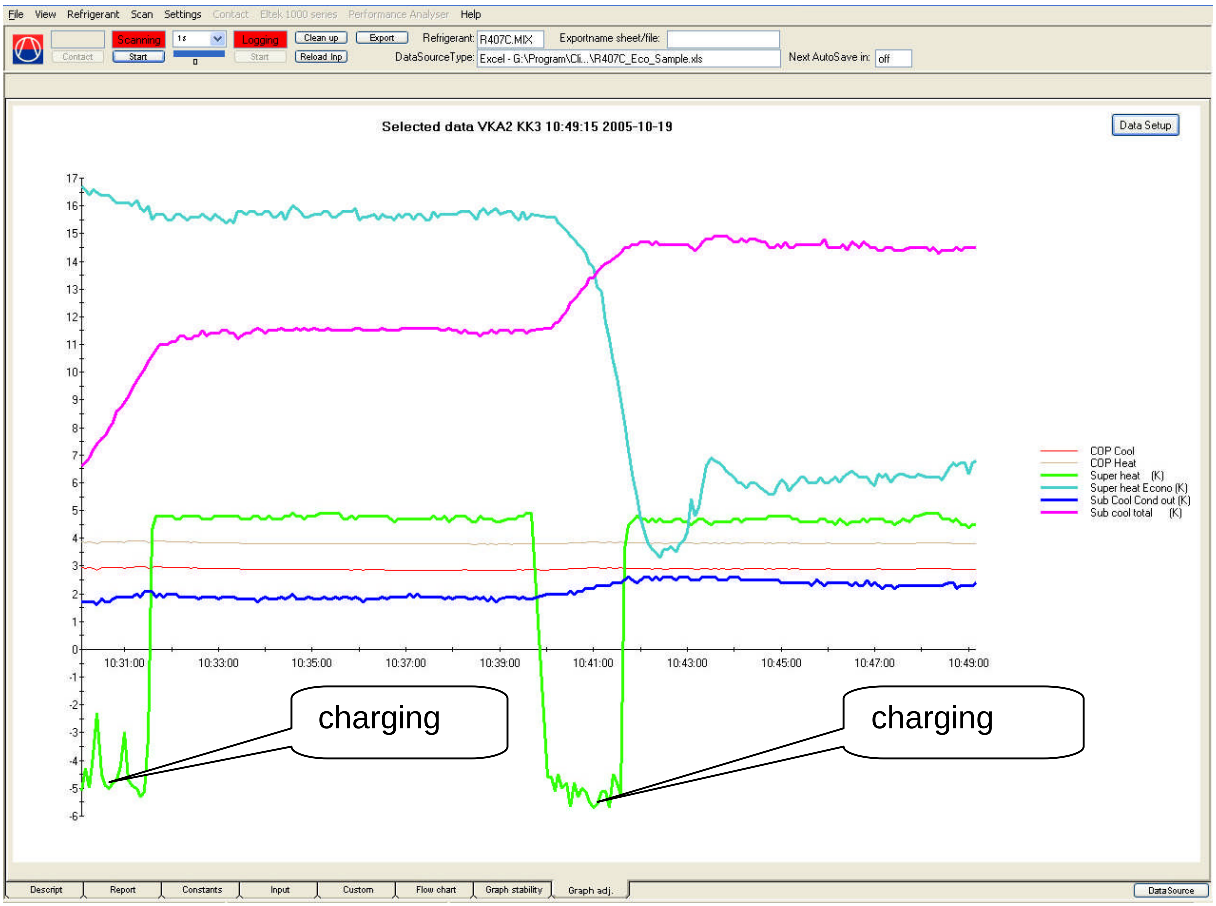


Figure31: Schematic Layout of the system along with the mounting of sensors.

In connection with the work for this report a follow up Performance inspection was done as the systems had not been logged since the first inspection where the problem was identified. When the measurements were made on the system, the most common problem faced was the low flow over the economiser and the high economiser superheat. This was overcome and the system performance was optimised by adjusting the economiser expansion valve and also by charging the system.

The variation of system performance after charging is clearly shown in the figure 32. The figure shows the performance of the circuit VKA2KK3 (3rd compressor in the 2nd circuit). It is evident from the figure that the economiser superheat starts to come down when the system is being charged. Also the economiser expansion valve was adjusted to optimise the flow through the economiser resulting in an increase in capacity.



Refrigerant: R407C.MIX

Exportname sheet/file:

DataSourceType: Excel - G:\Program\Cli...\R407C_Eco_Sample.xls

Next AutoSave in: off

Selected data VKA2 KK3 10:49:15 2005-10-19

Figure32: Variation of the system performance after charging

The above figure shows the effect of adding refrigerant to an undercharged economiser system. Initially the system is operating with low condenser sub cooling (Sub Cool Cond out) (in reality this is apparent sub cooling equivalent to the pressure drop across the high pressure side- the actual sub cooling is close to zero). The economiser expansion valve is unable to feed the economiser correctly. The result is high superheat after economiser (Super heat Econo) and limited sub cooling over economiser. This operation will decrease COP and limit the safe operating envelope.

First increase of refrigerant charge

In the first sequence up till 10:31:20 refrigerant is being charged resulting in apparent negative superheat as pressure increases during charging whereas the suction line temperature does not respond as quickly. The impact on Sub Cool Cond out is small but the total sub cooling rises 11.5K because much more liquid is passing through the economiser Thermostatic Expansion Valve. However there is still insufficient charge to bring down the economiser superheat to the correct value.

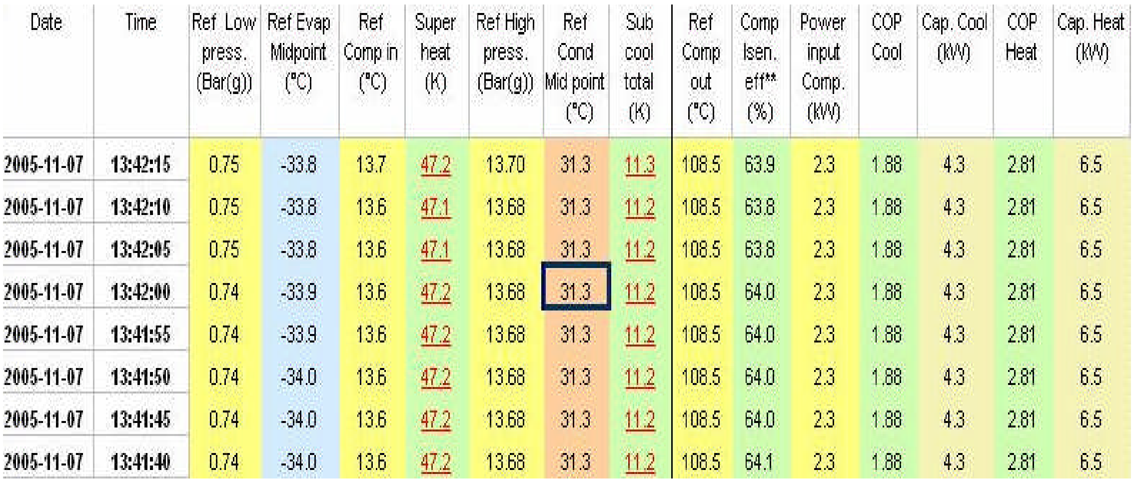
Second increase of refrigerant charge

Between 10:39:50 and 10:41:40 more refrigerant is added. The impact on the system is very clear with a sudden step reduction in economiser superheat and increase in total sub cooling. The typical “over-reaction” of the expansion valve with first a low superheat that is then adjusted by the valve can also be noted.

10.3 Commercial

The case study for the commercial sector was done on a DX-freezer unit at a Coop Supermarket in Norrtälje. The measurement was done on the system as a capacity check by ETM Kylteknik AB. The system was not reported to have any kind of faults or problems and the measurements were done only to analyse the current performance of the system. The cooling capacity of the system is 4.3kW and the COP is 1.8.

The measurements made on the system revealed that the compressor is functioning with high discharge temperature. The compressor had a discharge temperature of 108.5^{o}C for the condensing temperature of 33^{o}C during the winter outdoor conditions when the measurements were made. The discharge temperature can increase during the summer conditions and could reach well above the critical level for discharge temperature. This can eventually result in compressor damage. The system was functioning with low evaporation temperature which together with poor insulation of suction line resulted in high superheat thereby increasing the discharge temperature. The measurements made on the system are shown below in figure 35.



Date	Time	Ref Low press. (Bar(g))	Ref Evap Midpoint (°C)	Ref Comp in (°C)	Super heat (K)	Ref High press. (Bar(g))	Ref Cond Mid point (°C)	Sub cool total (K)	Ref Comp out (°C)	Comp Isen. eff** (%)	Power input Comp. (kW)	COP Cool	Cap. Cool (kW)	COP Heat	Cap. Heat (kW)
2005-11-07	13:42:15	0.75	-33.8	13.7	47.2	13.70	31.3	11.3	108.5	63.9	2.3	1.88	4.3	2.81	6.5
2005-11-07	13:42:10	0.75	-33.8	13.6	47.1	13.68	31.3	11.2	108.5	63.8	2.3	1.88	4.3	2.81	6.5
2005-11-07	13:42:05	0.75	-33.8	13.6	47.1	13.68	31.3	11.2	108.5	63.8	2.3	1.88	4.3	2.81	6.5
2005-11-07	13:42:00	0.74	-33.9	13.6	47.2	13.68	31.3	11.2	108.5	64.0	2.3	1.88	4.3	2.81	6.5
2005-11-07	13:41:55	0.74	-33.9	13.6	47.2	13.68	31.3	11.2	108.5	64.0	2.3	1.88	4.3	2.81	6.5
2005-11-07	13:41:50	0.74	-34.0	13.6	47.2	13.68	31.3	11.2	108.5	64.0	2.3	1.88	4.3	2.81	6.5
2005-11-07	13:41:45	0.74	-34.0	13.6	47.2	13.68	31.3	11.2	108.5	64.0	2.3	1.88	4.3	2.81	6.5
2005-11-07	13:41:40	0.74	-34.0	13.6	47.2	13.68	31.3	11.2	108.5	64.1	2.3	1.88	4.3	2.81	6.5

Figure33: System Parameters during the measurement.

11 POTENTIAL SAVINGS BY IMPROVED OPERATION OF REFRIGERATION SYSTEMS

This chapter quantifies energy and CO_2 emissions which can be saved by following improved maintenance and onsite analysing techniques as stated in the previous chapters of the report. The energy savings and reductions in CO_2 emissions presented below show the potential savings that would be the result of implementing improved performance inspection techniques in a larger scale. The calculations assume that the potential improvements found in the 164 Swedish inspections would be representative for a wider "population". As the inspections where done mainly on newer systems (commissioning or warranty inspections) and that the contractor had advanced notice of the inspections it could be expected that the average savings for all system could be even bigger. As the Swedish average leakage rates are among the lower reported it can be expected that an international comparison would show a higher frequency of charge problems. It should also be noted that the savings in this report are only referring to improvement on the installed system without modifications of primary or secondary systems or controls (except for corrections of obvious errors directly preventing the machine to operate at acceptable conditions). Through better designs, modification of operating conditions and controls there are significant additional potential for improved efficiencies.

The results from the database are extrapolated in terms of European level to determine the energy saving potential. To calculate the potential reduction of CO_2 emissions a carbon intensity factor of 353kg of CO_2/MWh electricity is used (21). If the impact is calculated on the margin decreasing the production from coal fuelled power plants, the reduction in CO_2 emissions will be nearly 2.5 times more since they have a carbon intensity factor of 850 kg of CO_2/MWh. (21)

It has been estimated that 15% (1) of electricity produced world wide is used by the Refrigeration and Air-conditioning systems. For Europe (EU25) this estimate would lead to consumption of 468.15TWh by Refrigeration and Air-conditioning systems out of the total 3121TWh (22) of electricity consumption for Europe . When the database results are extrapolated to this European consumption, it results in saving of 45.4TWh of electrical energy and 16.02 million tonnes of CO_2 equivalent (based on average CO_2/MWh). This is a very large number in terms of electricity production and is approximately equal to the electricity generation of Denmark or Portugal for the year 2003(22) or equal to the generation of electricity from all renewable sources for Germany or Italy (2003) (22) or the total amount of wind power generated in EU25 for 2003 (22).

Energy consumption TWh by Refrigeration systems (EU25)	Potential Saving in % (based on the findings in database)	Potential Saving in TWh	Potential Saving in million tonnes of CO2 equiv.
468.15	9.7	45.4	16.02

Table7: Potential savings (CO_2/electrical energy) for whole Refrigeration and Air-conditioning Sector for Europe (EU 25, year 2003).

12 CONCLUSION

Refrigeration sector is one of the energy intensive sectors in today's world using in the order of magnitude 15% (1) of the total electrical production. Even though much work has been done in the refrigeration sector with regard to energy efficiency, there is still a large potential for energy savings if these systems are better designed and the operation optimized. Optimization through adjustment of existing systems is often extremely cost effective and it also contributes to reduce service costs as there is often a close relation between energy efficiency and reliable operation.

The results from the database show that there is room for significant improvement to be made in optimising the performance of refrigeration systems. This can be done by improved and documented maintenance and periodic inspection of refrigeration systems. The inspections can play a major roll to increase the focus on energy efficiency if implemented in a good way so that the equipment owners get a competent evaluation and advice on possible improvements will be directly beneficial. It can also be expected that an increased awareness among the equipment owners will make it more interesting for the installers and service contractors to improve their competency and services.

The end users should be made aware of energy efficiency improvements on the systems, even when the system is fulfilling the criteria of maintaining the desired temperature. The legislations such as the Energy Performance of Building Directive need a more stringent interpretation than the vague "visual" inspections now discussed. It is only through measuring the key parameters of the refrigeration process the performance can be established with accuracy to an acceptable cost. The introduction of the innovative method of "internal" performance testing offers a possibility to improve the quality of maintenance and inspections at the same time reducing the cost significantly than the traditional methods. By integrating and harmonising the regulations and standards regarding maintenance, leak reduction and performance inspections the required measurements can be taken manually or preferably logged at minimal added cost.

REFERENCES

1. International Institute of Refrigeration, Refrigeration Report (2002).
2. EU 2002, EU Directive 2002/91 on Energy Performance of Buildings.
3. Fahlen P, 2004 Methods for Performance and commissioning and performance of heat pumps, IIR Compressor conference in Papiernicka, Slovakia 2004.
4. Maxime Dupont, Jerome Adnot, (2005). Inspection and auditing of air-conditioning facilities in Europe –A new efficiency target, Center for Energy and Process, France.
5. Granryd, E. General Challenges in Heat pumping technologies, IEA Conference in Las Vegas 2005.
6. Eurovent Certification as accessed on 2005.11.01, www.eurovent-cecomaf.org/web/eurovent/web/index.asp
7. Klas Berglöf, Methods and Potential for On-site performance validation of air-conditioning, refrigeration and heat pump systems, IEA Conference in Las Vegas 2005.
8. Jaime Arias (2005), Energy Usage in Supermarkets, Doctoral thesis, Department of Energy Technology (KTH), Sweden.
9. D W Hudson, Ammonia Absorption refrigeration plant, Ecolibrim August 2002, Australian Institute of Refrigeration Air-conditioning and Heating.
10. IIR Statement, Tenth Conference of Parties (COP-10) of the United Nations Framework Convention on Climate Change Buenos Aires, Argentina, December 6-17, 2004.
11. EECCAC, "Energy Efficiency and Certification of Central Air Conditioners", study for the D.G. Transportation-Energy (DGTREN) of the Commission of the E.U., Coordinator: J. ADNOT, September 2002.
12. Denis Clodic, Green house gas emissions in the commercial refrigeration sector due to energy consumption, IZW-IEA, Hanover, November 2005.
13. International Energy Agency, www.iea.org. As accessed on 15April 2006.
14. Robert Heap, Refrigeration and Air conditioning- the response to climate change, IIR Bulletin 2001-5.
15. EN378- Refrigerating systems and heat pumps- safety and environmental requirements, 2005, European standard, CEN.
16. Nils Holgersson ,Samt redovisning av 10 kommuner i urval 2004 (In Swedish)
17. The Montreal Protocol on Substances that Deplete the Ozone Layer (2000), Secretariat for the Vienna Convention for the Protection of the Ozone Layer &the Montreal Protocol on Substances that Deplete the Ozone Layer
18. Kyoto Protocol to The United Nations Framework Convention on Climate Change (1997), United Nations Frame Work Convention on Climate Change.
19. Naumburg P-H, Experience of performance tests on medium size hermetic compressors, Scan Ref 4/87.
20. Asercom 2003, Definition of Total Heat Rejection for compressors.
21. Climate Change and the Power Industry, Price Water House Coopers, 2005.
22. European Union, Energy and Transport in figures for the year 2003, European Commission, Directorate –General for Energy and Transport. http://www.eds-destatis.de/downloads/publ/en7_energy_transport.pdf

APPENDIX: DATABASE CALCULATIONS

Type	Fabricated COP	Measured COP	% Variation in COP	Fabricated Capacity Kw	Actual Capacity Kw	% Capacity Variation	Fabricated Comp Capacity Kw	Actual Comp Capacity Kw	% Variation in Comp input
Commercial	3,00	2,10	-30,00	163,00	147,00	-9,82	54,33	70,00	28,83
Commercial	3,00	2,30	-23,33	163,00	159,00	-2,45	54,33	69,13	27,23
Commercial	3,30	3,20	-3,03	26,50	23,70	-10,57	8,03	7,41	-7,77
Commercial	3,30	3,20	-3,03	26,20	25,20	-3,82	7,94	7,88	-0,81
Commercial	3,30	3,10	-6,06	27,00	24,20	-10,37	8,18	7,81	-4,59
Commercial	3,30	3,10	-6,06	27,00	25,20	-6,67	8,18	8,13	-0,65
Commercial	3,40	3,30	-2,94	26,10	24,50	-6,13	7,68	7,42	-3,29
Heat Pump	4,10	3,00	-26,83	40,80	26,30	-35,54	9,95	8,77	-11,90
Heat Pump	4,10	3,10	-24,39	40,80	25,30	-37,99	9,95	8,16	-17,99
Heat Pump	4,10	3,20	-21,95	40,80	27,10	-33,58	9,95	8,47	-14,90
Heat Pump	3,90	4,00	2,56	113,00	99,30	-12,12	28,97	24,83	-14,32
Heat Pump	3,90	3,30	-15,38	113,00	82,20	-27,26	28,97	24,91	-14,03
Heat Pump	3,40	3,15	-7,35	67,00	62,60	-6,57	19,71	19,87	0,85
Commercial	4,20	4,00	-4,76	649,10	595,40	-8,27	154,55	148,85	-3,69
Commercial	4,20	3,60	-14,29	649,10	554,50	-14,57	154,55	154,03	-0,34
Air-conditioning	3,80	3,60	-5,26	398,50	379,10	-4,87	104,87	105,31	0,42
Air-conditioning	3,70	3,20	-13,51	410,00	351,00	-14,39	110,81	109,69	-1,01
Air-conditioning	3,10	2,10	-32,26	245,00	182,80	-25,39	79,03	87,05	10,14
Air-conditioning	3,10	2,00	-35,48	245,00	176,70	-27,88	79,03	88,35	11,79
Heat Pump	3,90	3,40	-12,82	43,90	43,70	-0,46	11,26	12,85	14,18
Heat Pump	2,70	2,60	-3,70	35,00	34,30	-2,00	12,96	13,19	1,77
Heat Pump	2,70	2,70	0,00	35,00	34,90	-0,29	12,96	12,93	-0,29
Heat Pump	3,00	2,50	-16,67	9,40	9,00	-4,26	3,13	3,60	14,89
Heat Pump	3,10	2,50	-19,35	15,90	12,10	-23,90	5,13	4,84	-5,64
Heat Pump	4,70	3,30	-29,79	17,40	12,70	-27,01	3,70	3,85	3,95
Heat Pump	3,20	3,00	-6,25	25,50	24,70	-3,14	7,97	8,23	3,32
Heat Pump	3,90	2,60	-33,33	27,00	19,80	-26,67	6,92	7,62	10,00
Air-conditioning	2,40	2,00	-16,67	25,80	23,80	-7,75	10,75	11,90	10,70
Air-conditioning	2,40	2,00	-16,67	25,80	23,90	-7,36	10,75	11,95	11,16
Air-conditioning	2,40	2,30	-4,17	25,80	26,30	1,94	10,75	11,43	6,37
Air-conditioning	2,40	2,20	-8,33	25,80	25,80	0,00	10,75	11,73	9,09
Air-conditioning	2,40	2,20	-8,33	25,80	23,50	-8,91	10,75	10,68	-0,63
Air-conditioning	2,40	2,20	-8,33	25,80	23,50	-8,91	10,75	10,68	-0,63
Air-conditioning	2,40	2,10	-12,50	25,80	25,30	-1,94	10,75	12,05	12,07
Air-conditioning	2,40	2,10	-12,50	25,80	24,50	-5,04	10,75	11,67	8,53
Heat Pump	3,60	3,60	0,00	25,70	25,20	-1,95	7,14	7,00	-1,95
Heat Pump	3,40	3,50	2,94	24,70	25,60	3,64	7,26	7,31	0,68
Air-conditioning	3,50	3,40	-2,86	162,80	174,00	6,88	46,51	51,18	10,02
Air-conditioning	3,50	3,30	-5,71	162,80	172,00	5,65	46,51	52,12	12,05
Heat Pump	2,80	2,80	0,00	37,30	41,80	12,06	13,32	14,93	12,06
Heat Pump	2,80	2,80	0,00	36,40	39,10	7,42	13,00	13,96	7,42
Heat Pump	3,90	3,90	0,00	24,50	23,80	-2,86	6,28	6,10	-2,86
Heat Pump	4,30	4,10	-4,65	26,50	25,60	-3,40	6,16	6,24	1,32
Heat Pump	3,80	3,70	-2,63	22,30	23,00	3,14	5,87	6,22	5,93
Heat Pump	4,20	3,90	-7,14	25,70	25,00	-2,72	6,12	6,41	4,76

Heat Pump	4,70	4,00	-14,89	39,90	32,10	-19,55	8,49	8,03	-5,47
Heat Pump	4,70	3,70	-21,28	39,90	29,60	-25,81	8,49	8,00	-5,76
Heat Pump	4,70	3,90	-17,02	39,90	30,60	-23,31	8,49	7,85	-7,58
Heat Pump	4,50	4,20	-6,67	40,90	31,70	-22,49	9,09	7,55	-16,96
Heat Pump	4,50	4,40	-2,22	40,90	35,40	-13,45	9,09	8,05	-11,48
Heat Pump	4,20	3,70	-11,90	38,20	29,40	-23,04	9,10	7,95	-12,64
Heat Pump	4,20	3,60	-14,29	38,20	28,30	-25,92	9,10	7,86	-13,57
Heat Pump	4,20	3,80	-9,52	38,20	30,40	-20,42	9,10	8,00	-12,04
Heat Pump	3,20	3,10	-3,13	26,70	22,20	-16,85	8,34	7,16	-14,17
Heat Pump	4,00	3,90	-2,50	29,90	27,60	-7,69	7,48	7,08	-5,33
Heat Pump	4,00	4,10	2,50	32,10	33,60	4,67	8,03	8,20	2,12
Heat Pump	3,20	2,40	-25,00	655,00	213,10	-67,47	204,69	88,79	-56,62
Heat Pump	4,10	3,90	-4,88	555,00	501,00	-9,73	135,37	128,46	-5,10
Heat Pump	4,00	4,00	0,00	46,20	47,50	2,81	11,55	11,88	2,81
Heat Pump	4,00	3,90	-2,50	45,00	46,30	2,89	11,25	11,87	5,53
Heat Pump	2,90	2,80	-3,45	32,00	31,30	-2,19	11,03	11,18	1,31
Heat Pump	2,90	2,80	-3,45	32,00	31,40	-1,88	11,03	11,21	1,63
Heat Pump	2,80	2,80	0,00	35,00	34,90	-0,29	12,50	12,46	-0,29
Heat Pump	2,80	2,90	3,57	35,00	32,20	-8,00	12,50	11,10	-11,17
Heat Pump	3,00	3,00	0,00	20,40	19,20	-5,88	6,80	6,40	-5,88
Heat Pump	3,10	3,10	0,00	20,50	19,90	-2,93	6,61	6,42	-2,93
Heat Pump	2,80	2,90	3,57	30,50	32,00	4,92	10,89	11,03	1,30
Heat Pump	2,80	2,80	0,00	30,30	30,50	0,66	10,82	10,89	0,66
Heat Pump	2,70	2,70	0,00	30,20	29,30	-2,98	11,19	10,85	-2,98
Heat Pump	2,70	2,70	0,00	30,20	29,20	-3,31	11,19	10,81	-3,31
Heat Pump	2,80	2,80	0,00	30,60	29,90	-2,29	10,93	10,68	-2,29
Heat Pump	2,80	2,80	0,00	30,60	28,30	-7,52	10,93	10,11	-7,52
Heat Pump	2,90	2,90	0,00	29,00	29,10	0,34	10,00	10,03	0,34
Heat Pump	2,90	2,80	-3,45	29,00	28,70	-1,03	10,00	10,25	2,50
Heat Pump	3,00	2,90	-3,33	30,50	29,00	-4,92	10,17	10,00	-1,64
Heat Pump	3,00	3,00	0,00	30,50	29,50	-3,28	10,17	9,83	-3,28
Heat Pump	3,80	3,50	-7,89	40,20	40,50	0,75	10,58	11,57	9,38
Heat Pump	3,80	3,50	-7,89	39,30	41,10	4,58	10,34	11,74	13,54
Heat Pump	3,80	3,70	-2,63	42,50	43,80	3,06	11,18	11,84	5,84
Heat Pump	3,70	3,40	-8,11	34,90	35,90	2,87	9,43	10,56	11,94
Heat Pump	2,80	2,30	-17,86	32,00	25,70	-19,69	11,43	11,17	-2,23
Heat Pump	2,80	2,30	-17,86	32,00	28,20	-11,88	11,43	12,26	7,28
Heat Pump	2,80	2,30	-17,86	32,00	29,50	-7,81	11,43	12,83	12,23
Heat Pump	2,80	2,30	-17,86	32,00	28,70	-10,31	11,43	12,48	9,18
Heat Pump	2,80	2,20	-21,43	32,00	26,70	-16,56	11,43	12,14	6,19
Heat Pump	2,80	2,30	-17,86	32,00	27,80	-13,13	11,43	12,09	5,76
Heat Pump	2,80	2,30	-17,86	32,00	28,60	-10,63	11,43	12,43	8,80
Heat Pump	2,80	2,30	-17,86	32,00	28,30	-11,56	11,43	12,30	7,66
Heat Pump	3,40	3,30	-2,94	38,80	34,50	-11,08	11,41	10,45	-8,39
Heat Pump	3,20	3,10	-3,13	37,20	35,60	-4,30	11,63	11,48	-1,21
Heat Pump	3,40	3,20	-5,88	38,20	37,10	-2,88	11,24	11,59	3,19
Heat Pump	3,30	3,10	-6,06	36,20	35,10	-3,04	10,97	11,32	3,22
Heat Pump	3,70	3,30	-10,81	35,00	31,90	-8,86	9,46	9,67	2,19
Commercial	2,80	3,00	7,14	422,00	491,90	16,56	150,71	163,97	8,79
Commercial	2,80	2,80	0,00	422,00	439,60	4,17	150,71	157,00	4,17

Commercial	2,40	2,20	-8,33	93,60	86,50	-7,59	39,00	39,32	0,82
Commercial	2,40	2,30	-4,17	93,60	86,60	-7,48	39,00	37,65	-3,46
Air-conditioning	4,30	3,60	-16,28	459,00	378,00	-17,65	106,74	105,00	-1,63
Commercial	2,50	2,14	-14,40	56,30	50,70	-9,95	22,52	23,69	5,20
Commercial	2,00	1,70	-15,00	52,20	46,10	-11,69	26,10	27,12	3,90
Commercial	2,00	1,90	-5,00	52,20	49,90	-4,41	26,10	26,26	0,63
Commercial	2,00	1,80	-10,00	52,20	46,30	-11,30	26,10	25,72	-1,45
Commercial	4,20	3,40	-19,05	273,00	250,70	-8,17	65,00	73,74	13,44
Commercial	4,10	2,90	-29,27	270,00	222,80	-17,48	65,85	76,83	16,66
Commercial	2,80	2,10	-25,00	147,30	127,60	-13,37	52,61	60,76	15,50
Commercial	2,70	2,10	-22,22	147,10	135,20	-8,09	54,48	64,38	18,17
Commercial	1,80	1,60	-11,11	168,50	166,90	-0,95	93,61	104,31	11,43
Commercial	2,30	1,90	-17,39	199,00	189,20	-4,92	86,52	99,58	15,09
Air-conditioning	4,40	4,00	-9,09	859,00	737,00	-14,20	195,23	184,25	-5,62
Air-conditioning	4,40	3,90	-11,36	859,00	748,30	-12,89	195,23	191,87	-1,72
Air-conditioning	4,30	3,30	-23,26	65,00	42,80	-34,15	15,12	12,97	-14,20
Heat Pump	2,80	2,50	-10,71	48,60	43,00	-11,52	17,36	17,20	-0,91
Heat Pump	2,80	2,50	-10,71	48,60	41,50	-14,61	17,36	16,60	-4,36
Heat Pump	2,80	2,60	-7,14	48,60	42,60	-12,35	17,36	16,38	-5,60
Heat Pump	2,80	2,40	-14,29	48,60	39,00	-19,75	17,36	16,25	-6,38
Heat Pump	2,80	2,50	-10,71	48,60	42,60	-12,35	17,36	17,04	-1,83
Heat Pump	3,20	3,10	-3,13	25,90	24,90	-3,86	8,09	8,03	-0,76
Heat Pump	3,10	3,00	-3,23	26,10	23,20	-11,11	8,42	7,73	-8,15
Air-conditioning	4,00	3,60	-10,00	296,30	293,00	-1,11	74,08	81,39	9,87
Air-conditioning	4,00	3,70	-7,50	296,30	303,00	2,26	74,08	81,89	10,55
Air-conditioning	4,20	3,60	-14,29	303,00	283,00	-6,60	72,14	78,61	8,97
Air-conditioning	4,10	4,00	-2,44	16,90	17,60	4,14	4,12	4,40	6,75
Heat Pump	3,30	3,10	-6,06	16,00	14,60	-8,75	4,85	4,71	-2,86
Heat Pump	3,50	3,10	-11,43	13,30	11,70	-12,03	3,80	3,77	3,70
Heat Pump	3,50	3,00	-14,29	16,00	14,30	-10,63	4,57	4,77	4,27
Heat Pump	3,20	2,90	-9,38	16,50	14,20	-13,94	5,16	4,90	-5,04
Heat Pump	3,20	3,00	-6,25	16,50	14,40	-12,73	5,16	4,80	-6,91
Air-conditioning	3,20	3,20	0,00	98,20	103,70	5,60	30,69	32,41	5,60
Air-conditioning	3,00	2,90	-3,33	96,00	95,10	-0,94	32,00	32,79	2,48
Air-conditioning	3,00	2,70	-10,00	96,00	87,00	-9,38	32,00	32,22	0,69
Air-conditioning	3,00	2,70	-10,00	96,00	89,00	-7,29	32,00	32,96	3,01
Air-conditioning	3,00	2,70	-10,00	96,00	88,70	-7,60	32,00	32,85	2,66
Air-conditioning	3,00	2,70	-10,00	96,00	88,50	-7,81	32,00	32,78	2,43
Air-conditioning	3,00	2,70	-10,00	96,00	92,30	-3,85	32,00	34,19	6,83
Air-conditioning	3,00	2,80	-6,67	96,00	93,90	-2,19	32,00	33,54	4,80
Air-conditioning	3,00	2,70	-10,00	96,00	90,90	-5,31	32,00	33,67	5,21
Air-conditioning	3,00	2,70	-10,00	96,00	90,30	-5,94	32,00	33,44	4,51
Air-conditioning	3,00	2,80	-6,67	96,00	90,70	-5,52	32,00	32,39	1,23
Air-conditioning	3,00	2,80	-6,67	96,00	90,70	-5,52	32,00	32,39	1,23
Commercial	3,20	3,10	-3,13	39,50	40,10	1,52	12,34	12,94	4,79
Commercial	2,80	2,60	-7,14	37,30	37,90	1,61	13,32	14,58	9,42
Commercial	2,30	2,10	-8,70	22,50	22,30	-0,89	9,78	10,62	8,55
Commercial	2,10	1,90	-9,52	30,00	32,60	8,67	14,29	17,16	20,11
Commercial	1,80	1,60	-11,11	23,60	27,60	16,95	13,11	17,25	31,57
Commercial	1,70	1,70	0,00	18,80	19,30	2,66	11,06	11,35	2,66

Air-conditioning	4,40	3,90	-11,36	126,50	113,00	-10,67	28,75	28,97	0,78
Air-conditioning	4,40	3,50	-20,45	126,50	112,30	-11,23	28,75	32,09	11,60
Air-conditioning	4,40	3,80	-13,64	126,50	112,00	-11,46	28,75	29,47	2,52
Air-conditioning	4,40	3,40	-22,73	126,50	104,70	-17,23	28,75	30,79	7,11
Air-conditioning	3,10	2,90	-6,45	110,50	97,40	-11,86	35,65	33,59	-5,78
Air-conditioning	4,20	4,00	-4,76	159,60	140,90	-11,72	38,00	35,23	-7,30
Air-conditioning	3,90	3,80	-2,56	159,60	147,80	-7,39	40,92	38,89	-4,96
Air-conditioning	3,50	3,70	5,71	87,10	87,10	0,00	24,89	23,54	-5,41
Heat Pump	4,30	3,40	-20,93	208,60	150,00	-28,09	48,51	44,12	-9,06
Heat Pump	4,60	3,90	-15,22	214,30	183,00	-14,61	46,59	46,92	0,72
Air-conditioning	4,10	3,30	-19,51	117,90	94,40	-19,93	28,76	28,61	-0,52
Air-conditioning	4,30	3,60	-16,28	81,30	66,20	-18,57	18,91	18,39	-2,74
Air-conditioning	2,40	2,00	-16,67	25,80	23,80	-7,75	10,75	11,90	10,70
Air-conditioning	4,10	3,30	-19,51	115,80	96,50	-16,67	28,24	29,24	3,54
Air-conditioning	3,90	3,20	-17,95	74,00	60,50	-18,24	18,97	18,91	-0,36
Air-conditioning	3,10	2,70	-12,90	325,30	239,90	-26,25	104,94	88,85	-15,33
Air-conditioning	3,20	2,80	-12,50	325,20	245,40	-24,54	101,63	87,64	-13,76
Commercial	1,30	1,20	-7,69	20,00	19,00	-5,00	15,38	15,83	2,92
Commercial	1,30	1,30	0,00	20,00	20,00	0,00	15,38	15,38	0,00
Average	**3,29**	**2,96**	**-9,68**	**104,08**	**91,64**	**-8,64**	**30,31**	**30,28**	**1,32**