EXPERIENCE FROM ENERGY OPTIMISATION IN REFRIGERATION AND AIR-CONDITIONING PLANTS THROUGH FIELD MEASUREMENTS.

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Abstract

The paper presents the expanding experience of Performance Inspections and practical experiences of optimisation through a systematic approach of measuring - analysing - optimisation - validation based on the “Internal method”. The method is used at commissioning, inspections, trouble shooting, maintenance, monitoring and in energy optimisation projects. The “Internal method” for Performance Inspections is based on thermodynamic analysis of the vapour compression process and has proven to be a cost effective method to optimise air-conditioning and refrigeration plants in hundreds of thousands of systems around the world. Few systems show when measured in the field the performance they are designed for and expected to have. Savings of 10-40% are possible without significant investments, in a majority of the analysed systems. In most cases the cost of the inspection is paid in a few months. A challenge is that before measurements the return on investment cannot be defined. Without a request from equipment owners few consultants and contractors invest in tools and training to learn how to measure and analyse systems. There is no incentive to save on customers energy bill if the customer do not realise the value. Current legislation is too vague to put a pressure on the market to actually measure. “Performance Contracting” and Energy Saving Companies are entering the market but often need to build competence and experience in measuring and analysing of HVAC equipment before they become effective in this sector.
The saving potential from optimising existing systems is the most “low hanging fruit” to reduce the energy consumption in existing buildings. According to International Energy Agency (IEA, 2012) two-thirds of the existing buildings will still be used in 2050 indicating the importance of optimising existing buildings and systems. This understanding is resulting in requirements like EU´s for “Performance Inspections” on air-conditioning systems above 12 kW in the Energy Performance in Building Directive (EPBD, 2010) even if the interpretation of what these inspections involves vary widely. In most cases they are far from achieving the results anticipated e.g. validating that the system is operating efficiently. In USA and Canada there are many incentive programs through the utility companies to re-commissioning and optimise plants. Due to the on the many markets still prevailing believe that it is necessary to apply the costly and challenging method to measure flow of air or water and small temperature differences with high accuracy there is often a reluctance to require costly measurements. The experienced high cost and difficulty to achieve information of a quality sufficient for optimisation hold back measurements. The Internal method eliminate the need of costly installations of flow meters and give more detailed performance information, not only on the system level but also component by component. Performance analysers based on the Internal method can be hooked up in 20-40 minutes on most heat pump, refrigeration and air-conditioning systems. The method is capable to measure capacity with an accuracy of +-7% and COP with +-5% for most compressor driven refrigeration/air-conditioning system. Experiences from different sectors are presented.

1. Introduction– The need for the new measuring and validation methods

“**To measure is to know**” is a valid statement in particular when it comes to optimising air-conditioning, heat pump and refrigeration plants. There is a growing awareness that these systems are a major consumer of electricity at the same time as heat pumps are seen as an important part of the future energy systems as they can reduce energy consumption in heating and hot water systems. It is estimated that 15-20% of the global electricity is consumed by vapour compression systems (IIR, 2002). With stricter requirements and higher energy prices there are also many new opportunities to combine cooling and heating demand to minimize the total energy consumption by combining different needs instead of treating them as different applications. Currently most possibilities to re-use heat from cooling systems or use cooling loads as heat source for heat pumps are neglected. The cause is often an experienced difficulty for the contractors and service technicians to ensure that the systems are actually performing as intended. Improved methods to measure and validate the actual operating performance and receive early warning for deviation in dynamic plants increase the understanding and efficiency of existing systems as well as increase the possibilities to introduce new solutions.

2. Challenges with conventional measuring methods in field application

Today’s air-conditioning and refrigeration systems are often not operating with the efficiency and lifetime that the design say and is expected by the equipment owners (Prakash, 2006), (Roaf, 2013). A major reason that this can continue to be the case in-spite of the increasing cost of energy is the lack of established cost-effective methods for measuring and validation of performance. Without that the equipment owners, consultants and the installers/service companies experience that measurements actually improve the performance and reliability it is difficult to justify the required investments, even if they are low compared to the total investment, maintenance and failure costs. The introduction of state of the art controls and BMS systems give an often false impression that good performance is ensured. That the prevailing purchasing process in most cases do not deliver the desired efficiency, in spite of the high investments in advanced controls, is becoming more and more obvious (CABA, 2013). It is not uncommon that prestigious buildings that are marketed as sustainable consume 50-200% more energy than they were calculated to use (Roaf, 2013). One major cause is the poor coordination between involved contractors/experts and unclear responsibilities for that the building as a whole is optimised. Each subcontractor is delivering according to their contract whereas the overall functionality is believed to be there if all systems are delivered to specification. A lot of data collected from a huge number of measuring points is absolutely not the same as efficient operation. “Information overflow” to the operators often occur if the system does not assist in analysing the data to create information that can be handled by the operating staff and maintenance contractors. These categories often need different information.

2.1. Sub-metering of electricity and flow based energy performance measurements

Traditionally it has been rare that the actual electrical consumption of the refrigeration or air-conditioning systems is measured separately. With an increasing introduction of sub-meters and installation of flow based energy meters on heat pumps and chillers the challenges to analyse and make use of the data for optimisation is becoming obvious. The first challenge is to, in the field, measure flows and small temperature differences in dynamic systems with sufficient accuracy to make them useful for analyses. Due to the complexity of the systems, the variations in loads and climatic conditions any deviations in performance must be significant before a “warning” can be generated. If a flow based COP and/or Seasonal Performance Factor (SPF) is not showing the expected performance it does not give much help for the analyses as the data is generated in dynamic systems with a wide spread of operating conditions and performance. Systems are dynamic, has long time constants and temperatures continuously varies making it challenging to even determine if there is a deviations from “planned” performance. If there is an indication of low capacity, COP or SPF an often costly investigation of the cause is required to start basically from scratch as these data do not contain sufficient information for evaluation.

2.2. Building Managements Systems (BMS), Energy management Systems (EMS) and advanced controls

It is often believed that the investment in state of the art BMS and EMS ensure optimised systems even if they when it comes to air-conditioning, refrigeration and heat pump systems often present a number of measured parameters that if even possible require a high level of competence and many hours of analysing to make into useful information. If systems lack “tools” to convert measured data to information that can be understood, by the people involved with daily operation and maintenance, advanced systems do not contribute much to improving efficiency or reliability. When neither responsibility nor budget is assigned for the optimisation of the completed system the impact advanced and costly controls and monitoring system is limited. Adjustment and validation of the systems overall performance at different load and climate conditions must be carried out to achieve expected functionality and performance. Due to the complexity state of the art BMS/control systems can even be contra productive. It is not unusual that when problems are found in new complex control and monitoring systems it is challenging to get a new budget soon after approved hand-over to fix problems resulting in lack of functionality and visualisation. The author has in connection with insurance investigations and troubleshooting experienced repeated failures without alarms as well as systems with so many alarms that nobody on-site has the competence or patience to re-set controls and BMS to the level where only adequate alarms are generated. Due to that the systems, to be energy efficient, should operate at different capacities and operating conditions traditional alarm levels based on maximum or minimum limit becomes a very dull tool for energy optimisation and early warning of problems.

Efficient operation is rarely something that can be achieved based on theoretical prediction of the building. In principle all buildings need validation of systems and controls in normal operation to ensure that intended operation is achieved at varying operation loads and climate condition.

Few if any BMS systems on the market give key information for optimisation and early warning such as:

- ✓ Cooling/heating capacity (measured without use of manufacturers design data at correct operation)
- ✓ COP/EER (measured without use of manufacturers design data at correct operation)
- ✓ Compressor efficiency
- ✓ Evaporator heat transfer
- ✓ Condenser heat transfer
- ✓ Superheat/Sub-cool
- ✓ Indicators for refrigerant charge for early detection of leaks

Some systems show some of the above performance data based on theoretical data from compressor curves and/or swept volume. To use theoretical performance data obviously create a significant risk that actual deviations in performance are not identified. The Internal method can be added as a stand-alone monitoring system or integrated in

many BMS systems to add all the above and more information for early warning if compressor, heat exchangers, charge or expansion device deviate from expected performance.
The industry need to introduce the new technology and end-user should realise that they can and should request documentation of performance. Portable see Figure 1 as well as fixed equipment allowing cost-effective performance analysing is available.

3. EXPERIENCES FROM THE INTERNAL METHOD FOR PERFORMANCE ANALYSIS

To establish the baseline performance of a refrigeration or air-conditioning systems is a prerequisite for optimisation and to minimize risk of failures as well as to take proper decisions for investments to improve or replace existing equipment. Energy efficiency is on the agenda but focus is often on performance at rating conditions and sizing which are only a small part of what is important to system efficiency. A system can operate very efficiently at low load when the surfaces are oversized whereas another can be undersized and neither create comfort nor efficiency. Optimisation of existing equipment is often the lowest hanging fruit when it comes to cost effective measures and it is also clear that there is a close relation between efficient and reliable operation.

Figure 1, Performance Inspections give valuable information for optimisation

3.1. The internal method – how it works in short

The performance analyser based on the "Internal Method" offers a cost effective method to get not only an overall performance but also detailed information on a component level. The method is described in detail in earlier papers (Berglöf, 2011) but a very short summary follow here.
The advantage with the internal method that is based on a thermodynamic analysis of the refrigeration process is that it does not require any pre-installed sensors it can often be installed without stopping the compressors or only for a brief moment to open the electrical housing to connect the current clamps. Typically portable equipment can be hooked up in 20-30 minutes. If systems are permanently monitored early warning on a component level can be generated. That the method is based on well-defined properties and cycle of the refrigerant reduces the sensitivity to measuring errors and generate information in dynamic systems that can hardly be achieved by other method. It accurately determines a working system's:

- Coefficient of Performance (± 5%)
- Cooling and heating capacity (± 7%)
- Power input (± 2 %)
- Compressor isentropic efficiency

The basic system uses ten easy to apply sensors that are attached at strategic points around the system. This is seven temperatures, two pressures and active power as shown in Figure 2.
Required measuring points for a standard systems:
- Temperature and pressure at entrance of compressor.
- Temperature and pressure at compressor exit.
- Liquid refrigerant before expansion device.
- Active electrical power.

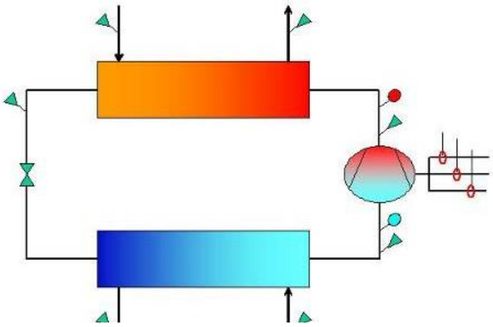

Figure 2, Sensors required and their location to establish performance of a standard refrigeration system.

For reference of operating condition and heat exchanger evaluation the temperature of air/liquid entering and exiting condenser and heat exchanger are measured. From the information gathered the key operating parameters that pinpoint the system's actual performance can be determined independent of any supplier data.

At the heart of the performance analyser is the energy balance over the compressor and a series of algorithms, based on the thermodynamic properties and operating characteristics of the refrigerant in use.

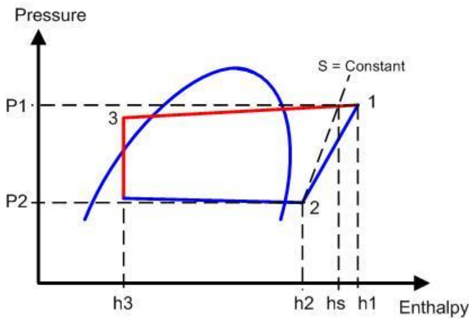

Figure 3, Pressure – enthalpy graph of "standard" refrigeration process.

Cooling Capacity = Mass flow * (h2 – h3)(2)

Heating Capacity = Mass flow * (h1 – h3) (3)

$$\text{Isentropic Effic} = \frac{(hs - h2) * (1 - \text{rel. heat loss})}{(h1 - h2)} \quad (4)$$

3.2. Well proven method

The method and technology was first developed in Sweden 1986 and validated by SP the national Swedish testing institute (Fahlén, 1989). More than 40 manufacturers and 600 contractors in 20 countries have introduced the "Internal Method" as a tool to improve their development, production and aftermarket activities. An increasing number of "Performance Inspectors and commissioning engineers are experiencing the value of documentation of actual performance versus a theoretical estimate. Many hundred systems are monitored 24/7 over Internet allowing the operating and maintenance technicians to follow the systems performance dynamically and receive warnings on deviation long before the symptoms becomes noticeable by the users. Equipment owners can have detailed energy reports with their buildings and equipment's energy profile documented in an unbiased way. This information can be used to identify opportunities for optimisation, follow the result of optimisation as well as for benchmarking different plants. There is an obvious advantage of have not only the resulting energy use but also the underlying information how efficient different parts of the system is. Examples of world leading companies in the industry that has validated and use the Internal Method to document the performance of their products and optimise the systems are Carrier, Johnson Control, Copeland, Gea, Danfoss Heat pumps and DuPont. More than 20 Universities around the world is using ClimaCheck in their education and research work to document and visualise performance of systems.

Figure 4, Field kit for Performance Analyser that does not require installation of flow meters to establish the performance and capacity.

3.3. Experiences - Heat pumps

Heat pumps are increasing in many countries and are seen as an important part of the future energy puzzle as they "use" the electrical energy in an efficient way by extracting "renewable" energy from i.e. the ground, ambient or exhaust air. Heat pumps systems tend to be more complex than a large majority of smaller air-conditioning systems but the customers also have a much stronger focus on their energy bill. When they have done a large investment they also check that they achieve the predicted savings. The booming Swedish ground source heat pump market was the sector where the internal method was first applied in the mid 80-ties. Since then there are experiences from hundreds of thousands of performance tests as several manufacturers use the method for development and production tests as well as for field tests of new designs. Portable equipment is also used to cost effectively solve warranty discussions. Many manufacturers have problems when contractors and house owners are disagreeing on the performance and functionality of the installed system. Frequently the problem is blamed on the heat pump based on vague information. A dissatisfied customer can seriously hurt the reputation of a brand in a community. It thus becomes important from a marketing perspective to quickly either pin-point and fixes the problem or show the customer an un-biased documentation that the unit is performing as specified. With the use of a standard performance analyser it is possible to without any manufacturer inputs validate the performance (COP/EER and capacity) not only of the whole heat pump but also on a component level validate the performance using all the indicators and limits of a factory test rig. The information contains all the details an expert need to evaluate the plant without having to go to the site. In Figure 5 shows the documentation that solved a two year long dispute on it's way to court. A heat pump owner was not satisfied with the performance of his ground source heat pump and complained to the contractor on performance as well as repeated stops caused by the pressure switches. The contractor spent much time trouble shooting and did a significant number of modifications like installing a bigger circulation pump to the ground collector, resetting safety limits, adjusting the expansion valve without creating a reliable operation. Before the case was taken to the court the house owner's insurance company requested an un-biased inspection of the system.

The inspection with a standard performance analyser documented the performance of the heat pump including all the components in less than two hours. With this information it became obvious to recapitulate the problem. The freeze depressor that had been used had not been of good quality or not handled in a proper way. As a result the evaporator had become fouled resulting in low evaporation which at low condensing resulted in tripping on the low pressure switch. The contractor had noticed the low evaporation and tried to fix that with increasing the flow and when that did not help he lower the evaporation to try to raise the evaporation. With a proper logging and documentation and visualisation of data it becomes obvious that the evaporator heat transfer was significantly lower than design and thus a quality test of the secondary media and cleaning of evaporator should have been the obvious measure. The performance inspection resulted after two years of frustrating battle and many hours of work in a change of the secondary media and cleaning of the evaporator. The courts could be avoided and the cost was significantly lower than the original claim to replace the heat pump which would likely not have solved the problem. It is with hind sight easy to say that the contractor and the manufacturer representative that had both visited the plant several time and taken the wrong measures should have solved this but without proper tools it often turns out to be difficult to pin point the problem. **To measure is to know.**

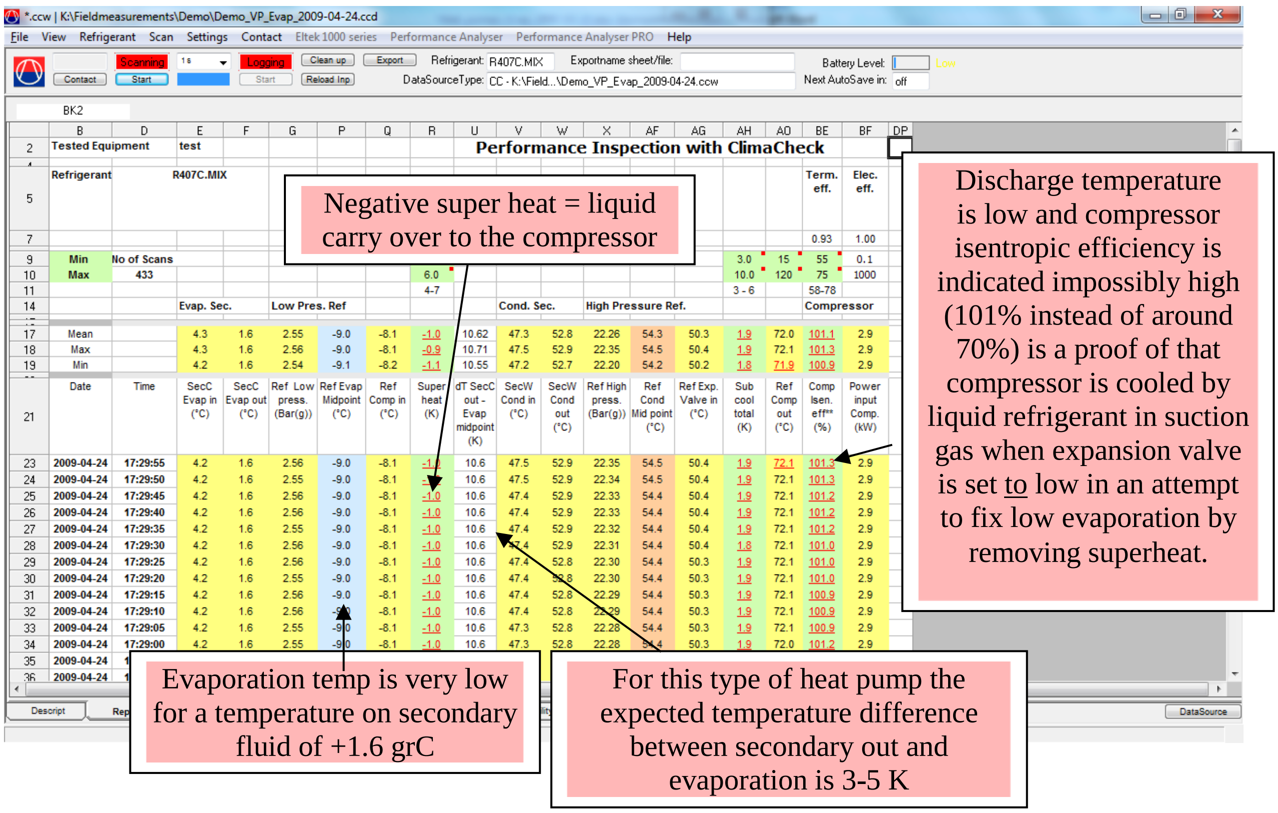

Figure 5, Example the complex fault scenario that can occur in a “simple” heat pump installation.

3.4. Experiences - Supermarket optimisation

Hundreds of supermarkets in Europe and North America are being monitored 24/7 with full visualisation of dynamic data of the refrigeration process where visualisation of COP and other key process parameters has proven a useful tool for the refrigeration technicians and engineer to optimise systems. Together with the possibility of visualising the impact of the savings for the equipment owners the energy optimisation becomes a stimulating and popular exercise. When the equipment owner can see the magnitude of the savings resulting from the work the time spent to understand and optimise the system is easily justified.

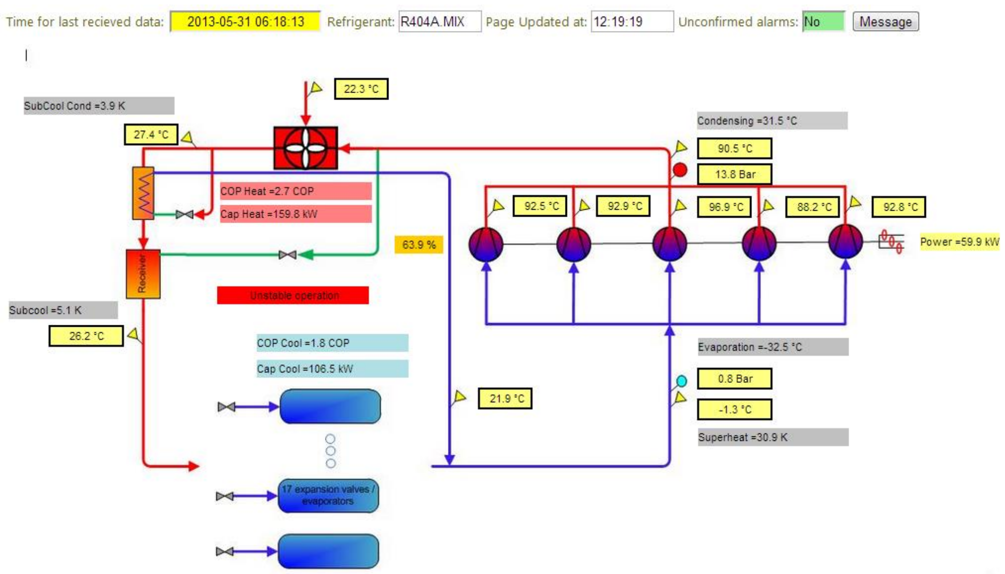

Figure 6, Super market pack system with on-line visualisation of key parameters such as COP, capacity and compressor efficiency.

Many not to say most refrigeration packs analysed has proven to be operating far from their optimum and there are several problems that seem to be universally common in spite of that they cost the owners huge amount of money every day. In Figure 7 it is shown an example on how the compressors are short cycling with long periods i.e. from 13:20 till 15:00 with more than one compressor start per minute. These types of control problems are often not corrected at commissioning and maintenance and plants work with increased wear on compressors and unnecessary waste of energy. The cause of this operation is a combination of controls that are not well developed to handle the situation with display cases that are opening and closing causing sudden almost instant changes in evaporation. There is no rush for the system to act on this but at the same time it can be challenging for the technician to adjust hysteresis and time delays to achieve stable operation. But in most systems there has been no attempt to adjust the parameters based on actual behaviour so even if it can be hard to get optimum operation with an old primitive system it can almost always be significantly improved when attention is on the actual behaviour. Obviously state of the art control systems with floating evaporation and condensing has a big potential if correctly set up as they also remove the prevailing situation that systems are balancing load and capacity at lower evaporation than what is required due to the hysteresis between capacity steps.

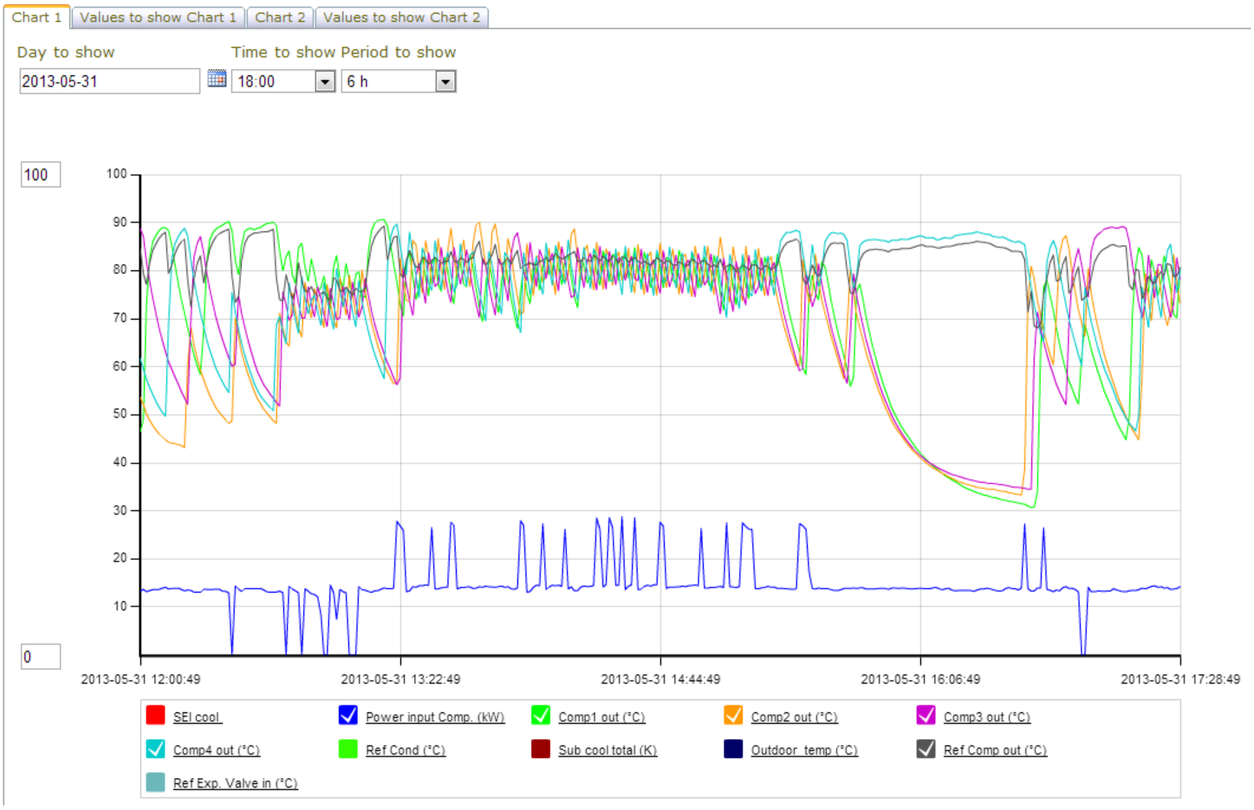

Figure 7, Short cycling compressors in supermarket pack

Another common problem contributing to short cycling in systems where fan control is used to avoid low condensing is that the consequence of fluctuating high pressure is not understood or observed. The following sequence then take place:

1. Fan/fans stop to avoid to low condensing.
2. Pressure increase and with this the liquid temperature in the receiver and liquid line.
3. Fan start when set-point to start fan is reached
4. Pressure decrease and thus condensing temperature pass below temperature in liquid line causing re evaporation of liquid.
5. With low condensing and flash-gas in liquid line there will not be enough liquid going through the expansion valve.
6. Evaporation decrease and control system often interpret this as the system is below it´s set point and stop compressor/compressors in spite of that the load is still the same.
7. As compressor capacity is decrease condensing decreases to the lower set-point and fan stops and the process starts again from 2 above.

For larger organisations with many refrigeration systems the possibility to compare process data between different plants to bench mark performance on a much more direct level to identify cost effective measures than the traditional way of working backwards from an energy consumption/m2 or meter of display case or other such comparators that are affected by many parameters such as climate and sales volumes.

3.5. “Energy profiling” as a method to visualise optimisation.

When optimisation based on analyses of performance is done the result is visualised in the energy statistics where the server can automatically generate an “energy profile” that reflects how many kWh the system is expected to use per hour at each ambient temperature. When an optimisation effort is done it will show as a deviation from the historical profile.
With the thermodynamic data on the process the technicians and engineers can pin point a problem and optimise the system before it affect the reliability of the plant. For the equipment owner the documentation of the energy consumption and operating cost is the key information. With fixed installed monitoring equipment the technicians as well as equipment owners can have continuous access to the information they require. Energy statistics and Energy profiles are important to visualise the performance and cost as well as a tool to get the bases for decisions on optimisation and their saving potential.

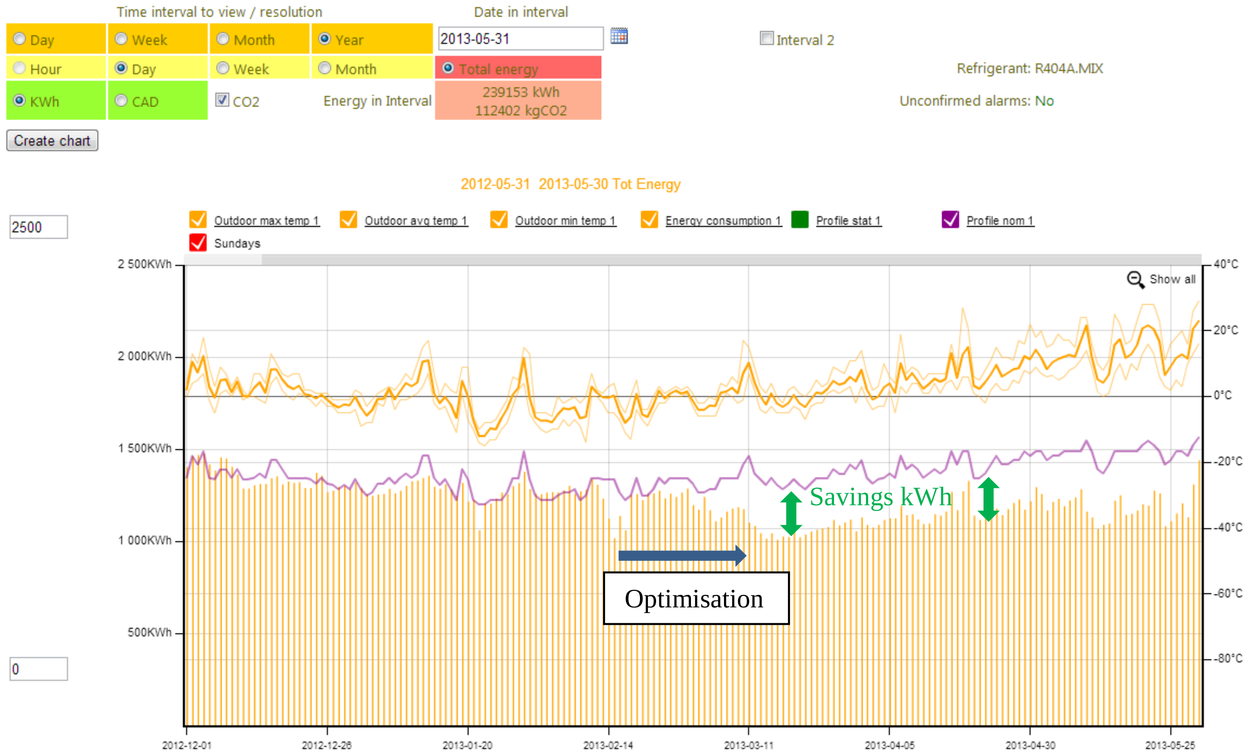

Figure 8, Visualisation of energy saving from optimisation in supermarket, Purple line is expected kWh consumption based on consumption before optimisation. Yellow bars is kWh consumption per day. Yellow line is ambient temperature. Documented savings from optimisation is indicated with green arrows between projected line (purple) and bars (yellow).

In an evaluation of the six Carrefour hypermarkets the savings of the total electrical consumption in the stores showed a saving of between 7 and 13 % of the total consumption of the store which corresponds to energy savings of the refrigeration process of from 15% to 30%. With the introduction of advanced CO2 systems the need of proper evaluation of the systems functionality and performance has been demonstrated in many measurements with the internal method.

3.6. Detection of leaks

In supermarkets and many other applications early detection of leaks is challenging but important due to the high cost and environmental impact of the refrigerants released. The costs are not only related to the refrigerants that with environmental taxes are getting very expensive in many countries but also to the increased energy cost caused by operating with low charge and damaged goods if detected to late. With access to a full thermodynamic evaluation of the process together with the energy profiling refrigerant leaks can in most cases be detected by a properly configured system long before they cause alarms in a normal monitoring system. In Figure 9 the green line show the expected kWh per day at the prevailing ambient temperatures (yellow line) and the yellow bars are the measured energy consumption. Here it can be noted that the consumption increase relative the expected increase caused by higher ambient temperature. To create a "profile" for a plant introduces an additional possibility to detect such changes that can be challenging to detect on system or component level. Energy consumption can change due to changed settings or use of the building.

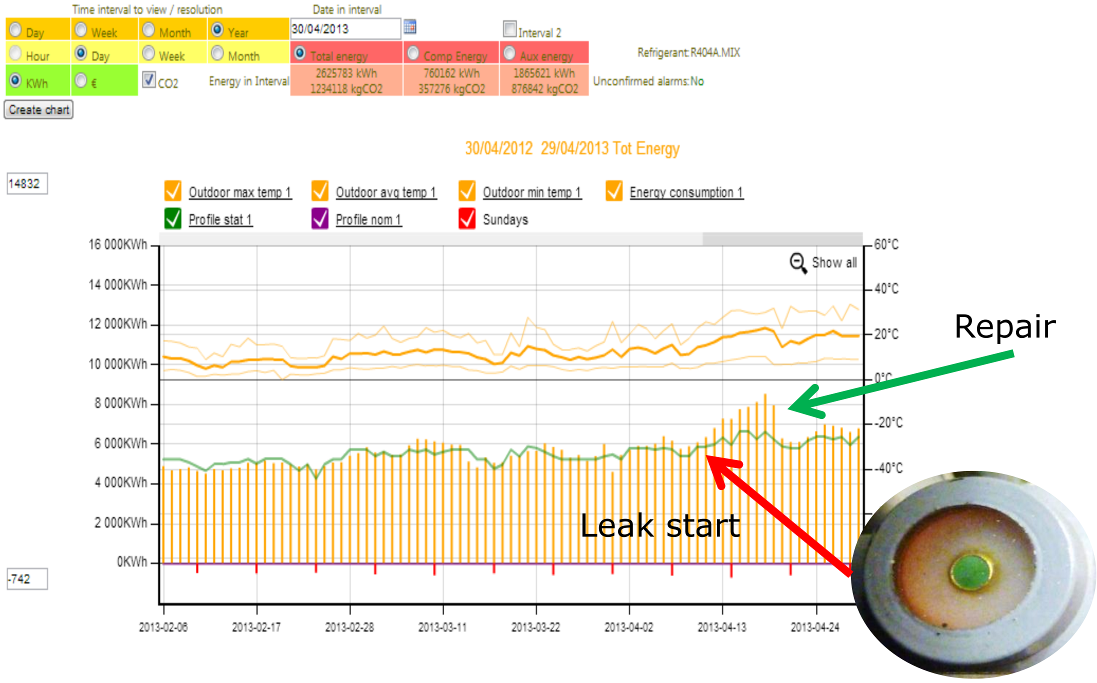

Figure 9, Example how a monitoring of change of performance can give early warning for leaks in supermarket systems.

3.7. Experiences from analysing air-conditioning and industrial systems.

Leading companies in the air-conditioning industry has tested and validated that the internal methods is reliable to measure performance and identifying problems in the plants. The method is suitable to document performance of any compressor driven refrigeration system and is frequently used in all different applications. In air-conditioning systems Performance inspections are a requirement in EU and in North America there are incentive programs that are pushing for re-commissioning of chillers. Performance Inspections has shown savings of 10-30% in many chillers projects. Experience has been built up in all types of applications such as hotels, malls, hospitals and industrial chillers. This type of analyses has after evaluation of several utilities in USA and Canada been approved for incentives. Thousands of inspections are carried out every year and hundreds of chillers in office buildings, hospitals, malls and industrial plants are monitored 24/7 to give early warning of faults and build up experience of energy use. Other areas where an increasing number of consultants and contractors apply thermodynamic performance inspection is in Ice rinks and industrial plants. Experiences exist in systems from 1 kW to 25 MW capacity. By documenting the process in detail the actual behaviour over varying loads can be defined and potential savings by optimisation efforts can be calculated and after measures are implemented the result can be validated.

3.8. Global access to on-line expertise through Internet open new ways to ensure best performance.

As all relevant parameters can be logged and analysed on Internet any in-house support staff, manufacturers and suppliers as well as independent experts can be consulted at low cost. They then have access to data from dynamic operation of the system including performance of all components in the system. They can give on site personal guidance on what can be done to trouble shoot and optimise systems or confirm correct operation. This makes it possible to in an extremely cost effective way access the best experts in the world and avoid that disputes, as now is common, are prolonged due to poor information.

4. CONCLUSIONS

The air-conditioning, heat pump and refrigeration industry is phasing a new market situation when energy efficiency becomes an important parameter and just keeping a temperature is not the only thing they are measured on. Experience show us that in many plants savings of 10-40% can be realised at low investments by ensuring that the plant is operating as intended. Work on supermarkets show savings in the refrigeration process between 15 and 30% with small investments. Significant decrease in energy cost and carbon footprint can be achieved by increased quality of commissioning and service. Benefits such as decreased repair cost, reduced losses, down-time and minimized bad-will from failures are also key driving forces to implement improved methods to document performance and functionality. The biggest challenge to introduce a more preventive practice with measurements is the necessity to change business-as-usual in an industry where equipment owners often have limited technical skills but strong focus on initial price and replacing components at failures is the bread and butter for many contractors.

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