Performance Monitoring Strategies for Effective Running of Commercial Refrigeration Systems

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Abstract: - Refrigeration systems often represent the largest electricity consumers in the supermarkets. Therefore there is a clear need for running these systems effectively. Performance monitoring uses different techniques to determine the actual system state. Another motivation for such monitoring is the existence of directives and regulations applying both to food manipulation and system equipment. Following article is devoted to state-of-art performance monitoring methods in commercial refrigeration systems and describes some of the challenges in the applications of these methods. Energy monitoring, as closely related topic, is described in a separate section.

Key-Words: - Performance measure, FDD, COP, energy monitoring, refrigeration

1 Performance Monitoring in Commercial Refrigeration

In commercial refrigeration, measuring plant performance can be difficult and experience has shown that two complementary monitoring strategies give the best results in ensuring maximum plant efficiency [2]. Ideally, both can be combined. The strategies are:

1. Overall plant performance. This involves measuring the power input into the plant over fairly long periods of time (e.g. weekly) and estimating the amount of cooling done in the same period, either by direct measurement or through calculation. This strategy allows building a comprehensive picture of plant performance over time.

2. Assessment of plant faults. This involves assessment of the performance of individual items of plant, such as condensers, to identify specific types of fault to be remedied. This approach usually involves taking a “snapshot” of instantaneous data (e.g. temperatures and pressures) and comparing these data with “expected values” - an example on this is provided later in the article. By understanding the interrelationship between measured parameters, different types of plant faults can be diagnosed. Individual degradation faults introduce inefficiencies to the operation of the refrigeration plant, and generally have negative impact on the operating cost. Presented strategy is also known as Fault Detection and Diagnostics (FDD). Although the diagnostic aspect is included primarily in the area related to monitoring of process data, the diagnostic functionality can be improved by considering also the data from the other areas, e.g. alarm monitoring and energy monitoring.

2 Plant Performance Assessments

As the plant performance deteriorates in time, the relative degree of such deterioration should be well captured by a good performance measure. The dynamics of performance degradation is usually slow. The basic performance monitoring method consists of calculating performance measure with regular step and plotting the calculated values in a trend plot. If the degradation curve is reaching a specific critical threshold, it may indicate that appropriate maintenance or repair action should be applied.

2.1 Overall Plant Performance

The performance measure traditionally used to express plant performance is the Coefficient Of Performance (COP) defined as

$$COP = \frac{Q}{P} \quad , \tag{1}$$

where Q is the amount of cooling being carried out measured in kW and P is the amount of power consumed, measured in kW as well. Therefore COP is a dimensionless measure and usually achieve values greater then 1. The denominator of COP includes compressor energy input together with auxiliary energy inputs (from condenser and evaporator fans) and energy meters or an alternative ways of measuring energy are used.

It is normal that the COP could be significantly different, if only the snapshots of the plant COP on two occasions are measured. This is because the COP is dependant on ambient temperature and cooling load. Therefore, in case of air cooled condensers, the dry bulb ambient temperature is usually measured. Measuring a cooling load represents a difficult task. In case of liquid (like glycol in secondary refrigeration circuit) being cooled, it is possible to directly measure flow rate and temperature difference. In most of the real supermarket application, when the air is used for product cooling, it is not possible to have air flow and the temperature difference across each cooling coil available. Then, the cooling load has to be estimated by some of these ways:

Estimation based on production throughput. It is mostly applied to process cooling in food and drink factories where certain product or products need to be frozen. The amount of cooling can be calculated once using reference books to obtain both specific and latent heat values. For example, if freezing fishes, the heat model includes three parts: sensible heat cooling of the fishes from the inlet temperature to freezing point, latent heat of freezing the fishes and sensible heat cooling from the freezing point to the storage temperature. The result can be calculated as the number of *kWh* per tone of the fishes being frozen. This method can provide reliable results [2]. However, such calculations are not always applicable for cold stores and chill stores, where the next method is applied frequently.

Estimation based on load modeling. The cooling load is modeled by listing the individual elements of the load (e.g. walls heat ingress, product load, evaporator defrosts, etc.) and modeling these in relation to relevant parameters such as ambient temperature. To set up load models may require expert help [2]. Although it is currently the best practice, this method does not provide accurate results.

Another way of load modeling for COP calculation represents the data-driven approach with the calculations based on site long time measurements and trying to identify the variables describing the system load more precisely.

2.2 Plant Faults Assessment

The Fault Detection and Diagnostics concepts developed so far for fault assessment in the areas of HVAC (Heating, Ventilation and Air Conditioning) and refrigeration struggled with achieving the right cost-to-benefit ratio. FDD usually requires a good quality data to be able to generate good quality conclusions. This naturally implies requirements on additional sensors and data archiving (better IT infrastructure), and thus there are additional costs associated with implementation of FDD. Recently the interest in FDD has grown as the costs of sensors and control hardware are lower. The future trends aim towards automated-FDD or AFDD [1]. Automated FDD systems can either be integrated into individual equipment controllers, or the FDD algorithms could be running in remote data centers. The use of such tools could allow small support staff to operate, monitor, and maintain a large number of different systems from one centralized location.

From the algorithmic viewpoint, fault detection and diagnostics methods spread over a quite large area. They vary from relatively simple engineering approaches and diagnostic rules to more sophisticated modeling methods.

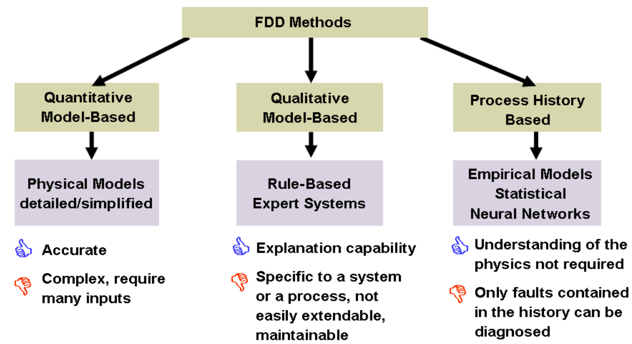

Fig. 1 Comparison of FDD approaches

Process history based approaches are based on collected historical data, and involve technologies like statistical modeling or neural networks. Their main advantage is no need for detailed understanding of physics and details about equipment, but they introduce known drawbacks of inferential modeling, namely that it cannot rely on data only – some process knowledge is always necessary.

Quantitative model-based approaches are based on physical and thermodynamic models, either detailed or simplified. Such models can be very accurate, but models are usually device-specific and rather complex and requiring number of input data. Using such a methodology is appropriate in specific cases only.

Qualitative model-based approaches are based on set of rules or physic-based qualities. The rules can either be defined by expert or based on first principles. Definition of limits and consequent alarms also falls into this category. Generally this method may provide pretty good explanation capability, but it is specific to a system or a process. This can be illustrated by a brief description of one of the very common faults in refrigeration systems – refrigerant leakage:

The refrigerant leak influences the overall refrigeration system performance. The loss of refrigerant in the system changes the pressure balance, so the suction and discharge pressure decrease. This leads to reduction in both evaporating and condensing temperatures. It also affects the expansion valves, resulting in lower refrigerant flow. Finally, comparatively lower amount of available refrigerant will cause that not much cooling occurs in the evaporators. This leads to higher superheats and increased discharge temperature from the compressor.

As it was said, definition of the rules set requires expert knowledge and so it may be difficult for the customer to extend it or maintain it.

Generally, all three FDD approaches have been researched and implemented for different types of HVAC and refrigeration applications under different conditions and different level of automation.

2.2.1 AFDD System Application Challenges

The use of presented performance assessments comes not only from financial motivations but also from recent regulations. The one related to refrigerant charge says that "the refrigeration systems containing over 300 *kg* of the refrigerant must have by law automatic leak detection installed - either direct or indirect" [8]. An indirect system requires built-in "intelligence" as it is quite difficult to interpret varying conditions of liquid level, pressures and temperatures within a refrigeration system, as these vary widely even if no leak has occurred.

The fact of widely changing conditions in the commercial refrigeration systems during its normal operation is a major challenge in any AFDD application. Therefore it must be reflected in its architecture. An application comparing the data snapshots with the expected values (as presented in the introduction) can have a structure as displayed in Fig. 2. All typical operations are periodically executed. The periodical execution is invoked by the timer and it is depending on the sampling period (typically the value is between 5 ÷ 10 minutes).

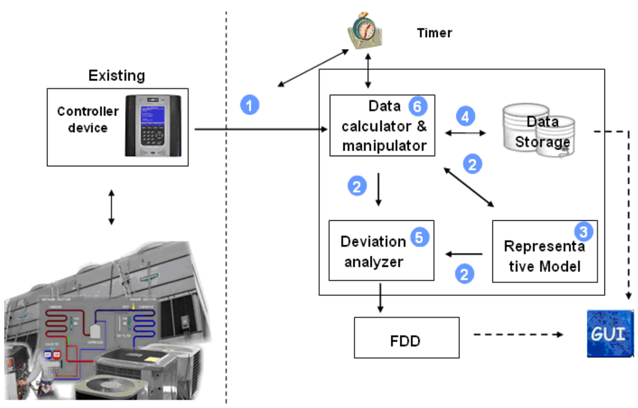

Fig. 2 Refrigeration AFDD application architecture

Controller device reads the actual values from typically available sensors in the system. The data are read from controller device {1} and stored to the database {4} together with data calculated {6} in the first block. The calculated data represent values of "virtual meters" which are not available in the system – e.g. condensing temperature of certain refrigerant at given pressure (based on pressure-temperature chart for given type of refrigerant) to determine current subcooling. The set of typically available system data points usually encompass suction and discharge pressures, evaporator temperatures (refrigerant outlet temperature, temperature air on and temperature air off), suction temperature, discharge temperature and liquid return temperature of refrigerant and finally the ambient temperature with relative humidity. However, the available data set (determining the constraints for AFDD system functionality) varies from site to site. This fact represents another challenge in the creation of AFDD system as plant owners typically do not incline to purchasing additional sensors.

The complete set of data (both measured and calculated) is not only being stored in the database but also sent {2} to the next blocks for further processing. First, the representative model {3} has to be identified. As mentioned earlier, the conditions in the system vary during the normal operation. This is because of varying system load and system complexity. The system operating conditions can be represented by ambient temperature in the combination with other measures (e.g. time of day, day of week or relative humidity). If the polynomial model is used to fit training data, the locally weighted regression is an appropriate method to provide good results. The modeled values (at given conditions) are finally compared {5} to the actual system values. The differences (residuals) representing the variations from expected values are then passed to FDD system which determines the relevance to possible fault.

3 Energy Monitoring of Supermarket

The rise of energy prices is putting increased pressure on owners of commercial buildings including supermarkets. Two important aspects of efficient supermarket operation include energy consumption and refrigeration equipment performance. They are interconnected and both of them have direct impact on monthly bills.

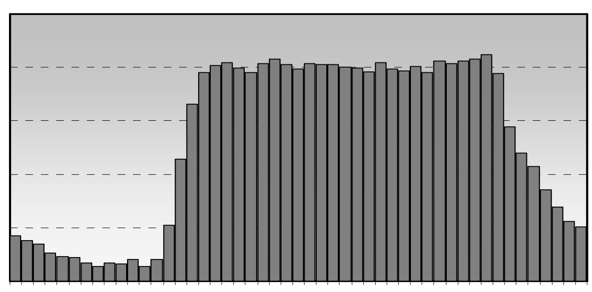

Fig.3 Supermarket energy consumption daily profile

The importance of solutions for automated monitoring and performance assessment has significantly increased over recent years. The automated tools should have capabilities to timely detect problems like gradually increasing energy consumption. Because operation of any commercial building follows more or less specific daily cycles (as displayed in Fig. 3 for the supermarket), it is a common practice to monitor energy consumption using its trend captured in the so-called daily profile. In other words, instead of monitoring energy consumption at a specific time of day without considering other times, all the measurements taken during the 24 hours are joined together and considered as one compact set of values [4].

Total supermarket energy consumption includes the consumption of the refrigeration systems, lights, shop services (e.g. cash desks) and HVAC equipment. Systematic monitoring of total energy consumption is implemented as a comparison of the actual daily energy consumption profile with a reference profile. This reference consumption can be determined in several ways, each leading to a different type of monitoring application. There are two basic ways for establishing the reference behavior [3].

The reference behavior can be defined as the previous or current performance of similar plant, which can be seen as a kind of benchmark, and this assumption then leads to *energy benchmarking*. The comparison is usually made in terms of whole plant electricity consumption. This approach will provide only an approximate assessment of relative performance because it is constrained by the number of attributes, which are used to measure the similarity, e.g. floor area and geographical location. Usually, benchmarking is used only as a screening tool allowing a quick assessment of the plant performance.

Alternatively, the reference behavior can be defined as the previous (historically best) or ideal (theoretical) performance of given plant and this principle leads to *energy baselining*. This approach requires a suitable model of daily consumption profiles. The model is usually created based on analysis of historical data. Applications of various statistical regression techniques represent the most popular approach, which can be implemented in two different ways. The first scenario assumes that the baseline regression model is created just once by fitting the historical data from a selected period of time, e.g. from the commissioning. This static baseline is not further updated. In contrast to that, the second, more sophisticated, scenario assumes that the baseline model is continually adapted to new data to reflect the changes.

Efficient modeling of daily profiles is an important pre-condition for any advanced application. Reporting is another mandatory function of any monitoring program. Key Performance Indicators (KPIs) serve for simple summarization of system performance and are calculated and regularly updated based on the collected data. Typically used indicators in refrigeration industry include total energy consumption of the plant, total number of leaks, percentage of cabinets running without alarms, number of system alarms, etc.

4 Conclusion

Because the refrigeration system is one the largest electricity consumers in supermarkets, the expected value of performance monitoring and diagnostics is the reduced cost to operate, which results from reduced equipment downtime, reduced service costs and also reduced operating electricity costs.

The research in the area of commercial refrigeration is focused on monitoring and reporting system degradations related to particular parts or the whole refrigeration system as described in the article. Refrigeration system assessment should also include energy monitoring and monetization of performance degradation for easier evaluation of losses. The acquired benefits are obvious. Improving the energy efficiency is a great challenge today and the reduction of carbon emissions helps to create the “green” industry.

References:

[1] Braun, J., Automated fault Detection and Diagnostics for vapor Compression Cooling Equipment, *Journal of solar energy engineering*, Vol. 125, 2003, http://poet.lbl.gov/diagworkshop/proceedings/braun.pdf

[2] Carbon Thrust Projects, Food & Drink Industry Refrigeration Efficiency Initiative, *Guide 3 - Operational Efficiency Improvements for Refrigeration Systems*, 2007, http://www.ior.org.uk/ior_/images/pdf/general/REI-G3%20Operational%20Improvements%20-%20Final%20Jul-07.pdf

[3] YEE, G., WEBSTER, T., *Review of Advanced Applications in Energy, Management, Control, and Information Systems*, Lawrence Berkeley National Laboratory, 2004, http://repositories.cdlib.org/lbnl/LBNL-53546/

[4] Stluka, P., Trojanová J., Rojíček, J., Automated Monitoring of Building Energy System Operation and Performance, *Proceedings of the Process Control 2008 conference,* Kouty nad Desnou, 2008

[5] Whitman, B., Johnson, B., Tomczyk, J., Silberstein, E., *Refrigeration & Air Conditioning Technology*, 6th edition, Delmar Cengage Learning, 2009

[6] Collective of contributors, *ASHRAE Handbook - Refrigeration*, American Society of heating, refrigerating and Air-Conditioning Engineers, 2006

[7] Chiang, L.H., Russell, E.L., Braatz, R.D., *Fault Detection and Diagnosis in Industrial Systems,* Springer, 2001

[8] http://fgassupport.com/etraining

[9] http://www.iifiir.org