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Energy savings of refrigerators in shopping centers with adaptive control and real-time energy management systems

***Abstract**. Refrigeration systems are the largest energy consumers in shopping centers, offering great potential for energy saving. In the paper we analyze the savings gained with an adaptive control system and a real-time energy management system, used to control different parameters and individual procedures remotely by a trained person. The results of two experiments show savings around 14.5 % by using an adaptive control system and additional 7.8 % by using real-time energy management system.*

***Streszczenie.** W artykule przeanalizowano metody oszczędzania zużycia energii w systemach chłodzenia stosowanych w centrach handlowych. Zastosowano metody adaptacyjne i uzyskano oszczędność energii rzędu 15%). (**Oszczędność zużycia energii przez systemy chłodzenia stosowane w centrach handlowych**)*

Keywords: Refrigeration systems, Energy saving, Adaptive control system, Real-time EMS.
Słowa kluczowe: systemy chłodzenia, oszczędnośc enmrgii, systemy adaptacyjne.

1. Introduction

With the increased awareness of the limited energy sources and while coping with the consequently constantly growing electricity prices, great attention is being paid to electricity saving. For retail companies, energy is one of the important parts of the costs; therefore energy efficiency is their strategic goal. Reduced electricity consumption sometime contributes to the lower CO_2 emission.

Compared to residential buildings, shopping centers are specific buildings consuming large amount of electricity. As established in [1], as much as 3% of the total electricity supplied in Sweden is used by shopping centers. The reason why shopping centers consume more electricity than residential buildings is mainly the use of large refrigeration systems which are huge electricity consumers [2]. Besides, shopping centers need to maintain their environment pleasant and comfortable both for their customers and employees. To make this environment comfortable, they provide sufficient artificial lighting, temperature and ventilation. The research results from Sweden and Slovenia [3] presenting the electricity uses of individual consumers in shopping centers are shown in Fig. 1. The reasons for the differences in the shares of various electricity consumers in the above two examples might be the different types of commercial buildings, i.e. supermarkets in Sweden and shopping centers in Slovenia. Nonetheless the three biggest electricity consumers in both cases are the refrigeration, illumination, fan and climate control systems.

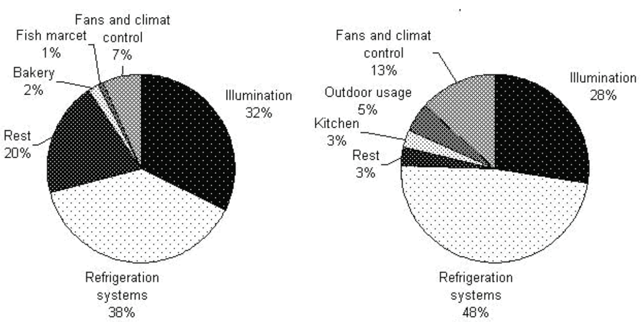

Fig. 1. Electricity use in shopping centers (left Slovenia, right Sweden)

As one can see, the area offering great potential for energy saving improvements in shopping centers is the refrigeration system. It is for this reason that some interesting researches have been done in past aiming of improving efficient use of energy in the refrigeration system. The approach in [1] shows that energy use can be reduced by utilizing heat recovery (or heat reclaim) from condensers for heating the premises. This option can be of course considered as interesting in relatively cold regions such as northern Europe, Canada, etc. An alternative to heat recovery is floating condensing pressure used to improve the performance coefficient and decrease the energy use of the refrigeration system at lower outdoor temperatures. Maintaining food temperatures below their critical values is the key to maximizing the high-quality display life of chilled foods. Another research [4] was based on computational fluid dynamic (CFD) modeling used for fast identification of the changes (i.e. food temperatures) in a multi-deck display cabinet. It was proven that by using CFD modeling the energy use in the refrigeration system was reduced. In approach [5] authors evaluate performance indices of a shopping center and propose new HVAC control principles by tuning the controller parameters by using the real-time Building Management System. Smart metering of energy consumption is also one of the approaches resulting in energy savings [6]. In approach [7] authors propose network-based energy management system for convenience stores using for analyzing energy consumption in air-conditioning, lighting, heating and refrigeration. The experimental results indicate that the proposed distributed energy management system suitably predicts the peak loading condition and successfully prevents its occurrence by switching the air-conditioning system without affecting the indoor temperature regulation.

The research presented in this paper has the goal to investigate possibilities for energy saving of the refrigeration system in shopping centers using modern automation and information technology. It consists of two parts. In the first part our focus was on adaptive control system enabling efficient energy use of the refrigeration system. The adaptive control system used in our experiment was of the ADAP-KOOL [8] type enabling floating condensing pressure and an additional energy-efficient control of the evaporator and compressor using functions described below. The experiment has been made at the Faculty of Mechanical Engineering in Ljubljana [9]. The practical experience using adaptive control system showed that different refrigerator parameters allowing energy efficient working of the refrigeration system vary in certain time period. They are quite often configured wrongly or have not been configured at all. The reason for that are often service interventions as well as management and controlling functions performance by a person lacking the necessary knowledge about the entire system. The second part of our research was based on these findings. In it we relied on the real-time energy management system (real-time EMS) enabling trained personal to remotely monitor and control the refrigeration system. The real-time EMS used in the experiment for improving the energy use of the refrigeration system was of the RETAILCARE [10] type.

2. The adaptive control system

Adaptive control is a nonlinear control strategy that varies the values of the controller parameters, depending on some criteria based upon the data collected from the previous movements, to achieve an optimal performance even when the changes in the plant are significant. A classification of the different adaptive schemes is detailed in [11], where four types are described: gain scheduling, which adjusts controller parameters on the basis of the operating conditions which change during the process; model-reference adaptive systems (MRAS) which compare the actual system output and the model output and modify the controller so that the error between them is small; self-tuning regulators (STR), which update the system parameters from the estimation process and obtain the controller constants from the solution of a design problem using the estimated parameters; and dual control schemes, where nonlinear stochastic control theory is used for achieving the abstract problem formulation [12].

The adaptive control system used in our research is presented in Fig. 2 and can be treated as gains scheduling type of adaptive control. It consists of two controllers, one for energy efficient control of compressor and condenser, and second for evaporator. By the specially designed controller, compressors and condensers are uninterruptedly controlled and operated at the energy-optimized pressure conditions. Both the suction pressure and the floating condensing pressure are controlled by signals from pressure transmitters [13]. The system also includes frequency converters enabling intelligent capacity control which is a "must" in any energy efficient operation of refrigeration system [14].

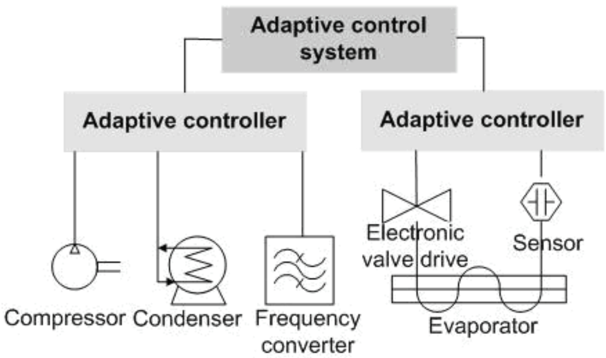

Fig. 2. Adaptive control system

A controller specific functions enable us adaptation of defrost cycles numbers in order to avoid using unnecessary defrost heat. All the controllers are based on a Lon Works [15] communication standard and can be monitored and controlled remotely by a PC [16]. The controllers in building automation industry can be also based on other network communication standards (i.e., Konnex [17], BACnet [18], Profibus [19], etc.) where different physical medium and application level protocols are used [20]. Our study is based on the LonWorks standard which is the most advanced in our opinion because of its flexibility and advanced services and is most commonly used in USA.

2.1. The adaptive control system

Our experiment was carried out on two different refrigeration systems in two different shopping centers, one with and the other without adaptive control system. The shopping centers are located in Slovenj Gradec and Novo mesto both in Slovenia. Intention was to compare running energy efficiency of these two refrigeration systems with regard to their specific electric load, i.e. the ratio between the actual electric load of refrigeration aggregates and the cooling power of refrigeration system.

2.1.1. Parameters definition

Our experiment began by defining the parameters having the biggest impact on the cooling load. These parameters are: goods transport, indoor and outdoor temperature. Goods transport includes all the logistics steps over the cooling chain, from cold store to the display case. As for the reason of different locations of goods along the cooling chain their temperatures and quantities vary as the amount of energy used by the refrigeration system. Therefore we investigated their impact on the electric load. Because of the indoor and outdoor temperature impact on the energy use in shopping centers, we studied them as well.

2.1.2. Parameters and electric load measurements

After defining the most impacting parameters, we implemented a system presented in Fig. 3. It enabled us to measure the electric load and the impact of the parameters on the electric load of the refrigeration system. The system consists of check lists and a computer measurement system. Check lists are used to record the quantity, temperature, location of goods in the cooling chain as well as temperature states in cold rooms and display cases.

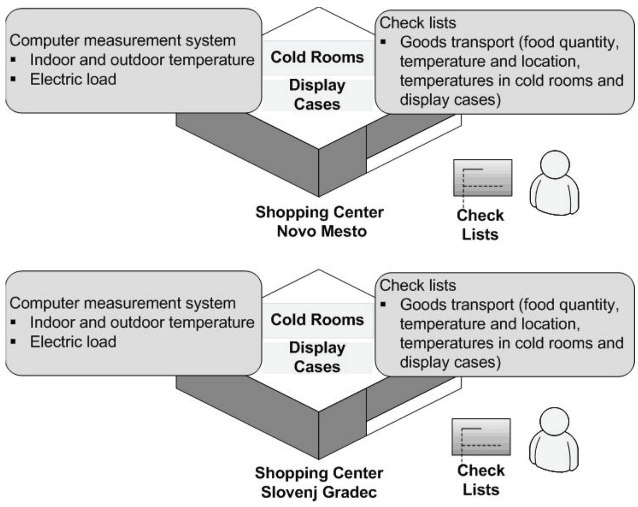

Fig. 3. Parameters and electric load measurements

With the computer we measured the indoor and outdoor temperatures and electric load of the refrigeration system. The indoor and outdoor temperatures and electric loads were measured by using temperature sensors of the Pt1000 type and electric load meters. They are both equipped with a communication unit and connected to the computer measurement system.

2.2. Experimental results

2.2.1. Goods transport, in– and outdoor temperatures

Using the data from the check lists we defined the impact of goods transport on the electric load of the refrigeration system. From the results analysis summarized in Figure 4 we can see that the impact of the goods transport on the temperatures and consequently on the electric load of the refrigeration system is very low. Variations in temperatures are very small when the goods are taken in or out of cold rooms or display cases and so are also variations in the energy use. The reason for that is in the high level of efficiency of goods transportation from the vehicle to cold rooms and further to display cases. The picks in Fig. 4 are caused by the defrost cycle whose impact on the energy use is considerable thus necessitating an advanced control system. Analysis of the results obtained with our computer measurement showed that indoor temperatures were constantly ranging between 18°C and 22°C. We can consequently conclude that the impact of the indoor temperature on the electric load of the refrigeration system is not considerable. The impact of the outdoor temperatures on the electric load of the refrigeration system obtained from the results is more important and is presented in the next paragraph.

The electric load of refrigeration system depends on the working hours of the shopping centers, mostly because of closed refrigerator shutters during the non-working hours. This is why we analyzed measurement results of both the open and closed shopping center independent. We have noted that the average monthly value and standard deviation of the electric load of an individual refrigeration system strongly depend on the time period. We therefore focused on the results obtained for July, November and December, the months with quite different outdoor temperatures. Approximation functions made on the basis of calculated values are presented in Fig. 5. They present dependence of the electric load of individual refrigeration systems from the outdoor temperatures for the open and closed shopping center.

2.3. Energy improvements achieved by adaptive control system

In accordance with approximation functions shown in Fig. 5 we defined the specific electric loads for the two shopping centers, i.e. the ratio between the actual electric load of refrigeration aggregates and the cooling power of refrigeration system. We then have calculated the average electric load as a function of the average annual outdoor temperature which is 7.7°C in Novo mesto and 9.4°C in Slovenj Gradec. Based on these values, the specific electric load of the refrigeration system with using the adaptive control system is 14.5 $\pm$ 3.5 % lower than the one without using the adaptive control system. That is in absolute values 7.0 kW during working time and 5.7 kW during closed time of the shopping center. If we take into consideration that the yearly working and closed time is 4380 h for each one, the yearly energy saving are 30835 kWh during working time and 24996 kWh during closed time, together 55831 kWh.

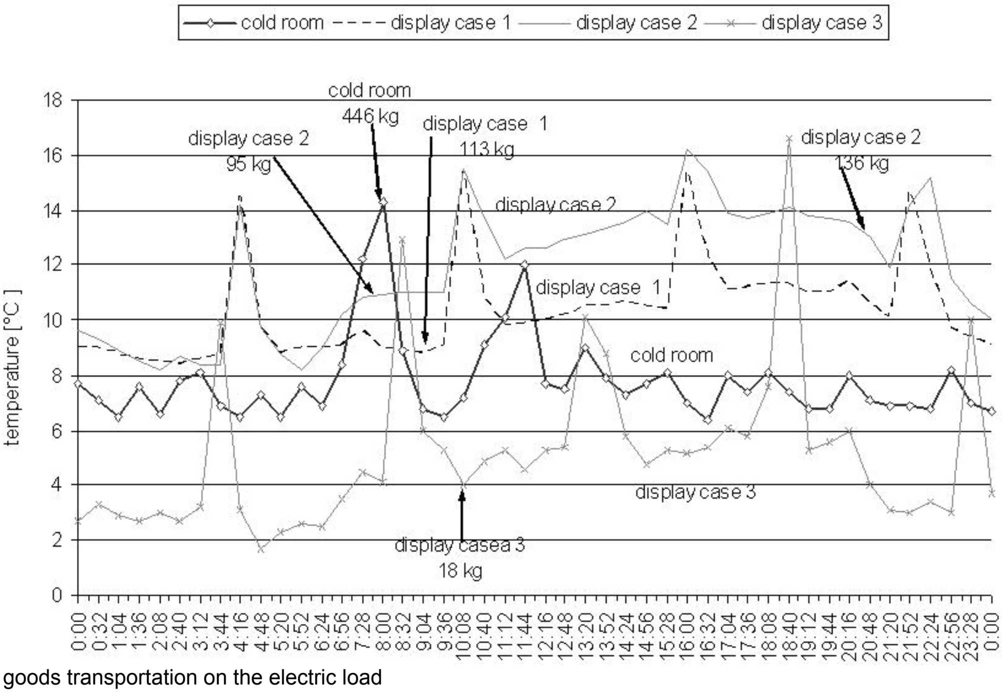

Fig. 4. Impact of goods transportation on the electric load

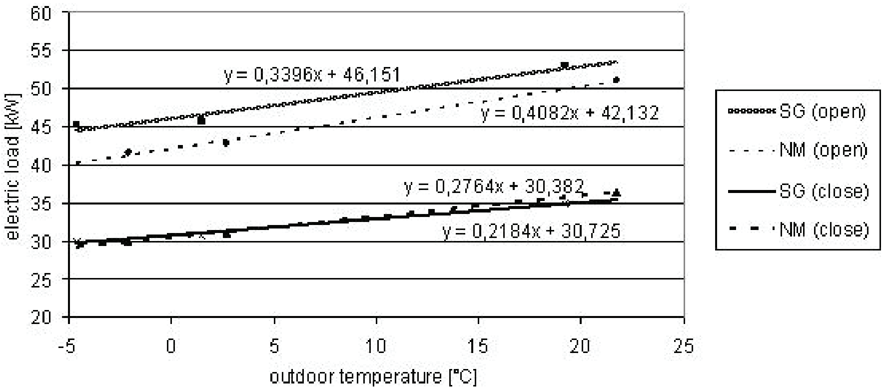

Fig. 5: Approximation functions presenting the relationship between the electric load and outdoor temperatures

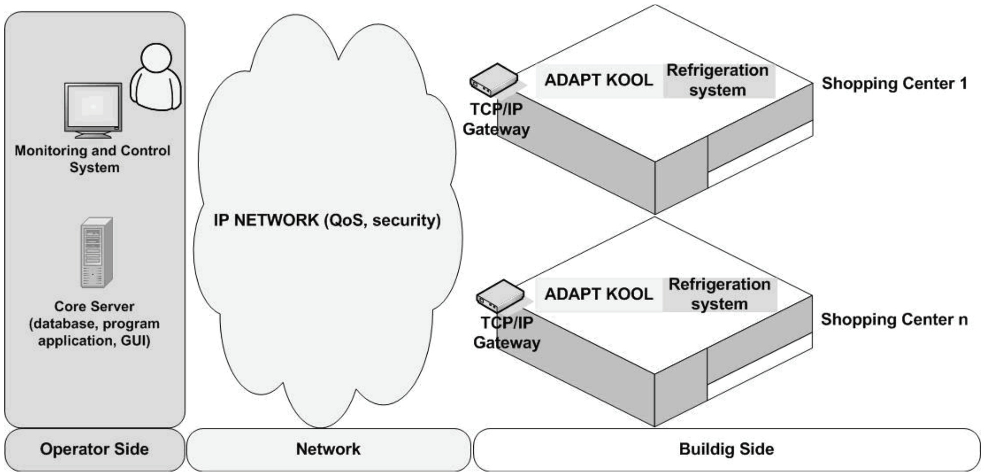

Fig. 6: The architecture of real-time EMS

3. Real-time EMS

The real-time EMS operated by trained personal enables interalia any refrigeration system to be remote controlled, monitored and managed. Its architecture is presented in Fig. 6 and is divided on building side, network and operator side. The real-time EMS consists of the adaptive control system upgraded by the operator enabling monitoring and control of refrigeration systems. Trained personal thus provides better costumer services such as energy management, alarm handling, maintenance management and food quality management. As our concern this time is energy management services, we shall deal with them alone.

The building side shown in Fig. 6 includes the refrigeration system, adaptive control system and TCP/IP gateway. The letter acts as an interface between the adaptive control system communication protocol and the TCP/IP protocol stack enabling a two-way communication with the Core server using the HTTP protocol. Network assures connection of the building side and the operator side using the IP network. On the operator side, there is the equipment needed to perform remote services such as the Core server and Monitoring and Control system. The Core server includes a web server and database. The function of the former is to serve the graphical user interface using the Flash [21] technology and to enable an interface for the database access. The Monitoring and Control system works as a client and includes a number of monitors to present the data about all the refrigeration systems in an appropriate way.

3.1. Experimental procedure

The experiment was carried out on a refrigeration system located in the shopping center in Kranj in Slovenia. The system consists of several different refrigerators enabling the inside temperature to be kept below (minus-mode refrigerators) and above (plus-mode refrigerators) the freezing point. Our goal was to show energy improvements of the refrigeration system achieved by using the real-time EMS by means of which all the parameters included in the adaptive control systems of the refrigeration system were monitored and controlled.

3.1.1. Parameters definition

At the beginning of our experiment we defined the parameter of the adaptive control system in order to reduce the electric load of the refrigeration system in case of real-time monitoring and control. This parameter is the temperature night-mode which increases the temperature value in the plus-mode refrigerators during the time the shopping center is closed. In this mode the refrigeration system still operates in compliance with HACCP standard; the food temperature remains unchanged although the temperature sensor shows a higher temperature. This can happen because of the process on the plus-mode refrigerators whose shutters get closed during the time the shopping center is closed and because of the temperature sensor is positioned near the open area of each plus-mode refrigerator. Regard to the results from first experiment we also observe the indoor and outdoor temperatures for the whole time-period of the experiment.

3.1.2. Parameters and electric load measurements

Upon defining the impacting parameters, we measured the electric load of the refrigeration system and the impact of the parameters on it. With our real-time EMS we conducted all requested measurements in real-time so no additional measurement system have been needed. We installed electric load meters and temperature sensors and connected them to the inputs on the adaptive control system thus enabling connection with the real-time EMS. To define the impact of the temperature night-mode parameter, we measured its value for the period of one week as foreseen by the refrigeration system configuration. We then changed its value to increase the temperature in the plus-mode refrigerators during the time the shopping center was closed. The electric load of the refrigeration system was measured in both cases.

3.2. Experimental results

From the measurement of the temperature night-mode parameter before changing for the time period of one week we noted that the parameter was not uninterruptedly used since the temperature in the refrigeration system during the night was unchanged and consequently there was no energy saved. Results obtained after changing of temperature night-mode parameter showed an increase in the temperature in the plus-mode refrigerators by 2°C during the time the shopping center was closed (from 9 p.m. to 7 a.m.). The values obtained for both cases are presented in Fig. 7.

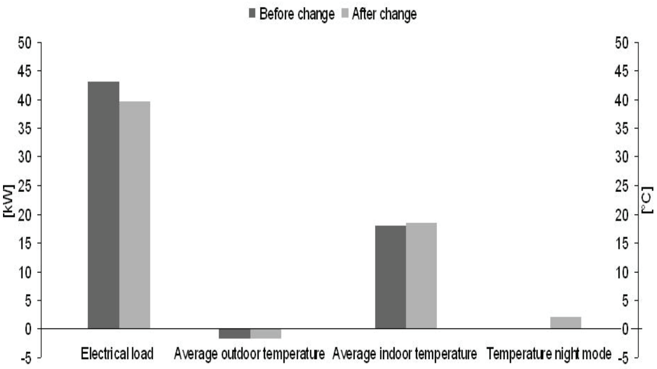

Fig. 7: Calculated values from the experiment

Based on results of our indoor and outdoor temperature measurements we calculated the average weekly temperatures for the week before and after changing the temperature night-mode parameter shown in Fig. 7. We can see that the differences in average weekly temperatures are minimal thus the comparison between electric loads is possible. On the basis of results of the electric load measurements of the refrigeration system we calculated the average weekly values and standard deviation of the electric load for the week before and after changing the parameter.

3.3. Energy improvements using the real-time EMS

From Figure 7 it is cleared that the average weekly electric load of the plus-mode refrigerators before changing the parameter is 43.1 kW and after it 39.8 kW this being a 7.8% decrease in the energy use. As the average indoor and outdoor temperatures on Figure 7 are similar, the cause for the decrease in the energy use is the night-mode parameter. This means that the absolute values difference is 3.4 kW. Knowing that the shopping center is closed for 76 hours a week, the decrease in electricity use on a weekly basis is 254.6 kWh. That is 13239.2 kWh yearly if we do not consider higher energy use in the time period of higher outdoor temperatures when the energy savings could be even higher.

4. Conclusion

According to the research, the highest potential of electricity savings in shopping center is achieved by using both, the adaptive control and the real-time EMS. The former enables an energy efficient control of refrigeration system. From the experiment we can conclude that the specific electric load of the refrigeration system with using the adaptive control system is 14.5 $\pm$ 3.5 % lower than the one without using the adaptive control system. But the practical experience using this system showed that different parameters allowing for energy efficient working of the refrigeration system vary or are not configured in certain time period. Therefore we used real-time EMS enabling remote monitoring and control of refrigeration systems by an adequately trained person thus providing better energy management services. In the experiment we showed that 7.78% decrease in the electricity consumption can be achieved by real-time monitoring and control of the temperature night-mode parameter. An average electricity saving of ~20–25% from both actions is achieved. In the experiment we were focused only on one parameter by which we proved electricity savings. Considering that the refrigeration system includes many parameters enabling its operation, another savings could be achieved using real-time EMS thus allows a perfect platform for further research and development resulting in energy efficient operation of refrigeration system.

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