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IMPROVING THE EXPLOITATION EFFICIENCY OF COOLING EQUIPMENT BY MONITORING OPERATIONAL PARAMETER

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Abstract

Cooling equipment is widely used in industry, commerce and households. Due to their widespread use, they are responsible for the consumption of a significant amount of electricity. They are subject to degradation and various types of damage. Most often, their energy efficiency decreases and electricity consumption increases. Practice shows that even a specialist service is unable to diagnose damage at an early stage of its development. The paper presents a comparison of continuous monitoring of the temperature of the cooling chamber as a utility standard, with constant monitoring of the temperature of the cooling chamber and electricity consumption of a professional refrigeration cabinet with a built-in condensing unit. The comparative analysis was intended to confirm the thesis about unconscious waste resulting from assessing the correct operation of the device based on limited information. The experiment showed an increase in daily electricity consumption on average by over 30% during the period of unconscious exploitation of the device in a state of failure and an increase in daily electricity consumption on average above 300% during the period of conscious exploitation of the device in a state of failure, but still at an acceptable level of temperature of cooling chamber.

Keywords: refrigeration machines, fault detection, diagnostic model, energy efficiency

1. INTRODUCTION

Over the last decade, many legal and economic factors have influenced manufacturers of energy-related products to seek and conduct research towards energy savings. In the European Union, the main impact on these activities was Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009, establishing general principles for establishing ecodesign requirements for energy-related products[12], commonly known as ecodesign. In the initial phase, ecodesign concerned mainly household products and was certainly successful in mobilizing the manufacturing industry from R&D activities in this area. In 2021, ecodesign, through the directives introducing it [13][14], also started deep changes on the market of industrial energy-related devices, including professional refrigeration devices for the display and direct sale of food products. Customer for such refrigeration products received a new opportunity to evaluate these industrial products, i.e. the energy efficiency label. On the other hand, manufacturers faced a new challenge of searching for innovative solutions as part of their competitiveness.

A number of efforts in the field of new optimization analysis of the product was initiated in terms of:

- construction[1], especially insulating materials [2], which significantly improve energy efficiency not only of the refrigeration devices themselves but also of the refrigeration installations,
- refrigerants whose impact on the natural environment and efficiency in the overall heat balance are of key importance[3][4],
- components such as: compressors, expansion valves, evaporator fans, condenser fans, the proper, optimal selection of which increases the economy of the refrigeration unit[5],
- control systems and control algorithms[6][7], and other research and development works aimed at reducing electricity consumption.

The scope of energy optimization described above is vividly presented by a case study of the reduction of electricity consumption and R&D work in 2019-2023 on the LMI INSU1.2 scoop ice cream dispenser, with a twelve-flavor display of scoop ice cream [17][8].

The innovative design while keeping the same product storage space allowed for reducing electricity consumption by >50% (as of 2019) compared to the conventional LML LIMOSA1.2 [9] ice cream dispenser. In the next stage, replacing the synthetic refrigerant with a natural, ecological refrigerant R290 (Propane), reduced electricity consumption by an additional >10%. The

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development and wider availability of variable capacity compressors allowed for the introduction of another modification, which turned out to be even more energy efficient than the previous INSU version by over >20%. Modifications whose pre-premiere demonstration took place at the EUROSHOP 2023[10] trade fair, consisted of optimizing the refrigeration system and using intelligent control, as well as introducing design changes involving the use of insulating glass units with increased insulation, which allowed for further savings in electricity consumption.

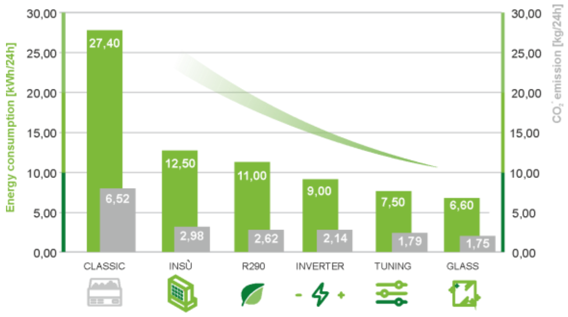

Fig. 1. Stages of optimization of an ice cream dispenser in the period: 2019 - 2023

This continuous improvement of the product from the manufacturer's point of view is intended to encourage not only a new customer to choose this brand or product, but also to encourage the consumer who already has this type of device to replace it with a new one in order to protect the environment, through safe utilization of the synthetic refrigerant, reducing electricity consumption and therefore reducing greenhouse gas emission, presents Fig. 1. Such a large difference in electricity consumption between a classic dispenser and the described innovative INSU ice cream dispenser allows for a quick return on investment from savings resulting from the difference in electricity consumption costs.

There is a fundamental question about what guarantee does the consumer receive? Is the level of electricity consumption declared by the manufacturer not a marketing trick but a fact? The legislator, with the introduction of the previously mentioned directive [12], which not only obliges the manufacturer to label the product with an energy label but also to make an entry in the public EPREL [16] database – the European register of products for energy labeling purposes - which allows not only to verify the information received from the manufacturer about the product, but also to potentially report a violation of the law on unfair competition and misleading the consumer. The consumer has the right to assess his doubts by entering to the EPREL [16] database for a specific product used, and the manufacturer must address these doubts.

However, in order to reliably verify whether the device is working or its energy classification is consistent with the data included on the energy label, the consumer must reproduce the process, research and classification method in accordance with the legislator's regulation [12].

It is not enough to connect the device to the energy meter and check the electricity consumption within 24 hours, multiply the result by the number of days in the year and, when the result is greater than the value indicated on the label in the kWh/annum, raise an objection. The research process itself, during which the normative electricity consumption is determined, is carried out in accordance with the PN-EN ISO 23953-2 [15] standard and can only be performed in stabilized laboratory climatic conditions. Additionally, the refrigeration device under test should be properly stocked and measured. During the test it should be working under the operational load in accordance with the standard, so that the result can be comparable and reproducible. Only then it can be the basis for any complaints submitted by the consumer. Such a standard test method, the same for all manufacturers, is difficult to verify from the consumer's point of view. In most cases, if the sale of refrigeration equipment concerns a large project, e.g. to a large food retail establishment, the investor expects from the manufacturer an additional declaration of electricity consumption in the specific conditions where the refrigeration equipment will be operated and, on this basis, selects the most advantageous offer by way of a tender and this specific declaration may be the basis for a possible complaint.

It can be safely said that electricity consumption is important from the consumer's point of view at the selection and decision-making stage, but already during operation, even due to the complicated verification, it is not as important as the functionality of the refrigeration device itself, and the other operational parameters, e.g. stability temperature of the refrigerating space, refrigerating chamber, so that the exposed, stored goods are not degraded or damaged, and the consumer does not incur losses in the goods.

Analyzing the R&D works carried out by manufacturer in terms of reducing electricity consumption, it can be noticed that they do not result directly from the expectations of consumers, but mainly from the regulations imposed by the legislator and competitiveness on the market, where the energy class is also a tender element. If manufacturers of refrigeration equipment did not compete with each other in terms of energy optimization, at least due to the costs of R&D activities, and stopped at a certain level, the consumer would accept this level as the norm.

So isn't electricity consumption over the lifespan important? It is important and results not only from the economic and ecological aspects, but also from the obligation of new regulations and a new type of reporting, such as: non-financial ESG reporting (Environment, Social responsibility, corporate Governance), which is not only another obligation for companies, but the data included the report will be the basis for assessing how a given company rationally uses resources in the broad sense of the word.

So, is there a method for the consumer to verify the correct consumption of electricity under the conditions of use? Such a method exists and it is possible to roughly estimate whether the declared average annual value of electricity consumption is not exceeded by the refrigeration device in use.

2. DESCRIPTION OF THE METHOD

In order to be able to roughly but correctly estimate whether the actual level of electricity consumption of the refrigeration device in use does not exceed the value declared by the manufacturer, we should:

- firstly, make sure that the device is working properly, the device's control module does not generate any errors, the temperature of the products displayed in it is correct, i.e. consistent with the declared temperature class, and the room in which it works is properly air-conditioned,
- secondly, connect the device to the power supply via an electricity meter and, under normal operating conditions and during night operation, i.e. within one 24-hour period, measure the electricity consumption expressed in kWh.

We multiply such a rough measurement of 24-hour electricity consumption by the number of days in a year and compare the obtained value of annual electricity consumption to the value of annual electricity consumption included in the energy label supplied with the refrigeration device by the manufacturer or according to the data available in EPREL [16] database for this device.

The lower value of the measured annual electricity consumption than the value shown on the energy label allows us to conclude that we are using the device correctly and in accordance with its intended purpose.

The energy label therefore becomes a standard reference point for assessing correct operation, but it does not give us 100% certainty that the electricity consumption is correct, because the test was approximate and the manufacturer, when providing the value of annual electricity consumption, refers it to specific laboratory test conditions in accordance with the standard harmonized [15].

Exceeding the value of the measured annual electricity consumption above the value shown on the energy label should raise doubts, but if it does not significantly exceed it, it also does not guarantee that the measured value indicates incorrect operation of the device and our "rough research environment" and 24-hour test in do not differ significantly from the method and measurement conditions of refrigerating furniture described in the harmonized standard.

Rough measurement, as its name suggests, allows us to roughly assess the correct operation of a refrigeration device, so there is a second important problem. Does it make sense to simply observe the temperature of the products exposed in the device?

These doubts were the basis for conducting a study in the form of an experiment to clearly answer the question whether monitoring electricity consumption and temperature in relation to monitoring only temperature as operating parameters of a professional refrigeration device can bring benefits to the consumer in the form of reducing unconscious waste of electricity.

3. CASE STUDY

The subject of the experiment were two identical in terms of design professional refrigeration devices (PUCh1, PUCh2) with a built-in condensing unit with a very similar exploitation load. According to the energy label, the declared daily electricity consumption was: 3.2 kWh/24h.

The exploitation of the experimental items took place in Italy, near Milan, in outdoor conditions.

The cooling devices worked outside the convenience store, directly at its main entrance. It can therefore be assumed that the ambient conditions were similar to atmospheric conditions and were equally variable seasonally, presents Fig. 2.

Additionally, the autumn and winter period was chosen to perform the experiment due to low temperatures, when the thermal load is lower and sometimes even supports the reduction of electricity consumption. On the other hand, it makes even more difficult to recognize a failure based on electricity consumption.

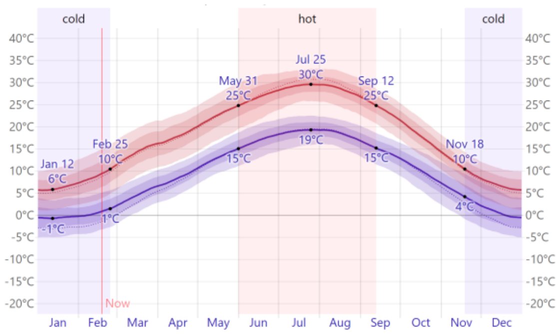

Fig. 2. Average minimum and maximum temperature in Milan [11]

The staff was informed that it is not required, and should not be used, any other procedure for use, maintenance and monitoring of proper operation than the standard one, i.e. based on temperature control of the cooling chamber.

Both devices have been equipped with advanced control with a remote monitoring and data acquisition system along with measuring electricity consumption. Monitored data was sent via the Internet and registered on a remote server in a database.

The devices were equipped with a control thermostat acting as a closed two-state regulator system with static, asymmetric characteristics and hysteresis, where the control signal turned on or turned off the power supply to the compressor condensing unit as the control object, presents Fig. 3.

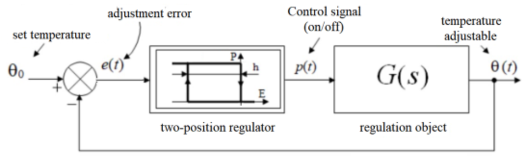

Fig. 3. Schematic of a closed two-state controller

The basic controller settings were as follows:

- set temperature: +2 °C;
- hysteresis: 2;
- low temperature alarm threshold: -2 °C;
- high temperature alarm threshold: +8 °C.

The experiment was assumed to last no longer than 12 months or until the first conscious failure occurred. A conscious failure is defined as exceeding at least one measured quantity: regulated temperature, electricity consumption above the alarm thresholds:

- low temperature alarm: -2 °C;
- high temperature alarm: +8 °C;
- daily electricity consumption: 3.2 kWh.

The period in which the device was found to be operating incorrectly despite the lack of conscious failure was called unconscious operation.

During the experiment period, each of the PUCh1 and PUCh2 devices was analyzed both as test devices and as reference devices against each other.

The experiment started on September 1 and lasted until January 31, presents Fig. 4.

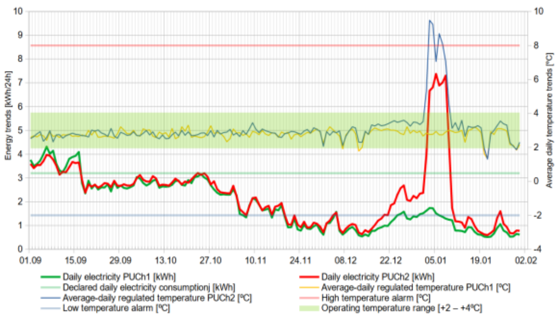

Fig. 4. Graphical presentation of the experiment

During the experiment period, correct operation of the PUCh1 and PUCh2 devices, unconscious operation and conscious failures were observed.

Analysis of the record of the regulated temperature – presents on Fig. 5 – of the PUCh1 device showed that throughout the entire experiment period 01.09 – 31.01, the regulated temperature remained within the operating temperature range +2ºC – +4ºC with single incidents of exceedances below the operating range by a value of no more than 0.5 ºC.

On this basis, the period 01.09 – 31.01 was included in the correct operation of the PUCh1 device.

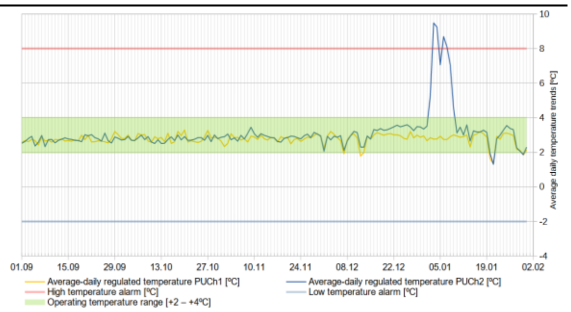

Fig. 5. Graphical presentation of the record of regulated temperatures

The analysis of the regulated temperature record – presents on Fig. 5 – of the PUCh2 device showed that during the period 02.01 – 09.01, the recorded temperature was regulated above the operating temperature range. On four days (03.01, 04.01, 06.01, 07.01) of this period, the electronic thermostat signaled a high temperature alarm and the maximum of the regulated temperature exceeded the alarm threshold of 8 ºC.

During the remaining period of the experiment, i.e. 01.09 – 01.01 and 09.01 – 31.01, the regulated temperature PUCh2 remained within the operating temperature range with single incidents of exceedances below the operating range by a value of no more than 0.5 ºC.

On this basis, days 03.01, 04.01, 06.01, 07.01 was classified as a conscious failure of the PUCh2 device, and the remaining period was considered as a period of proper operation.

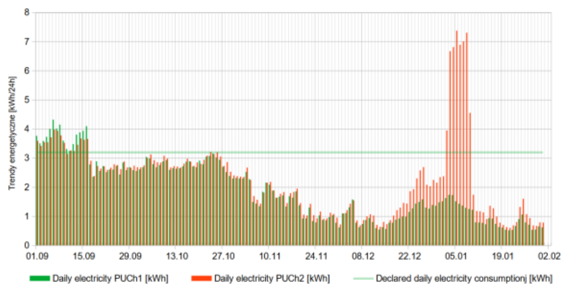

Fig. 6. Graphical representation of electricity consumption

Analysis of the electricity consumption – presents on Fig. 6 – record of the PUCh1 device showed that in the period 01.09 – 16.09 inclusive, the device daily consumed electricity above the 3.2 kWh/24h limit, as declared by the manufacturer.

Apart from this period, in the remaining part of the experiment 16.09 – 31.01, the daily electricity consumption of the PUCh1 device was lower than the daily electricity consumption declared by the manufacturer.

On this basis, the period 01.09 – 16.09 was included as a conscious failure of the PUCh1 device and the remaining period as a period of proper operation.

The analysis of the electricity consumption – presents on Fig. 6 – record of the PUCh2 device showed that in the period 01.09 – 16.09 inclusive and in the period 02.01 – 09.01 inclusive, it consumed electricity above the 3.2 kWh/24h limit.

On this basis, the periods 01.09 – 16.09 and 02.01 – 09.01 of operation of the PUCh2 device can be classified as conscious failure and the remaining period as correct operation.

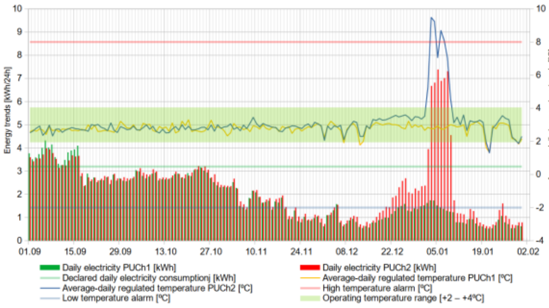

Fig. 7. Graphical presentation of the record of regulated temperatures and electricity consumption

Analyzing the data in parallel the temperature and electricity consumption – presents on Fig. 7 – records, included the period 01.09 – 16.09 as a conscious failure of the PUCh1 and PUCh2 devices, because the electricity consumption exceeded the value declared by the manufacturer, even though the regulated temperature was within the operating range.

The period 02.01 – 09.01 was also a conscious failure of the PUCh2 device, because both the regulated temperature and electricity consumption exceeded the alarm thresholds. It worth noting that the PUCh1 device worked properly in this period.

The last analysis was a comparative analysis aimed at confirming the thesis that it is possible to detect unconscious waste of electricity based on the analysis of only the sewing of electricity.

For this purpose, Author proposed the parameter of the unconscious waste indicator UWI (Unconscious Waste Indicator). It refers to the electricity consumption of the professional refrigeration device under test ($ZEEPUCh_{tested}$) in relation to the electricity consumption of the reference device ($ZEEPUCh_{reference}$). The indicator was defined as:

$$UWI\,12 = \frac{ZEEPUCh1_{tested} - ZEEPUCh2_{reference}}{ZEEPUCh2_{reference}} * 100\,\%$$

for the PUCh1 device as the tested one and the PUCh2 device as the reference device,

$$UWI\,21 = \frac{ZEEPUCh2_{tested} - ZEEPUCh1_{reference}}{ZEEPUCh1_{R\,ference}} * 100\,\%$$

for the PUCh2 device as the tested device and the PUCh1 device as the reference device.

Analyzing the data, calculated in this way – present on Fig. 8 – and assuming ±10% level of indicator insensitivity, it can be concluded that the PUCh1 device recorded a negative value of the UWI12 indicator throughout the entire experiment period, which means that the PUCh1 device showed electricity savings compared to the PUCh2 device.

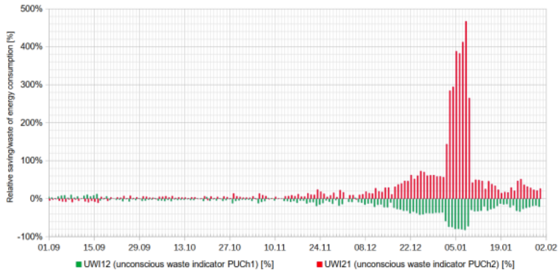

Fig. 8. Graphical representation of the energy index of unconscious waste

The PUCh2 device recorded a positive value of the UWI21 index throughout the entire experiment period, which means that the PUCh2 device wasted electricity compared to the PUCh1 device.

During the period of conscious failure 01.09 – 16.09 detected in the analysis of electricity consumption, the UWI12 and UWI21 indicators showed no activity in both PUCh1 and PUCh2, which may indicate the proper operation of both devices, and exceedances in electricity consumption indicate the operation of these devices with a higher operational load, e.g. caused by higher ambient temperature.

During the period of conscious failure 02.01 – 09.01, the UWI21 indicator showed excessive energy usage of the PUCh2 device. The usage was on average 300% higher, compared to the PUCh1 device.

The UWI12 and UWI21 indicators detected anomalies in the period 23.11 – 02.01, when previous analyzes did not detect any irregularities. This period was marked as unconscious exploitation. On 23.11, the UWI21 indicator registered a 20% excess of electricity consumption of PUCh2 compared to PUCh1. From 07.12, a constant upward trend of the UWI21 index was observed, which on 22.12 reached the level of 60% and lasted until 02.01 of the conscious failure, which means that PUCh2 consumed on average >40% more electricity compared to the consumption of PUCh1 in the period 7.12 – 02.01.

In the period after the theoretical removal of the failure by the service technician, i.e. in the period from 09.01 to 31.01 (the end of the experiment), the UWI21 indicator still remained at an average level of >30% increased electricity consumption of PUCh2 compared to PUCh1, which may indicate an incorrect diagnosis and failure to repair PUCh2 device.

4. CONCLUSIONS

The analysis showed that there is an area for improving the efficiency of the operation of industrial refrigeration equipment in terms of saving electricity consumption by monitoring its consumption. The experiment demonstrated the possibility of detecting unconscious exploitation already at the initial stage.

It has been additionally shown that:

- seemingly low electricity consumption below the average value of daily electricity consumption and the correct value of the temperature regulated in the refrigeration device does not always indicate its correct operation,
- exceeding electricity consumption does not always mean an emergency condition but may indicate increased operational load,
- removal of the fault, even by a specialist service, does not always mean that the refrigeration device is fully operational,
- there is a large potential for reducing electricity consumption only by detecting unconscious energy waste through appropriate monitoring.

The proposed UWI indicator, despite such a spectacular level of detecting unconscious waste, will not replace a full analysis of the data generated by the refrigeration device, which can provide an answer not only about the failure status of the device but also about the cause and how to remove it, which will ensure full effectiveness of the failure removal.

In order for the proposed methods to be introduced into Maintenance practice, it is necessary to develop a modern condition monitoring system according to the proposed/used architecture as part of the experiment, equipped with automatic methods for detecting malfunctions and damages.

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