EXPERIMENTAL OPTIMIZATION OF ENERGY CONSUMPTION FOR DIRECT CURRENT REFRIGERATOR BY PID CONTROLLER TUNING AND COMPARISON WITH ON/OFF REFRIGERATOR

by

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In this research the optimization of energy consumption for DC refrigerator used in commercial cold store was conducted. To achieve this object a test facility was installed into the introduction room of a national refrigeration company. Due to the imperfect data given by the producer, the proportional-integral-derivative controller of DC refrigerator had to be tuned by setting the correct proportional, integral and derivative parameter values to achieve optimal energetic operation. During the research the energy consumption of this system was compared with a very commonly used traditional refrigerator system on the home market operated by reciprocating compressor, mechanical expansion valve and on/off controller technic in the similar cooling capacity range. The combined effects of electronic expansion valve, scroll compressor operation and the correct experimental settings of proportional-integral-derivative controller in DC refrigerator results around 62.4% energy saving opposed to the traditional on/off controlled appliance under the same operational conditions in the same cold store.

Key words: *commercial refrigeration, cold store, energy consumption, variable speed DC compressor, experiment, proportional-integral-derivative control*

Introduction

Reduction in the energy consumption of refrigeration systems is crucial topic of the industry. The energy consumption is significant influenced by the type of the compressor, the control techniques of compressor, expansion valve and refrigerant [1-3]. In the study conducted by Ekren [4], performance of the variable speed operation and constant speed operation during ON and on/off mode of the same DC compressor has been compared. The comparisons are realized in terms of cooling capacity, $COP/COP_{\mathrm{Carnot}}$, and exergy efficiency. According to the analysis, variable speed operation of the DC compressor provides higher *COP* (0.380) and exergy efficiency (7.4%) than the constant speed operation at 2500 rpm, 3000 rpm, and 3500 rpm. This is related to lower energy consumption at the same cooling capacity [5]. The most existing operating commercial and domestic air-to-air refrigeration sys-

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tems worldwide are mostly still based on traditional on/off controller systems resulting high energy consumption, poor temperature control and limited operational conditions [6]. It is a simple controller where the output from the device is either on or off. It is a type of control action in which the manipulated variable is changed to a max or min value, depending on whether the controlled variable is greater or less than. When the temperature is above the setting in the thermostat a switch is closed which turn on the compressor and air blowing fan causing indoor air temperature decrease in the chamber. When the temperature gets to the thermostat's setting, the switch is opened shutting off the compressor. Basically, the on/off controller in the refrigerator compares the real inner temperature with the desired temperature and feeds this error signal to the control input of the switch block of the controller. A proportional-integral-derivative (PID) controller is more appropriate to control the inner temperature of the refrigerator and thus gives the best performance for the response opposed to on/off controller. The controller takes a measured value from a process or other apparatus and compares it with a reference set point value, then intervention process is achieved in order to bring the process measured value back to its desired set point [7].

The input signal of the PID controller is described by equation 1 [8-10].

$$u(t) = K_\mathrm{p} e(t) + K_i \int_0^t e(t)\mathrm{d}t + K_\mathrm{d} \frac{\mathrm{d}e(t)}{\mathrm{d}t} \tag{1}$$

The PID controller makes rapid and precise control possible. This is also true in reality, provided that the system is correctly defined, taking disturbances into consideration accurately. These are the conditions for the proper definition of constants based on the use of the appliance. If these are realized, a properly operating system is established, which is capable of correcting the error on the basis of its past development and its predictable degree. This is why PID control is widely spread these days, especially their application in HVAC systems [8-11].

In practice there are several ways of tuning a PID controller. In the study conducted by Raut and Vaishnav [12] total six PID tuning techniques were implemented and their performances analyzed. The results showed that the largest peak overshoot and settling time is achieved with Amigo tuning technique. Fine-tuned algorithm proved the smallest maximum overshoot and settling time. Among the six PID tuning techniques, the fine-tuned PID controller gives the best results. The Ziegler-Nichols [13] design method is the most popular and simplest methods used in process control to determine the parameters of a PID controller. Although these methods were presented in the 1940s, they are still widely used. The step response method is based on an open-loop step response test of the process [8]. Based on the research conducted by Beghi *et al.* [14] the PID parameters can be re-tuned also by online to better fit the operative conditions and improve further the overall closed-loop performance.

There are several other further advanced hard and soft control strategies for refrigeration systems, such as optimal, nonlinear, adaptive, and robust, neural networks, fuzzy logic, genetic algorithms and identification of the application of the technique fusion of hard and soft control has to be determined by the best features of hard and soft control techniques are captured [15-18].

In the close future, the use of developed controlled compressors will be also mandatory in industrial refrigeration technologies, as it happened in the case of air-conditioners in year 2013 by introduction of the ErP-Directive in the territory of the EU. This stipulates, that all air-conditioners with a cooling capacity lower, than 11 kW must apply inverter control, and 125 W power fans (a component of the appliance) need to be certified. Addressing this regulation, the producer of Sinclair has developed the already described, universal control unit, with the application of which their own refrigerator generators became controllable in terms of speed of rotation, but their product has been not tested in real cold store under real environmental operation conditions before and their PID controller is untuned.

The motivation for energetic comparison investigation, conducted in this research, is that cold stores operated by minor enterprises, primary producer have become more and more popular in our country, primarily used for some type of food industrial (meat, or fruit/vegetable) storage purposes. With government support these minor enterprises are also given the opportunity to purchase the cooling technology for up-to-date, low-consumption, high advanced cold stores. This could not only result in energy savings [19], but through the solution described in the automatic control section, a more stable air temperature of the chamber, consequently, a more stable conservation (preservation) of the consistence of goods stored within could be achieved. In this research the optimization of energy consumption for DC refrigerator used in commercial cold store was conducted including the significant elements as scroll compressor, electronic expansion valve and PID controller system. To achieve the object a test facility was installed into the introduction room of a national refrigeration company. The main part of the measuring system is cold store which includes internally two equal evaporators: one is operated with the DC inverter condensing units and the other is installed with a very commonly used traditional refrigerator system on the home market operated by reciprocating compressor, mechanical expansion valve and on/off controller technic. The PID controller used in the experimental investigation is manufactured specifically for the condensing unit produced by Sincalair manufacturer. Actually this controller can be used only for Sinclair products, but due to the imperfect data given by the producer it has to be tuned by setting the correct proportional, integral and derivative parameter values to achieve optimal energetic operation during every new installation. It is important to know that with the change of operating conditions, everything can be altered and it can be necessary to perform tuning again.

The novelty of this research is to show the significance of the proper adjustment of PID controller for the designed cooling conditions and its effect to the energy consumption of DC refrigerator. Even if the refrigerator is sized satisfactory and its cooling capacity meets the cooling demand, an un-tuned PID controller results higher energy consumption than a refrigerator utilized on/off control.

Set-up of the test facility

Survey measurements were taken in the show room of Kassai-Klima Ltd., a refrigeration-, and air-conditioning technology merchant and service provider company in Budapest. Basically two different refrigeration systems are installed into the same cold store. One of it is a very commonly used traditional refrigerator system on the home market operated by reciprocating compressor, mechanical expansion valve and on/off controller technic. The other one is a DC inverter refrigerator with electronic expansion valve, scroll compressor and PID controller. The performance of condensing units was selected to provide a similar cooling capacity range for the given size cooling chamber.

Structure of the cold store

The chamber was built by Gabler-Mirelta Hungarian Ltd. Properties of the wall structure of the chamber are summarized in tab. 1.

Table 1. Properties of the wall of the chamber

Size	1660 × 1660 × 2330 [mm]
Type and thickness of wall	NZ70-70 [mm]
Type of insulation	polyurethane foam
Overall heat transfer coefficient	0.27 W m^2/K

It must also be noted with respect to the cooling chamber, that it has a separate floor, which means that it is thermally insulated towards the ground. According to the developing company, the applied solution eliminates the heat bridge effect, so there is no point within the chamber, where heat can escape easily.

In the present case there is value difference between the inside air temperature (0 °C) of the chamber, and a constant 23 °C indoor air temperature around the chamber in the laboratory room. In the knowledge of this temperature difference, the overall heat transfer coefficient and the heat transfer area of the surface based on the chamber geometry, tab. 1, the amount of heat transfer from the chamber over the chamber structure to the laboratory room 130.3 W was calculated.

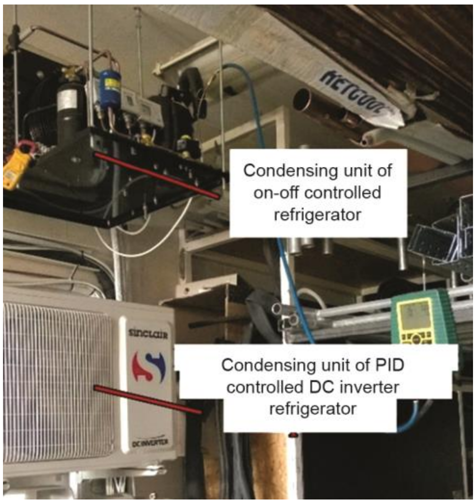

Figure 1. Set-up of the condenser side of the test facility

This way the structure, the dimensions and thermal loss of the chamber are known. For the purpose of accurate measurement, an on/off controlled and a PID controlled, refrigerator heat remover, which is the evaporator units of such with the same rated cooling capacity are placed inside the chamber.

Description of the condensing units

The condenser side of the measurement stand is shown in fig. 1.

The specifications of on/off controlled and PID controlled condensing units can be read in tabs. 2 and 3.

Table 2. Specifications of on/off controlled condensing unit

Type of the condensing unit	NJ9226GK
Refrigerant	R404A
Type of the compressor	Embraco reciprocating compressor
Rated voltage/frequency	230 V/50 Hz
Type of expansion device	Mechanical expansion valve
Cooling capacity	3708 W (1731-5881)

Table 3. Specifications of PID controlled condensing unit

Type of the condensing unit	Sinclair ASGE-09AIN WK
Refrigerant	R410A
Type of the compressor	Scroll compressor
Rated voltage/frequency	230 V/50 Hz
Type of expansion device	Electronic expansion valve
Cooling capacity	2700 W (800-3400)

Specifications of evaporators installed into the chamber

The position of evaporators is shown in fig. 2.
The specifications of both evaporators can be read in tab. 4.

Figure 2. The position of the evaporators in the chamber

Table 4. Specifications of evaporators

Type of the evaporator	Inter-Thermo IT-FM-25-1-017 A/5 E
Cooling capacity	1700 W ($t_{evaporate}$ = –10 °C)
Cooling surface	3.8 m^2
Air volume flow rate	820 m^3/h
Rated voltage/frequency	230 V/50 Hz
Power input	68 W

Description of the control systems

In terms of control, the on/off controlled refrigerator appliance is made up of an air temperature sensor, a control panel for the temperature setting, and an electronic unit to start/stop the system. The position of control units can be seen in fig. 3.

The Sinclair SCMI-01 type PID controller of the DC inverter refrigerator is more complicated. Besides the possibility of setting the inside air temperature of the chamber the constants relevant to the PID controller can also be set. Furthermore, it displays the actual speed of rotation (in percentage value) of the compressor, the temperature of the evaporator and the chamber, as well as the position of the expansion valve. The controller varies the rotation speed of the compressor and the position of electronic expansion valve (varying the cooling capacity, meeting the cooling demand) measuring the indoor air temperature of the chamber and comparing this value with the maintaining air temperature set on the controller continuously.

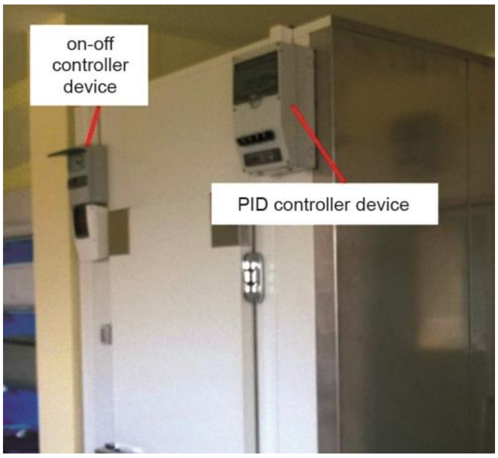

Figure 3. The position of the controllers

The PID controller is shown in fig. 4.

The specifications of electricity meter were used to monitor the energy consumption of both refrigeration systems can be read in tab. 5.

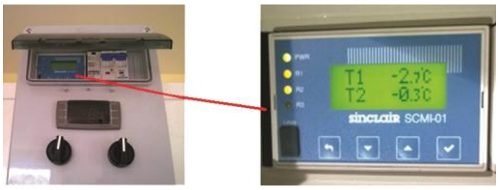

Figure 4. The PID control unit of the DC inverter refrigerator

Description of experimental process

Technical parameters monitored in the course of measurement:

- on/off controlled refrigerator:
  - chamber temperature,
  - current drain of compressor,
  - evaporation temperature,
  - evaporation pressure, and
  - energy consumption.
- PID controlled refrigerator:
  - chamber temperature,
  - current drain of compressor,
  - speed of rotation of compressor,
  - evaporation temperature,
  - evaporation pressure, and
  - energy consumption.

Table 5. Specifications of electricity meter

Type of the electricity meter	Single-phase static electricity meter
Reference voltage/frequency	230 V/50 Hz
Meter constant	1000 [imp $kW^{-1}h^{-1}$]
Impulse constant output SO	1000 [imp $kW^{-1}h^{-1}$]
Rated voltage/frequency	230 V/50 Hz
Current range	5 [A]
Precision class	1

The energy consumption was measured by an electricity meter installed within the controllers, while current drain with a MAXWELL MC-25605 type digital tong-test ammeter. The evaporating temperature was measured by REFCO DIGIMON Digital Refrigeration Manifold instrument.

Each appliance was operated for 24 hours, of which some smaller intervals were selected, when the parameters of the chamber and the appliance were recorded at the least possible intervals. Measurement was started only after the desired chamber temperature was achieved, thus, even if air got warmer within the chamber during the standstill of the refrigerator, the re-cooling process was not considered in the measurement. After a day, the appliance was operated long enough for the accurate measurement of energy consumption.

Results and discussion

Experimental test using the basic factory PID controller settings

In the course of the first measurement, the indoor air temperature in the chamber was set to 1 °C. First, the on/off controlled appliance was started. Then the development of chamber temperature was studied during randomly selected intervals, which are shown in fig. 5. The mean indoor air temperature was calculated by arithmetic mean from the measured indoor air temperature.

It can be seen that the appliance operates periodically, as described previously. It is striking, that the length of operation (from peak points to lowest points on the diagrams) is significantly shorter, than the length of standstill. This is due to the fact, that the chamber was not filled with goods during measurements. Therefore the refrigerator was much oversized, as only air was cooled, and *i. e.* the thermal loss of the chamber was compensated. In order to receive further information of operation, periodicity was also examined, which is represented in fig. 6.

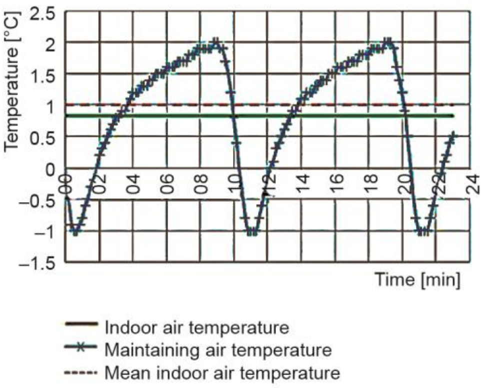

Figure 5. Cabinet temperature at 1 °C maintaining air temperature with on/off controlled refrigerator

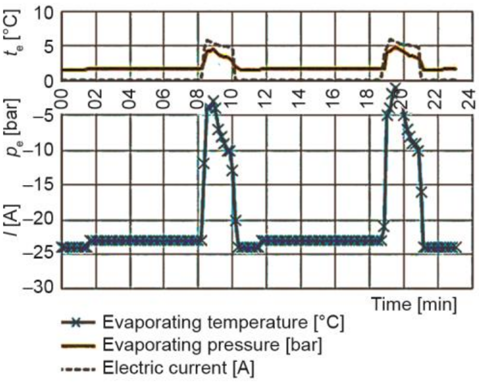

Figure 6. Measured parameters at 1 °C maintaining air temperature with on/off controlled refrigerator

The –24/–23 °C value of evaporating temperature during standstill is not realistic. This is due to the fact, as a result of closing of the safety valves, circulation stops and the sensor of the metering device measures a low pressure value and evaporating temperature is calculated with consideration to the refrigerant. It can also be observed, that in the beginning of operation, current drain increases abruptly, then decreases gradually flatter. In terms of its cycle, the appliance operated for 8 minutes and 30 seconds and was off for 1 minute and 41 seconds on average. At the end of the measurement the electricity meter read 9.41 kWh.

A similar procedure was applied for the measurement of the DC inverter type appliance; however the constant values of the PID controller were also set in this case. The basic factory setting recommendation for this was (showing the interval of possible values in brackets):

– time constant: 30 (10-999),
– proportional parameter: 35 (0-999),
– integral parameter: 0 (0-999), and
– derivative parameter: 60 (0-999).

Inside air temperature in this case was 1 °C, and the electricity meter of the PID controlled refrigerator read 61.8 kWh in the beginning of the measurement. Development of the inside temperature of the chamber is shown in fig. 8.

Figure 7 is not much similar to the temperature behavior represented by PID controller. This is due to the fact that the refrigerator is oversized in this case as well, and the speed of rotation of the compressor, cannot be decreased to a speed lower, than 15% of the operating rpm for reasons of construction. This means that even the minimum cooling capacity is higher, than needed. As a consequence, the compressor stops and only starts again after a certain amount of time, irrespectively of the temperature of the chamber. Since such a measurement would have been ineffective, measurement parameters were modified: the temperature

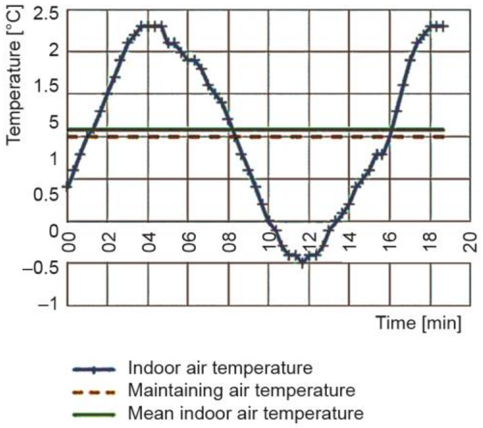

Figure 7. Cabinet temperature at 1 °C maintaining air temperature with PID controlled refrigerator

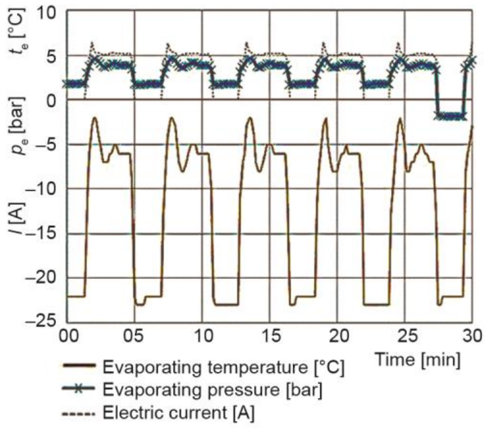

Figure 8. Cabinet temperature at 0 °C maintaining air temperature with 500 W heat loads with on/off controlled refrigerator

of the chamber was decreased to 0 °C, and it was also verified, that no melting occurs, which also assisted easier comparison.

Following the measurement, the electricity meter read 67.62 kWh. The comparison of measurements is shown in tab. 6.

Table 6. Results of the first experimental test by the basic factory settings

Parameter	On-Off	PID
Maintaining air temperature [°C]	1	1
Mean air temperature [°C]	0.823	1.08
Energy consumption [kWh per day]	5.71	5.82

It can be observed, that actual consumption is different from the one expected, the on/off controlled solution is more economic. Although the inverter type solution approached the desired temperature the best, the maintenance of this value was not ideal. It may be concluded, that in the case of an oversized system, under factory set (PID) parameters, the PID controller will not work even as good as the on/off type one.

Tuning of the PID controller and energetic investigation

For a more optimal operation of an appliance, the PID controller needs to be tuned. This is expected to result in setting the air temperature of the chamber sufficiently close to the desired value within adequate time.

In practice there are several ways of tuning a PID controller. In the present case, the simplest solution, the Ziegler-Nichols method was applied (herein referred to as Z-N). The idea is that the system is operated with a setting, where the integral and the derivative parameter are eliminated, and only the proportional parameter takes values. Also, the system needs to be operated at the boundary of instability, and the periodicity of the system has to be examined at this very position. This gives the critical time (as oscillation period) and the critical proportional parameter (as ultimate gain) values. Further values of the appliance can be calculated from these in accordance with tab. 7 [9, 18].

Table 7. The Z-N method for terms of PID controller tuning

PID terms		
K_p	T_i	T_d
0.6 K_{kr}	0.5 T_{kr}	0.12 T_{kr}

Tuning the correct terms of PID controller by Z-N method is uniqueness in the field of refrigerator, because the most commercial refrigerators in the given cooling capacity range on the market are controlled differently. Considering the fact that the interface into the software of the controller was not enabled by the producer, empirical manually tuning was applied till the PID controlled appliance followed the cooling demand with much higher accuracy, than an on/off refrigerator.

The correct constants were:

- time constant: 10 (10-999),
- proportional parameter: 25 (0-999),
- integral parameter: 0 (0-999), and
- derivative parameter: 500 (0-999).

The inside temperature of the chamber was set to 0 °C and a 500 W heat source was installed inside the chamber.

In case of the on/off controlled appliance, this increased operating times, and decreased standstill times significantly, which is clearly represented by the development of inside temperature of the chamber in fig. 8 and by the development of parameters on the condenser side, in fig. 9.

In the beginning of the measurement, the electricity meter read 18.04 kWh.

It is in fact evident, that cycles became more frequent. The appliance was operating for 3 minutes and 32 seconds, and off for 2 minutes and 3 seconds on average. At the end of the 24 hours long measurement, the electricity meter showed 32.69 kWh. Parameters of the inverter type appliance were also left unchanged. In the beginning of the measurement it was anticipated that it will maintain inside temperature as stable, and it will operate the same as in case of the second measurement, with only the compressor operating at a higher speed of rotation. The electricity meter read 130.6 kWh in the beginning. Development of inside temperature and the changes of condenser side parameters are shown in figs. 10 and 11, respectively.

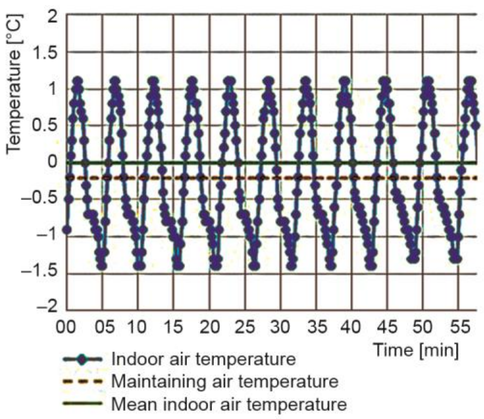

Figure 9. Measured parameters at 0 °C maintaining air temperature with 500 W heat load with on/off controlled refrigerator

The average speed of rotation in the course of measurement was 23.2% of the nominal speed of rotation. This result was as expected, just as the increase of current drain upon increase of the cooling demand. At the end of the measurement, the electricity meter showed 136.1 kWh. The third measurement is summarized in tab. 8.

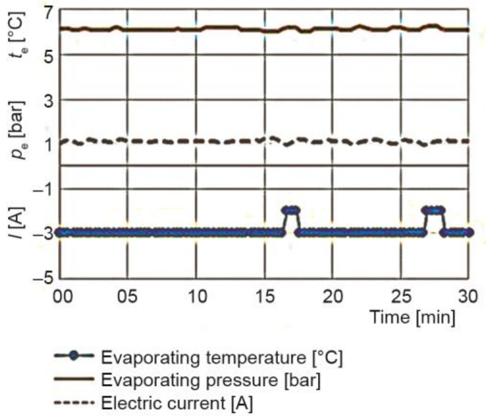

Figure 10. Cabinet temperature at 0 °C maintaining air temperature with 500 W heat loads with PID controlled refrigerator

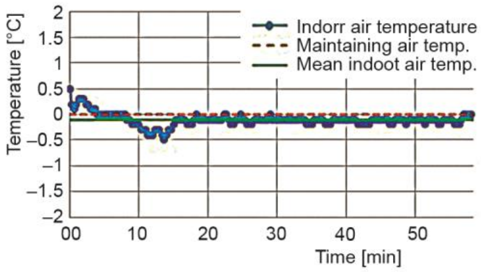

Figure 11. Measured parameters on the condenser side at 0 °C maintaining air temperature with 500 W heat load with PID controlled refrigerator

Table 8. Results of the third experimental test

Parameter	On/Off	PID
Maintaining air temperature [°C]	0	0
Mean air temperature [°C]	–0.203	–0.103
Energy consumption [kWh day^{-1}]	14.65	5.5

It can be observed, that in the given case, the inverter controlled appliance is more advantageous in all aspects. The increase of consumption of the on/off controlled appliance is dramatic due to the fact that the appliance is off for only third of the time, than in case of the second measurement, while it operates three times as much.

On the other hand, the PID controlled appliance follows the cooling demand. Therefore, under the given conditions a 62,4% energy saving is possible as opposed to the on/off controlled appliance.

Conclusions

In this study the optimization of energy consumption for DC refrigerator used in commercial cold store is conducted experimentally. It is a known fact that the energy consumption of the traditional refrigerators (operated with reciprocating compressor, mechanical expansion valve, on/off controller technic) are quite high and this technique has widely spread on the national market in the past decades. There are not exact reports or technical data in the difference in energy consumption between the mentioned traditional refrigerator and refrigerator systems that are operated with variable-frequency driven scroll compressor and electronic expansion valve currently. By this way the object of this research work was to compare the energy consumption of a novel developed DC inverter refrigerator and a traditional on/off controlled system under the same operational conditions by experimental tests. Additionally during the first tests the operation of DC refrigerator with the suggested basic settings of PID terms given by the producer has resulted higher energy consumption then the on/off controlled refrigerator. By this way the PID controller of DC refrigerator had to be tuned by setting the correct proportional, integral and derivative parameter values to achieve optimal energetic operation. The major findings obtained from this work are summarized as follows.

– The PID controlled DC inverter appliance follows the cooling demand with much higher accuracy, than an on/off refrigerator. The difference is exactly determined by experiments in this study.

- The untuned PID controller of DC refrigerator resulted 1.92% higher energy consumption opposed to the traditional on/off controlled appliance under the same operational conditions in the same cold store.
- After the proper tuning of PID terms, the average speed of rotation in the course of measurement was 23.2% of the nominal speed of rotation under partial load.
- The combined effects of electronic expansion valve, scroll compressor operation and the correct experimental settings of PID controller in DC refrigerator results around 62.4% energy saving opposed to the traditional on/off controlled appliance under the same operational conditions.

The novelty of this research is to show the significance of the proper adjustment of PID controller for the designed cooling conditions and its effect to the energy consumption of DC refrigerator. Even if the refrigerator is sized satisfactory and its cooling capacity meets the cooling demand, an un-tuned PID controller results higher energy consumption than a refrigerator utilized on/off control. Based on the experiments conducted and the results obtained in the present work, it is recommended and more economical to use a proper tuned PID control DC refrigerator than an on/off refrigerator for commercial application.

Acknowledgment

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Nomenclature

A – surface area, [m^2]
$e(t)$ – error signal, [–]
K_d – derivative coefficient, [–]
K_i – integral coefficient, [–]
K_{Kr} – ultimate gain, [–]
K_p – proportional coefficient, [–]
Q – heat flow rate, [W]
T_{Kr} – oscillation period, [s]
t – time, [s]
Δt – temperature difference between the cabinet air and indoor air temperature of the laboratory room, [°C]
$u(t)$ – control signal, [–]
U – overall heat transfer coefficient [Wm^{-2}K^{-1}]

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