Research Article

Development of a New Door System with High Thermal Resistance and Improved Sealing Performance for Refrigerated Display Cabinets

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Abstract

In this study, a new door system design was developed for the door-to-door and door-to-frame junctions of the Refrigerated Display Cabinet (RDC), where energy savings are concentrated. The aim is to improve sealing performance by reducing thermal bridges, thereby reducing the system's overall energy consumption. As part of the design, the silicone filling volume in the door bottom mold was increased, a magnetic seal element was integrated, and a new door gasket was developed. Test studies were conducted in accordance with ISO 23953-2:2023, and comparative analyses were performed using the current system. Experimental results showed that the new design *improved heat transfer efficiency by increasing the temperature difference between the evaporator inlet and outlet. Additionally, the average product temperature in the cabinet was improved by up to 5%. According to energy consumption analyses, annual energy consumption decreased from 13,231 kWh to 6,906 kWh, resulting in approximately 47.8% energy savings. Carbon emissions calculations over a ten-year lifespan showed a decrease from 82,033 kg of CO_2 to 42,816 kg of CO_2. As a result, the new door system was evaluated as a long-lasting solution that increases energy efficiency, contributes to environmental sustainability, and provides a more sustainable solution.*

Keywords: Refrigerated display cabinet, energy efficiency, sealing performance, thermal resistance, door design

1. Introduction

Commercial refrigerators are among the highest energy-consuming pieces of equipment in the retail sector. In businesses such as supermarkets and food retailers, the share of electricity consumed by these systems is reported to exceed 40% in many studies [1]. This highlights the strategic importance of efforts to increase energy efficiency, both for reducing operating costs and limiting greenhouse gas emissions.

The primary factors contributing to energy loss in Refrigerated Display Cabinets (RDC) are conductive heat transfer through the cabinet frame and door surfaces, condensation resulting from low surface temperatures, and uncontrolled air leaks at the door-frame junctions. Each of these factors disrupts the stability of the cabinet's internal temperature, causing the compressor to run longer, ultimately increasing the system's total energy requirements. Inadequate insulation, aged or deformed seal profiles, and inappropriate material selection, particularly indoor systems, significantly increase heat losses, resulting in reduced energy efficiency and undesirable conditions such as condensation and product temperature fluctuations.

Experimental and numerical studies have shown that improving door and frame design, eliminating thermal bridges, optimizing sealing elements, and implementing intelligent systems for condensation control are effective methods for reducing such losses. Design changes, such as improving sealing at door joints, using low-thermal-conductivity elastomer-based gaskets, and increasing the insulation fill volume, reduce cooling loads and significantly improve the cabinet's overall energy performance.

Improving the body design of RDCs is crucial for reducing heat losses and increasing energy efficiency. In this context, studies have highlighted the use of vacuum insulated panels (VIPs) instead of traditional polyurethane (PU) foam. Verma and Singh's research has shown that VIPs with a thermal conductivity below approximately 7 mW/mK have the potential to increase usable interior volume while reducing energy consumption. The study demonstrates that panel performance is closely related to material properties, design parameters, and the effects of aging. It has been stated that costs must fall below 25ε/m² for economic viability [2].

Thiessen and colleagues reported that covering 56% of the refrigerator's surface area with VIP reduced energy consumption by 21%, and that rear wall insulation was more effective than side wall insulation [3]. These findings demonstrate that using VIP in the body design offers an effective solution for reducing heat losses.

One of the fundamental approaches to preventing condensation in RDCs focuses on optimizing the design and performance of door gaskets. This approach seeks to reduce the intrusion of warm, and humid air into the cabinet by enhancing the airtight barrier between the interior and exterior when the RDC doors are closed. Properly designed gaskets and weatherstripping limit the ingress of outdoor air, preventing condensation on glass surfaces, reducing the thermal load on the cooling system, and improving energy efficiency.

Liu and colleagues conducted a comprehensive evaluation of the heat and mass transfer behavior, structural properties, and material development trends of refrigerator gaskets. The study compared the thermal performance of different polymer-based gaskets, examining the effects of gasket geometry, magnetic strip configuration, and seal quality on both condensation formation and energy losses. The findings indicate that new-generation composite materials and optimized gasket profiles offer significant advantages in preventing condensation and reducing overall energy consumption [4].

Ha and colleagues conducted a comprehensive numerical simulation study to analyze the thermal behavior of refrigerator gaskets. According to the results, removing the steel component within the gasket reduces heat transfer by approximately 24.8%, while removing the magnetic strip reduces heat transfer by 17%. These results highlight the critical impact of the material components in the gasket structure on thermal performance [5–6].

Gao and his colleagues proposed an innovative method combining inverse heat load experiments with computational fluid dynamics simulations to determine the heat flow in the seal region. The findings show that the average effective heat leakage at the seal surface is approximately 0.2 W/mK, accounting for 17% of the total heat leakage in the refrigerator compartment and 14% of the total heat leakage in the freezer compartment. This approach provides a new methodological framework for steady-state analysis of seal-related thermal losses [7–8].

Zheng and his colleagues investigated the sealing performance of a composite seal structure made of Ethylene Propylene Diene Monomer (EPDM)-based rubber O-rings under different temperature and pressure conditions using finite element analysis. Analyses conducted at temperatures of -60 °C, 15 °C, and 130 °C revealed that stress concentration and sealing effectiveness increased at low temperatures, while this performance decreased at higher temperatures. Additionally, it was determined that a thickness range of 0.85–1.05 mm yielded optimal results, and appropriate gas pressures had a positive effect on sealing. These findings provide important design criteria for increasing the mechanical and thermal resistance of gaskets under extreme operating conditions [9].

In another study conducted by Liu et al., the effect of rigid and flexible contact conditions on heat transfer in refrigerator gaskets was numerically analyzed. When real assembly deformations were included in the model, the resulting temperature distribution was more consistent with experimental measurements. According to the findings, the heat leakage load decreased by approximately 19% when the gasket was compressed, while it increased by 4% when stretched. Most of the heat transfer occurs at the interfaces between the gasket rubber, the outer casing, and the cold air; the cold bridge effect in these areas has been reported to exceed 20%. The research emphasizes the need to minimize these heat transfer paths and increase contact resistance in gasket design [10].

Qi et al., on the other hand, investigated the heat transfer occurring in the gasket area between the refrigerator door and body using both experimental and computational fluid dynamics simulations. Analyses showed that the total thermal load in the gasket area was 2.2 W, accounting for 5.5% of the cabinet's overall heat loss. Heat flows in the gasket-to-heatsink and gasket-to-body directions account for 41.56% and 45.07% of the total load, respectively. Furthermore, it was determined that the magnetic stripe section contributed significantly to heat transfer, and that reducing the gasket width from 9.6 mm to 8.4 mm reduced the thermal load by approximately 21.1%. These results clearly demonstrate the key role of gasket design in improving energy efficiency [11].

In glass door systems used in RDC applications, the long-term performance of sealing materials plays a critical role in energy efficiency, condensation control, and structural integrity. Studies in the literature examine both the effects of environmental conditions on sealing materials and the thermal behavior of different material combinations. Yang et al. comprehensively investigated the effects of environmental factors such as temperature, humidity, stress, and UV radiation on the tensile bond strength (TBS) of silicone structural glass sealants. Based on multi-gradient aging tests, a new mathematical model was developed to explain the degradation behavior of TBS. The findings indicate that UV radiation has the strongest effect on TBS degradation, followed by temperature, humidity, and stress. Furthermore, strong synergistic interactions were found among these factors, and UV radiation, in particular, accelerated degradation when combined with other factors [12].

In their study, Cwyl et al. investigated the long-term performance and causes of deformation of the double sealing system (PIB/silicone) structure used in warm-edge insulated glass units. The study evaluated the effects of sealants used in the edge area on the heat transfer coefficient and condensation resistance. The findings indicate that polyisobutylene sealants provide advantages in terms of vapor impermeability, while silicone-based sealants exhibit a more flexible structure against thermal expansion, maintaining long-term insulation integrity. The study revealed that hybrid systems using the two materials in combination minimize thermal bridging and reduce the risk of condensation, particularly in glass-fronted refrigerator and display cabinet applications [13].

Consequently, design optimization and material development studies aimed at minimizing heat losses and energy consumption in RDCs are considered a priority research area not only for the sustainability of product storage quality but also for supporting energy management and environmental sustainability goals.

In this study, a new door design was developed to reduce heat loss in the door-to-door and door-to-frame junctions, a key factor reducing RDC energy efficiency. The primary objective of the study is to reduce the system's annual energy consumption, improve its energy label, and thereby contribute to environmental sustainability.

Accordingly, the research focused on the following objectives:

- Reducing thermal bridging effects and improving insulation resistance by increasing the silicone fill volume in the door bottom mold;
- Improving sealing performance between the door and frame by integrating a magnetic gasket;
- Reducing air leaks and heat gains in the door-to-door section by developing a new, long-lasting, and highly flexible gasket structure;
- Maintaining cabin temperature stability and examining its effects on annual energy consumption.

2. Theoretical Analysis

Heat gains in the current system are directly related to the materials used in areas that come into contact with the external environment and their dimensions. In this study, heat transfer is demonstrated using the following equations:

The heat transfer coefficient (U) is calculated using Eq. (1) [14]:

$$U = \frac{1}{\left(\frac{1}{h_i} + \frac{2l_{gl}}{k_{gl}} + \frac{l_{ga}}{k_{ga}} + \frac{1}{h_o}\right)} \quad (1)$$

Heat transfer ($\dot{Q}$) for glass doors is calculated by Eq. (2):

$$\dot{Q} = U.A.(T_o - T_i) \quad (2)$$

The heat flux in the glass ($\dot{q}$) is calculated by Eq. (3):

$$\dot{q} = U.\Delta T \quad (3)$$

The formulas and calculation methods used in this study for energy consumption are based on the equations of ISO 23953-2:2023, the international standard for refrigerated cabinets and display cases [15]. Eq. (4) gives the cooling capacity (Q_{tot}) as the sum of the measured instantaneous cooling capacities (ϕ_n):

$$Q_{tot}=\sum_{n=1}^{Nmax} \phi_n \times Dt \quad (4)$$

To calculate a refrigerator's energy consumption, the arithmetic average of the cooling capacities measured throughout the day is taken. Eq. (5) takes into account the start (t_{run}) and stop (t_{stop}) times:

$$\phi_{24\text{-deft}} = \frac{Q_{tot}}{(t_{run} + t_{stop})} \quad (5)$$

Daily direct electrical energy consumption (DEC) will be the sum of all electrical energy consumed. DEC is calculated by Eq. (6) shown below:

$$E_{DEC,24h} = E_{FEC,24h} + E_{LEC,24h} + E_{DT,24h} \quad (6)$$

The daily cooling electrical energy consumption (REC) of a chiller with a motor group located in the outdoor unit is calculated using Eq. (7):

$$E_{REC,24h} = (24 - t_{deft}) \times \Phi_{24-deft} \times \frac{(T_c - T_{mrun})}{(0.34 \times T_{mrun})} = Q_{tot} \times \frac{(T_c - T_{mrun})}{(0.34 \times T_{mrun})} \quad (7)$$

Total daily energy consumption (TEC) is calculated by Equation (8):

$$E_{TEC,24h} = E_{DEC,24h} + E_{REC,24h} \quad (8)$$

Annual energy consumption is calculated by Eq. (9), standard annual energy consumption by Eq. (10), and energy efficiency index by Eq. (11) [16]:

$$AE=365 \times E_{TEC,24h} \quad (9)$$

$$SAE=(M+N \times Y) \times 365 \times C \times P \quad (10)$$

$$EEI = AE/SAE \quad (11)$$

The average lifetime carbon emissions from the energy consumption of the refrigeration system are determined in a guide published by the International Institute of Refrigeration. This value is calculated by Eq. (12) [17]:

$$\Phi CO_2 = LxAExEM \tag{12}$$

3. Materials and Methods

In this study, designs were developed to reduce heat losses and air leaks at the door-to-door and door-to-frame junctions, which negatively impact RDC efficiency.

The first improvement in the door structure focused on reducing the thermal bridge effect. By increasing the width of the silicone filling points in the door lower mold (Figure 1, 13), more insulation material was applied within the same mold geometry. The increased amount of silicone expanded the contact area with the frame when the door was closed, thereby reducing the effect of thermal bridges and significantly contributing to the sealing performance.

Secondly, the issue of conventional door gaskets losing their adhesive properties over time, resulting in air leaks at the junctions and user complaints, was addressed. These old gaskets were removed entirely, and a new door gasket structure was designed to provide high sealing (Figure 1, 11). The new gasket's geometric structure aims to ensure full and continuous contact with the door during closing and to reduce the risk of deformation due to long-term use. Finally, to maintain continuity of contact after closing and further enhance sealing performance, an additional magnetic sealing element was integrated into the lower door mold (Figure 1, 12). This element minimized the risk of leakage by creating additional holding force between the door and the frame.

3.1. Test Method

This study examines the effects of door design on performance in a remote and door-type RDC. An RDC with a module length of 2500 mm was used, employing natural refrigerant R744 (CO_2) as the refrigerant for the test studies. In the study, the new door design developed to provide high thermal resistance and tightness was evaluated comparatively with the current standard door design. Both RDCs tested were identical except for the door configurations and were subjected to testing under the same technical conditions.

All measurements were conducted in accordance with the requirements specified in ISO 23953-2:2023. The tests were conducted under Climate Class-3 conditions specified by the standard, namely, 25°C indoor temperature and 60% relative humidity. Furthermore, the air velocity in front of the cabin was maintained at a constant level between 0.1 and 0.2 m/s to ensure environmental stability [15]. RDCs were tested with a full package load in accordance with the standard, and M-Packs (test packages with temperature sensors) were installed for product temperature monitoring, specified in accordance with ISO 23953-2:2023. To evaluate the actual performance of the new door design under market conditions, an opening-closing test was conducted. This test was performed automatically using four hydraulic systems, details of which are presented in Figure 1. At the beginning of the test, each door was held open for 3 minutes to allow the cooling load to reach equilibrium, followed by 5 minutes after the last door closed. Following this cycle, each door was programmed to open 10 times per hour for the 24-hour test period, remaining open for 15 seconds each time [15]. M-Pack temperature data was recorded at one data point per minute, and other measurements were recorded at three data points per minute.

To ensure the reliability and high precision of the measurement results, all devices used during the test (temperature sensors, energy analyzers, humidity, and anemometer) were calibrated at regular intervals.

Following the completion of the performance tests, an additional test procedure was conducted to determine the durability and operational life of the developed magnetic gasket and the newly designed door gasket. This procedure continued with door opening-closing cycle tests, independent of the test environment (outdoors). A detailed visual of the life test is presented in Figure 2.

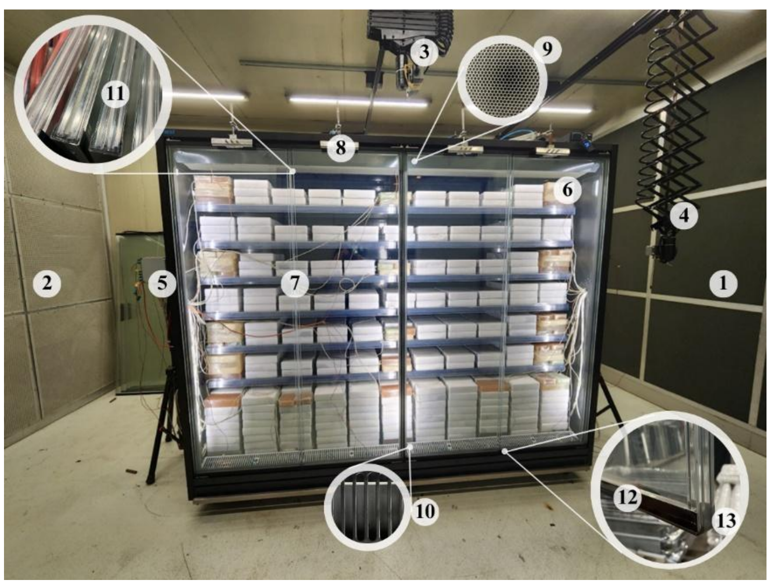

Figure 1: Test Room: 1: Test room air discharge, 2: Test room air return, 3: Thermohygrometer, 4: Anemometer, 5: Thermocouples, 6: M-packages, 7: Glass doors, 8: Door opening test mechanism, 9: Discharge air grill, 10: Return air grill, 11: New design door gasket, 12: Magnetic sealing element, 13: Silicone filling point

Figure 2: Outdoor door opening and closing test

4. Results

In this section, the results of experimental studies conducted to assess the impact of the developed door designs on the thermal performance and energy efficiency of the RDC are analyzed, and the findings are presented with graphical support. Figure 3 presents a comparison of the 24-hour average values of the refrigerant evaporator inlet (E.I.) and evaporator outlet (E.O.) temperatures of the current and new systems. An examination of the graph reveals that in the new system, the refrigerant enters the evaporator at a lower temperature and exits at a higher temperature. This increases the temperature difference (ΔT) across the evaporator, which has a positive effect on the heat transfer rate. The E.I. and E.O.

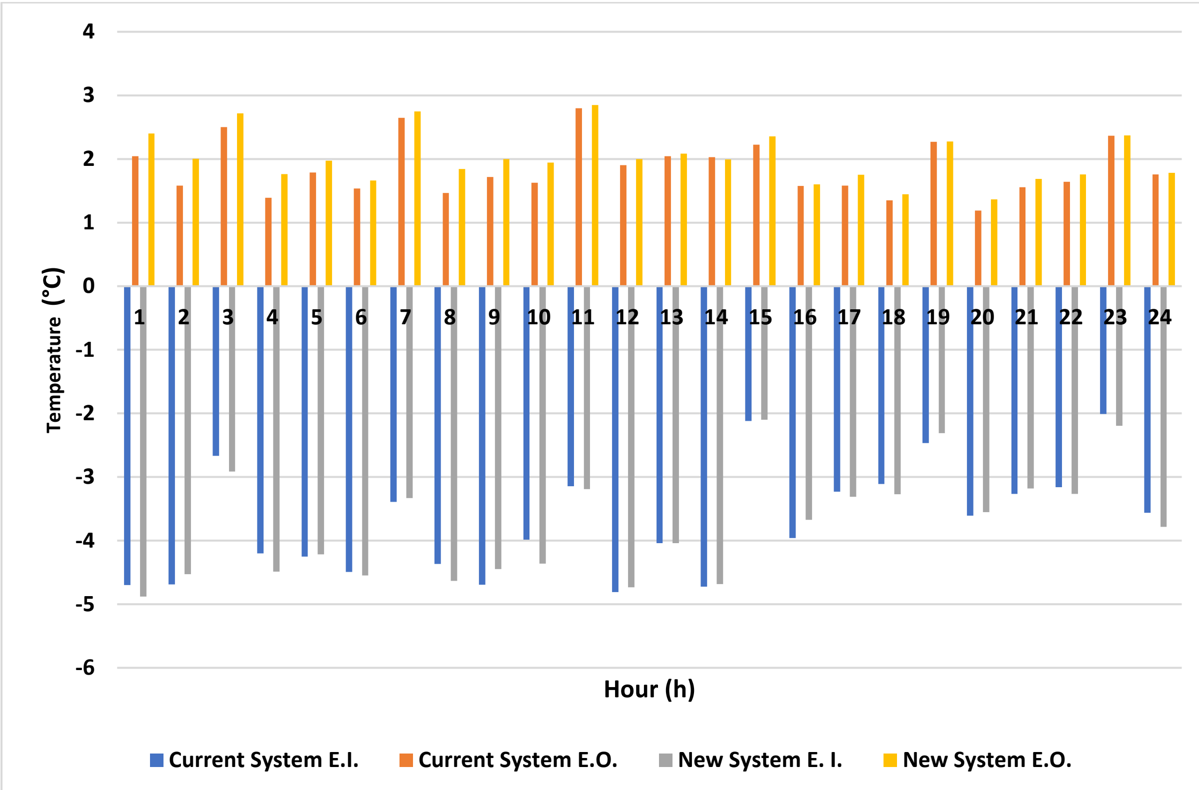

Figure 3. Comparative graph of 24-hour average values of E.I. and E.O. temperatures of the refrigerant of the current and new systems

Figure 4 shows a comparison of the package temperature changes in the left, middle, and right regions of the current and new systems over a 24-hour measurement period. An examination of the graph reveals that both systems meet the requirements of temperature class M1, indicating that the temperatures ranged from -1°C to +5°C. When Table 1 and Figure 4 are evaluated together, it appears that the package temperatures in the new system are generally lower than those in the current system. This finding demonstrates that the structural improvements made to the door design in the new system have enhanced thermal insulation and sealing performance, thereby contributing positively to maintaining a stable indoor temperature.

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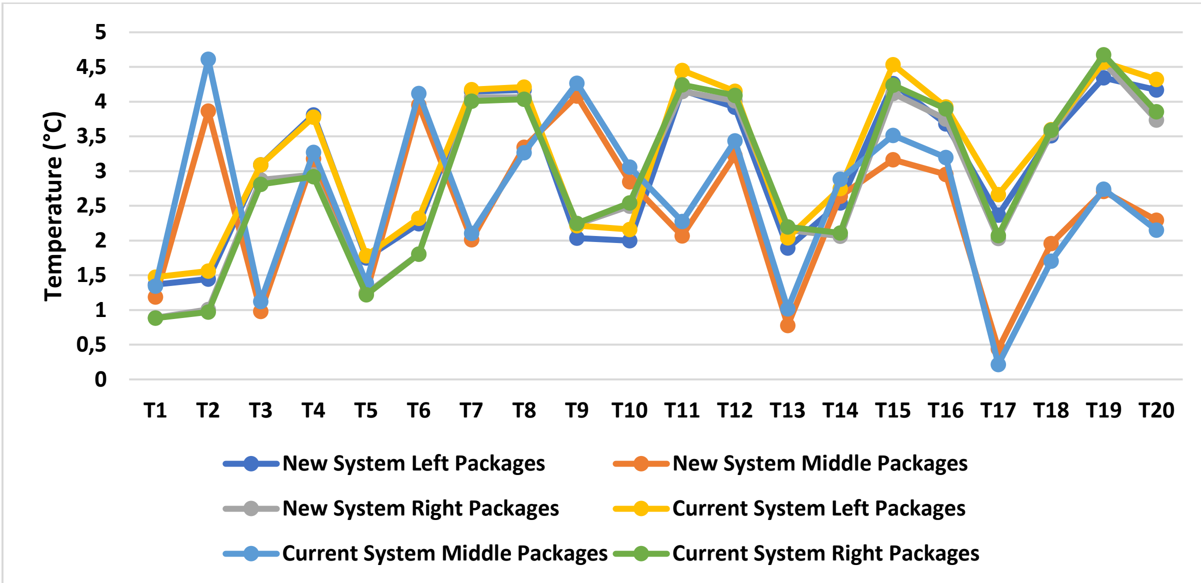

Figure 4: Change graph of package temperatures in the left, middle, and right regions of the current and new systems during the 24-hour measurement period.

Table 1: 24-hour average package temperature values

Pack location	Temperature	Percent Improvement
The new system left packages	3.04°C	%4.5
The current system left packages	3.19°C	
New system middle packages	2.44°C	%5.36
Current system middle packages	2.58°C	
New system right packages	2.89°C	%1.13
Current system right packages	2.92°C	

To assess the long-term operational reliability of the improved magnetic gasket and the newly designed gasket, lifespan tests were conducted under outdoor conditions independent of the test environment. A total of 305,000 door opening and closing cycles were successfully completed during this testing period. As a result of the tests, no permanent deformation or structural deterioration was detected in the gaskets or critical components of the door structure that would impair use or require material replacement due to a performance reduction.

The tests revealed that the annual energy consumption of the current system was 13,231 kWh, while this figure decreased to 6,906 kWh for the new system with the improved door design. As a result of this significant reduction in energy consumption, the system's energy label class was upgraded from "E" to "C." An examination of the energy labels presented in Figure 5 reveals that the total display area (TDA = 4.54 m^2) was preserved in both systems. Since TDA is a critical parameter in both the visual design of display coolers and energy label calculations, the improvements made in the new system are designed not to affect the TDA value.

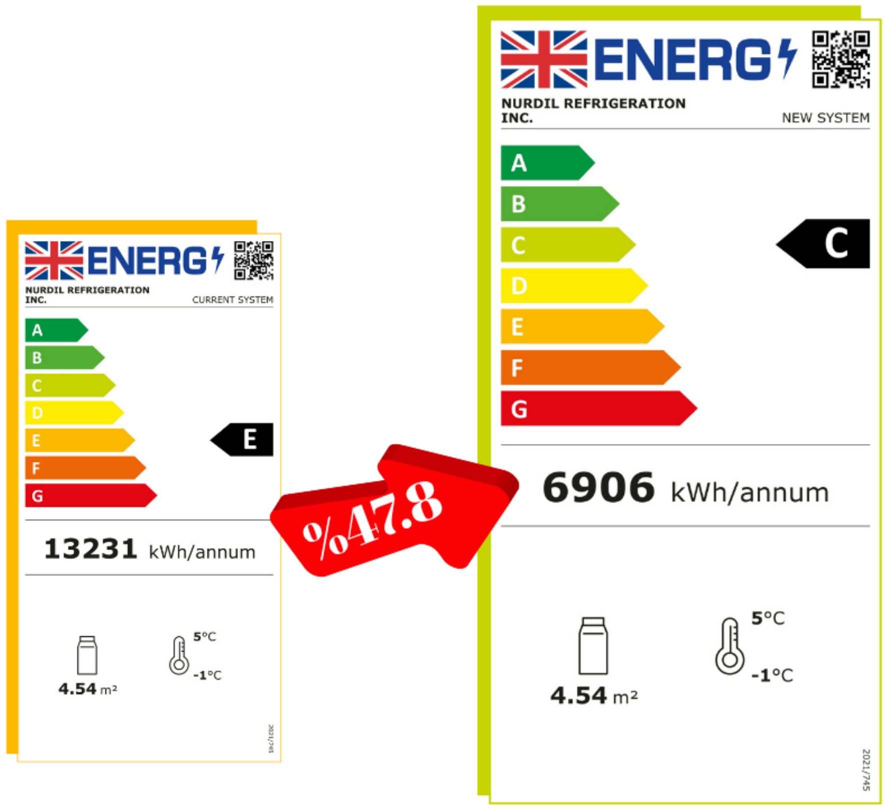

Figure 5: Energy labels of the current and new systems

To assess the environmental impact of the significant reduction in energy consumption, estimated carbon emission values for a 10-year operational period were calculated using Equation 12. While the 10-year total emissions from annual consumption in the current system were determined to be 82,033 kg CO_2, this value decreased to 42,816 kg CO_2 in the improved new door system.

5. Conclusions

In this study, design improvements for the door-to-door and door-to-frame junction areas, where energy losses are concentrated in RDCs, were experimentally evaluated. To reduce thermal bridging and improve sealing performance, the silicone fill volume in the

lower mold was increased, a magnetic sealing element was integrated, and a sealing door gasket was used.
The findings indicate that these design improvements increased the evaporator inlet and outlet temperature difference, thereby improving heat transfer efficiency. Furthermore, lower interior product temperatures in the new system revealed improved insulation and sealing performance. Energy analysis showed a reduction in annual energy consumption from 13,231 kWh to 6,906 kWh, representing savings of approximately 47.8%. This improvement resulted in the system's energy label class being upgraded from "E" to "C." Furthermore, when the environmental impact of these energy savings was analyzed, the transition from the current system to the new one resulted in a reduction of approximately 47.8% in projected carbon emissions over its 10-year lifespan. The new design not only reduces operating costs but also contributes to environmental sustainability by significantly reducing the system's carbon emissions.
The absence of any deformation during a 305,000-cycle outdoor lifespan test confirms the long-term durability of the new door design. This finding suggests that the new design will maintain its high sealing performance under heavy commercial use, thereby reducing customer complaints and enhancing competitiveness in the sector. Consequently, the developed design offers a viable and efficient solution that reduces door-related energy losses in RDCs.

Acronyms and Symbols

$E_{DEC,24h}$	Direct daily electrical energy consumption, kWh
$E_{FEC,24h}$	Fan energy consumption, kWh
$E_{LEC,24h}$	Lighting energy consumption, kWh
$E_{DT,24h}$	Digital energy consumption, kWh
$E_{REC,24h}$	Refrigeration of electrical energy consumption, kWh
$E_{TEC,24h}$	Total energy consumption, kWh
EEI	Energy Efficiency Index
SAE	Standard annual energy consumption, kWh
AE	Annual energy consumption, kWh
A	Area, m^2
EM	Produced emission, $kgCO_2/kWh$
k_{gl}	Thermal conductivity coefficient of the glass, W/mK
k_{ga}	Thermal conductivity coefficient of the gas, W/mK
L	System lifetime, year
l	Length, m
U	Heat transfer coefficient, W/m^2K
t_{run}	Running time, h
t_{stop}	Stopping time, h
t_{deft}	Defrost time, h

T_0	Inlet temperature, K
T_i	Outlet temperature, K
T_c	Condensing temperature, K
T_{mrun}	Evaporating temperature, K
Q_{tot}	Total heat extraction, kWh
Φ_n	Instant cooling capacity, kW
$\Phi_{24-deft}$	Heat extraction rate (excepting defrost time), kW
ΦCO_2	Carbon emission value, $kgCO_2$

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