Acta Mechanica Slovaca **29 (4): 58 - 63,** December **2025**
https://doi.org/10.21496/ams.2026.006

Acta Mechanica Slovaca
ISSN 1335-2393
www.actamechanica.sk

Energy-Efficient Optimization of Refrigeration Systems for Large-Volume Cooling Applications

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Abstract: This work aims to analyse and optimise key parameters of refrigeration technology intended for large-capacity spaces, with an emphasis on energy efficiency, temperature stability, and operational reliability. The research focuses on identifying the factors that influence the efficiency of cooling systems, including temperature and pressure conditions, flow parameters, cooling distribution, and equipment structural layout. Through simulation models and experimental measurements, optimisation procedures are proposed to reduce energy consumption, minimise thermal losses, and increase overall system performance. The results provide recommendations for the design and operation of modern refrigeration systems to achieve sustainable and economically efficient operation in large-capacity facilities

Keywords: cooling; optimization; energy; efficiency.

1. Introduction

The pursuit of energy-efficient and environmentally sustainable thermal management systems has become a key priority in both industrial and large-capacity built environments. Refrigeration and heat pump technologies play a central role in achieving this goal, as they enable controlled cooling and heating with significantly higher energy utilisation efficiency compared to direct resistive heating or conventional fossil fuel-based systems [1,2,3]. Unlike heat engines that convert energy into work, heat pumps transfer thermal energy from a low-temperature reservoir to a higher-temperature sink, thereby delivering more useful heat output per unit of input energy – a performance metric quantified by the Coefficient of Performance (COP).

In thermodynamic terms, the most widely adopted configuration for both cooling and heating applications is the vapour-compression cycle, consisting of four fundamental components: compressor, condenser, expansion valve, and evaporator. These elements facilitate the continuous phase change of the refrigerant, enabling efficient heat transfer between the heat source and the heat sink. Modern variations of this cycle have been explored extensively, with research focusing on working fluids, cycle configurations, and integration with renewable energy sources to enhance efficiency and reduce environmental impact [4,5]. Recent studies also investigate advanced compressor technologies and improved regulation strategies aimed at improving overall energy performance [6,7].

Heat pumps represent a broad category of thermal systems used in applications ranging from residential heating to industrial heat recovery. Research efforts in this field can be organised into several domains including optimisation of vapour-compression systems, development of alternative compressor technologies, exploration of non-conventional thermodynamic cycles, and investigation of the interaction between heat pumps and the built environment. These research directions aim to increase system

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efficiency under variable operating conditions and reduce the environmental impact associated with refrigerants with high global warming potential [7,8].

In recent years, increasing attention has been devoted to the use of natural refrigerants and the recovery of waste heat from refrigeration processes. Ammonia-based refrigeration systems remain among the most efficient solutions for large-scale cooling applications due to their favourable thermodynamic properties and negligible global warming potential. However, several studies highlight that the overall efficiency of such systems depends not only on the refrigerant itself but also on operational parameters such as compressor performance, pressure levels, condenser temperature control, and system regulation strategies [9].

The practical relevance of such advancements becomes particularly evident in large-scale facilities where refrigeration and heating systems account for a significant share of total energy consumption. Optimising these technologies reduces energy consumption, enhances system stability, and enables more flexible responses to dynamic load profiles [10,11,12]. Facilities such as ice arenas represent energy-intensive environments where continuous refrigeration is required to maintain stable ice conditions. Previous studies have shown that significant energy losses occur mainly during compression and condensation processes of refrigeration systems [13]. Consequently, recent research increasingly focuses on improving system control and implementing waste heat recovery strategies that allow recovered thermal energy to be utilised for domestic hot water preparation, space heating, or other auxiliary applications [14,15].

Another important research direction concerns the integration of refrigeration systems with renewable energy sources, particularly photovoltaic systems. Adaptive control strategies based on the availability of renewable electricity can significantly reduce electricity consumption from the grid and improve the utilisation of locally generated energy [16,17]. Integrated heating and cooling systems combining refrigeration technologies with heat pumps and waste heat recovery have also demonstrated considerable potential for improving overall energy performance [18,19].

This study focuses on the optimisation of refrigeration technology parameters within large-capacity environments through a combination of theoretical and empirical approaches. Systematic measurement, modelling, and simulation allow identification of parameters with the greatest influence on energy efficiency. The proposed methodology includes adjustments to operational controls that leverage real-time data, including integration with photovoltaic generation and district heating systems.

Specifically, the proposed enhancements, including automated control strategies synchronised with renewable energy output and utilisation of waste heat through municipal heating network integration, demonstrate measurable energy savings and improved performance. Such strategies emphasise the importance of continuous monitoring, data archiving, and adaptive management for long-term system optimisation and decision support [10,12,20].

The study aims to evaluate the economic efficiency of the proposed optimisation in view of the actual state of the enterprise. The individual proposals were divided into two solution variants. Variant A – adjustment of the control of the operation of the cooling technology in the summer periods based on the superior automated control by changing the output of the photovoltaic power plant on the roof of the elementary school. Variant B consists in connecting to the returning branch of the municipal heating company with preheating. It is proposed to use the supplied excess heat from the technology for pre-heating, which would otherwise be cooled in the cooling tower. In the conclusion, the results and the optimal variant are evaluated with respect to the monitored optimisation parameters.

2. Experimental Section

2.1 Cooling Technology and Its Configuration

The cooling technology of the winter stadium uses direct cooling using 1,500 kg of ammonia (NH_3). The system is operated in parallel through a bypass configuration, with the V600 GEA Grasso compressors serving as both the triggering and primary components. The compressors are powered via frequency converters with automatic control for optimal ramp-up, ensuring a gentle load start and energy savings. The system diagram is shown in a cyclic representation, as the cooling medium (NH_3) continuously circulates within the system,

Figure 1. Heat exchangers are integrated into the heating circuit throughout the entire facility. Heat distribution is provided via underfloor heating with individual temperature control, supported by automated management through a PC system. Residual waste heat from the cooling system is recovered for the domestic hot water (DHW) system through an Alpha Laval heat exchanger. Excess cooling heat circulates through an inserted safety glycol circuit, which ensures that ammonia does not enter the DHW circuit. Backup sources for hot water in both the heating system and DHW are provided via a gas connection and Rendamax and Rinnai gas boilers, also connected in parallel to ensure redundancy in case of failure.

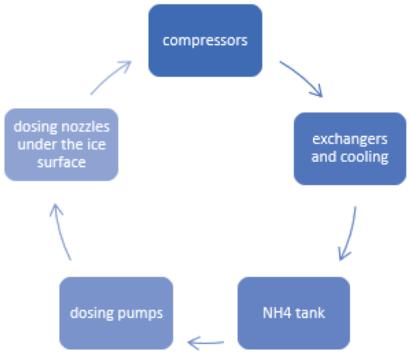

Figure 1: Cooling technology cycle diagram.

2.2 Measurable parameters of cooling technology

In addressing specific problems, the system was approached holistically, as a set of black boxes with variable parameters measured within the technology. At key points in the system, control values and diagnostically meaningful indicators were monitored. The fundamental measured parameters include:

- *Low-pressure (ice pad) temperature (1, 2, 3, 4, average) – °C*
- *Daily operating time of the system – hh:mm:ss*
- *Current system output – %*
- *Compressor discharge pressure – bar*
- *Ammonia level in the reservoir – cm*
- *Cooling tower fan speed – RPM*
- *Outdoor and indoor temperature – °C*
- *Opening position of the ammonia dosing valve at the ice pad side – %*

To influence and regulate these parameters, the user or operator can adjust several variables within safety limits defined by the system designer. These adjustable parameters are used to ensure the required quality of ice pad operation and to reduce the operating costs of the technology.

Variable parameters:

- *Minimum required ice pad temperature – the surface temperature of the ice pad unit at which the system shuts down once the set value is reached (e.g., –6 °C).*
- *Maximum required ice pad temperature – the surface temperature of the ice pad unit at which the system automatically activates the cooling process upon reaching the set temperature. This triggers the operation of the entire system, and in accordance with safety regulations, all components are engaged algorithmically in addition to the compressors.*
- *Maximum opening of the ammonia dosing valve – a component that limits ammonia flow toward the ice pad side on the low-pressure side. This creates a vacuum and regulates the supply of cold ammonia into the ice pad unit.*
- *Maximum discharge pressure from the compressor – the maximum pressure at which the compressor can draw ammonia from the ice pad unit and delivering it back into the ammonia reservoir.*
- *Minimum ammonia level in the reservoir – a crucial parameter controlling the quantity of ammonia circulating in the system. It affects the pressure balance throughout the process and at individual system nodes.*

3. Results and Discussion

3.1 Optimization of Technological Operation Control – Variant A

Throughout the implementation period, several operational configurations were tested. Nevertheless, during summer months, a recurring and substantial increase in electricity consumption was observed, primarily caused by elevated ambient temperatures. Following a comprehensive analysis, a revised control strategy for the refrigeration technology was proposed. During the peak summer period, characterized by the highest solar irradiance and external temperatures, the system is no longer governed by the ice rink surface temperature. Instead, it is managed by a supervisory control mechanism that responds to the instantaneous electrical output of the photovoltaic (PV) panels installed on the stadium roof. The operation of the refrigeration technology is thus directly linked to the available PV power, under the assumption that the ice pad maintains a sufficient ice layer. The benefits of this approach extend beyond the elimination of direct electricity consumption from the grid. The system achieves full utilization of the PV-generated energy, avoids grid access charges, and reduces dependency on the public electricity network.

Given the presence of a 100 kW photovoltaic installation on the roof of the ice arena, it was possible to simulate this operational model during a dedicated one-week testing period. The simulation was conducted in manual mode with controlled performance modulation. Electricity meter readings taken at 30-minute intervals provided data on the real-time output of the PV system during summer days. These measurements, collected in June, showed peak generation during midday hours. Average performance curves were subsequently derived from these half-hourly records to establish a representative power profile. Based on the measurement results from the first week, the second week applied a manual operational regime in which technology activation followed the PV generation profile, while ensuring that the minimum required cooling duration was maintained.

The operational cycle replicated a full one-week period, during which not only the activation intervals but also the cooling capacity were adjusted in accordance with the previous week's PV data. A comparative assessment of compressor performance – with and without optimization – is presented in Figure 2. Under the conventional operational strategy, the refrigeration system functions either in an off state or at full (100%) capacity, with a 30-minute ramp-up time. In contrast, the simulated PV-based strategy enabled modulation of output down to a minimum of 30%, adjustable in increments of 10%, up to a maximum of 100%.

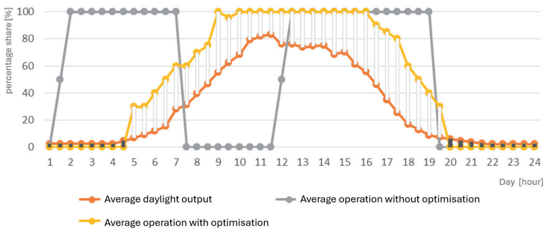

Figure 2: Comparison of compressor performance without optimization vs. with optimization

Concerns were raised regarding potential increases in equipment wear due to prolonged operating hours. A consultation with the technology supplier was therefore conducted. The supplier confirmed that the equipment is designed to accommodate such an operational regime. Nevertheless, any potential increase in maintenance costs will be incorporated into the evaluation of the simulation results and the overall implementation assessment.

3.2 Optimization of Technological Operation Control – Variant B

Another potential operational bottleneck is the incomplete utilisation of the available waste-heat capacity. During compressor operation, surplus thermal energy is generated and subsequently transferred through heat exchangers to the domestic hot-water (DHW) and central-heating (CH) systems; however, the capacities of these systems are insufficient for full heat recovery. The remaining unutilised heat is dissipated in an atmospheric cooling tower with a cooling capacity of 1 MW/h. An analysis of historical data from the measurement and control system (MaR) revealed the actual performance parameters of the cooling tower, which is supplied via a frequency converter and governed by a thermostatic control valve at the inlet. The 24-hour operation profile of the cooling tower in relation to compressor operation without optimisation is shown in Figure 3. Based on the archived data and the operational trend depicted in Figure 3, it is evident that the cooling tower is forced to activate approximately 3.5 hours after the start-up of the technology.

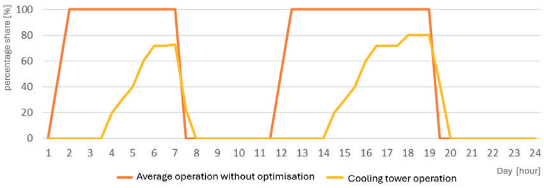

Figure 3: Cooling tower operation relative to compressor operation without optimization

For reliable system operation, continuous cooling of the working medium (NH_4) is indispensable. It is therefore essential to integrate a process component capable of reducing the medium's temperature to the required level. Among the initially proposed construction-oriented solutions were the enlargement of the snow pit or the expansion of thermal storage tanks for DHW or CH. However, these measures were assessed as commercially disadvantageous, as they would restrict operation and reduce spatial capacity in the machine room. Based on the technical background materials, an alternative solution was proposed: connecting the system to the existing municipal district-heating return network for the purpose of preheating the returning branch to the heat-supply source of the municipal heating utility. Due to fluctuating heat output and the persistent need for cooling-tower operation, the connection must be established specifically to the return (i.e., low-temperature) branch. The billing meter would be installed in accordance with regulatory requirements and technological feasibility. The technical manual stipulates mandatory safety reserves for technological integration. Due to significant deviations in cooling and sub-cooling performance relative to target temperatures, the full capacity of the generated waste heat cannot be utilised; only the portion exceeding 30% of the cooling tower's nominal output can be effectively transferred. Evaluation of the operational data confirmed an average annual heat-delivery rate to the public network of 402 MWh. A secondary economic benefit results from reduced cooling-tower operation—specifically, a daily cost reduction of €4.14 through decreased fan runtime.

4. Conclusions

The conducted factual analysis confirmed the importance of thoroughly examining the refrigeration technology in terms of its energy demand, operational efficiency, and potential for further technical development. Based on theoretical knowledge and precisely defined measurement procedures, a comprehensive model evaluating the performance and energy parameters of the system was created. By comparing the standard operational model with a specific model based on current operational data, several areas with optimisation potential were identified. The implementation of the proposed optimization measures – specifically Variant A, which involved adjusting the control of the technology during summer periods through a superior automated system reacting to the output of the photovoltaic power plant on the roof of the elementary school, and Variant B, which utilized the return branch of the municipal heating network for preheating using excess heat from the technology – resulted in demonstrable energy savings. The company accepted these proposals and integrated them into its operational strategy, confirming their practical feasibility and economic benefit. The analysis results also showed that further development and optimisation of the technology require continuous monitoring of key operational parameters. Systematic data archiving is essential not only for retrospective verification and trend evaluation but also as a basis for future investments and technological innovations, enabling objective assessments of efficiency. Based on the calculations and analyses, it can be concluded that the modern ice arena, thanks to its optimized refrigeration technologies, has the potential to respond flexibly to new challenges posed by sports, cultural, or social events. This positions it as a competitive and forward-looking facility, prepared for long-term sustainable operation and future technological advancements.

Acknowledgments

This publication was created as part of the implementation of the project under Measure 1.1 R&D Projects of enterprises; Sub-measure 1.1.1 industrial research and development works carried out by enterprises of the Smart Growth Operational Programme. Contract number POIR.01.01.01-00-0783/19. Project title: Development and implementation of high-effective automatised and robotised technology for making knurled ecological rubbish bags from three-layered film produced by blow film extrusion, financed by the National Centre for Research and Development.

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