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*Received 16.06.2025*
*Revised 17.09.2025*
*Accepted 20.09.2025*

https://doi.org/10.53360/2788-7995-2025-4(20)-67



IRSTI: 44.31.03

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# INVESTIGATION OF THE DYNAMICS OF THE RESPONSE OF THE REFRIGERATION SYSTEM UNDER CONDITIONS OF SEVERE HEAT EXPOSURE

***Annotation:*** *This article presents an assessment of the performance of a vapor-compression refrigeration system under shock thermal load. The study was carried out on a modernized experimental stand «Kholodilnik-2» equipped with a digital monitoring system, including 24 DS18B20 sensors and an STM32 microcontroller. The main objective was to compare the system behavior when introducing an object with temperatures of 40, 60, and 80°C after reaching a quasi-steady-state mode. Temperature curves, transient process duration, and stabilization times were analyzed. Additionally, features of temperature distribution* *inside the freezer compartment and the influence of thermal load on the main elements of the cycle were examined.*

*The scientific novelty of the study lies in the comprehensive analysis of transient processes occurring under sudden thermal impacts, with a focus on their duration and system stability. The practical significance of the work is related to the possibility of applying the obtained results to optimize the operating modes of refrigeration systems and to diagnose faults under conditions close to real operation. The optimal regime was found at 60°C, which ensures a balance between transient process duration and uniformity of temperature distribution.*

***Key words:*** *refrigeration system, shock load, transient processes, temperature monitoring, operational stability, cold production.*

Modern refrigeration systems operate under variable loads, which requires the analysis of not only steady-state conditions but also transient operating modes [1, 2]. Particular interest is directed toward the system's behavior under a sudden change in heat flux – known as a shock thermal load – which may occur during the rapid introduction of warm objects into the chamber, such as food products [3, 4]. The importance of analyzing transient processes is supported by numerous studies demonstrating that these regimes largely determine the stability and overall efficiency of the refrigeration cycle [5-7].

Despite significant progress in the modeling and automation of refrigeration systems [8, 9], the issues related to the quantitative assessment of transient process characteristics under different levels of thermal impact remain insufficiently explored. In this regard, an important objective is to perform an experimental analysis of the system's dynamic behavior, enabling a comparison of its performance under varying thermal loads and the identification of optimal operating conditions [10-12].

The experiments were conducted on the «Kholodilnik-2» RTB 02.00.01 experimental refrigeration stand installed in the laboratory of non-profit Joint Stock Company «Shakarim University» [13]. The stand was upgraded with a digital temperature monitoring system [14]. Digital DS18B20 sensors were used to record operating parameters, arranged at 11 control points of the refrigeration cycle and inside the chambers (Fig. 1). The key measurement zones included: the compressor discharge line (sensor 1), the condenser inlet (sensor 2) and midpoint (sensor 3), condenser outlet (sensor 4), the section after the filter-drier (sensor 5), the expansion device outlet (sensor 6), the evaporator inlet (sensor 7), midpoint (sensor 8), and outlet (sensor 9), the compressor suction line (sensor 10), as well as the air inside the freezer compartment (sensor 11). This configuration provided a comprehensive view of the temperature distribution along the main components of the cycle and the dynamics of their changes under different thermal loads. Temperature measurement and data logging were performed using an STM32F103 microcontroller, which ensured high accuracy of registration and facilitated subsequent processing of the experimental results.

Figure 1 – General view of the «Kholodilnik-2» RTB 02.00.01 experimental stand

Previous studies conducted on this test bench demonstrated that, under steady-state operating conditions of the refrigeration system (without shock thermal loading), the system reaches the target parameters on average 28 minutes after start-up [15]. These data formed the basis for planning the experiments under shock thermal exposure: knowing the characteristics of the established steady-state mode made it possible to accurately determine the moment of applying the thermal disturbance and to objectively evaluate the subsequent evolution of the transient processes.

Thus, the preceding experimental investigation not only established a dataset describing the dynamic characteristics of the refrigeration system, but also enabled a comparative analysis of transient processes under internal anomalies and under external thermal loading. This provides a comprehensive understanding of the mechanisms of deviations in the operation of the refrigeration system and increases the reliability of the analysis performed in the present study.

To analyze the influence of different levels of thermal load, three characteristic temperatures were selected: 40°C – simulating the placement of warmed products after being stored in a warm environment; 60°C – representing partially cooked or reheated items; and 80°C – an extreme shock thermal load close to the upper limit of conditions that may occur in practical applications.

After the system reached a quasi-steady operating state (approximately 25 minutes after startup), a thermal load was introduced into the freezer compartment. The load consisted of a 1.5-liter vessel filled with water and preheated to the required temperature (40°C, 60°C, or 80°C). This choice was motivated by the high specific heat capacity of water, which ensures reproducibility of the thermal impact and comparability of results across repeated tests.

Before placing the vessel into the freezer compartment, the actual water temperature was verified using an infrared thermometer (Fig. 2). This ensured the accuracy of the initial conditions and eliminated the influence of temperature deviations on the experimental results.

Figure 2 – Verification of water temperature before the experiment using an infrared thermometer

Each test was repeated five times, and the averaged results were used for analysis. During the experiment, temperatures at all control points were recorded using DS18B20 digital sensors at 5-minute intervals, along with the duration of transient processes at each level of thermal exposure.

After completing the repeated trials, the average temperature value for each measurement point was calculated as:

$$\bar{T} = \frac{T_1+T_2+T_3+T_4+T_5}{5}. \quad (1)$$

The random component of the measurement error was determined using the root-mean-square deviation method:

$$S = \sqrt{\frac{(T_1-\bar{T})^2+(T_2-\bar{T})^2+(T_3-\bar{T})^2+(T_4-\bar{T})^2+(T_5-\bar{T})^2}{5-1}} \quad (2)$$

The root-mean-square error of the mean value is given by:

$$S_{\bar{T}} = \frac{S}{\sqrt{5}} \quad (3)$$

The total measurement error accounts for both the random component and the instrumental accuracy of the sensor (±0.5 °C):

$$\Delta T = \sqrt{S_{\bar{T}}^{\,2} + (0.5)^2} \quad (4)$$

At the same time, the random component $S_{\bar{T}}$ was significantly smaller than the sensor's specified accuracy; therefore, the total measurement error was determined primarily by the characteristics of the sensor.

All experimental tests were carried out under strictly identical conditions. The position of the installation, the configuration of the equipment, and the layout of the sensors remained unchanged throughout the entire research cycle. The temperature in the laboratory room where the experiments were performed was maintained at a constant level, which eliminated the influence of external thermal fluctuations on the results. This approach ensured data reproducibility and allowed for a correct comparison of results across different operating modes of the system.

The primary criterion for evaluation was the time required for the system to reach a new steady-state regime after a sudden thermal load. Particular attention was paid to the pattern of temperature changes within the freezer chamber, as well as to the uniformity of cooling across different zones.

Under shock-loading conditions, the following time intervals to reach steady state were recorded:

at 40 °C – 41 minutes;

at 60 °C – 59 minutes;

at 80 °C – 165 minutes.

The obtained values indicate a consistent increase in the duration of the transient process with rising object temperature. The temperature dynamics recorded by the internal sensors confirm the growing inertia of the system under higher thermal loads. Thus, the transient process is significantly prolonged as the initial temperature of the loaded element increases, which should be taken into account when assessing the efficiency and adaptability of refrigeration systems to external disturbances.

Comparative analysis of the operating modes showed that an increase in thermal load leads to a longer stabilization time of system parameters, which is also corroborated by the findings reported in [10-12].

Figures 3÷5 show temperature diagrams obtained during full-scale experiments at the specified temperatures of the loaded object. Each diagram reflects the dynamics of temperature changes in the freezer chamber at 11 control points located in key zones of the volume.

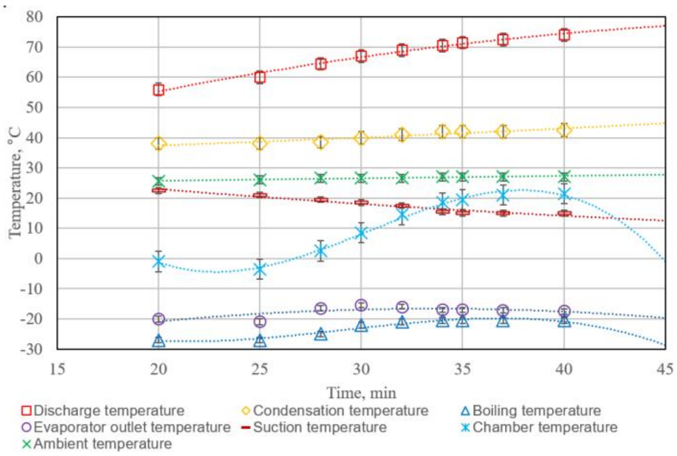


Figure 3 – Dynamics of temperature changes in the refrigeration cycle when a vessel with water at 40 °C is introduced

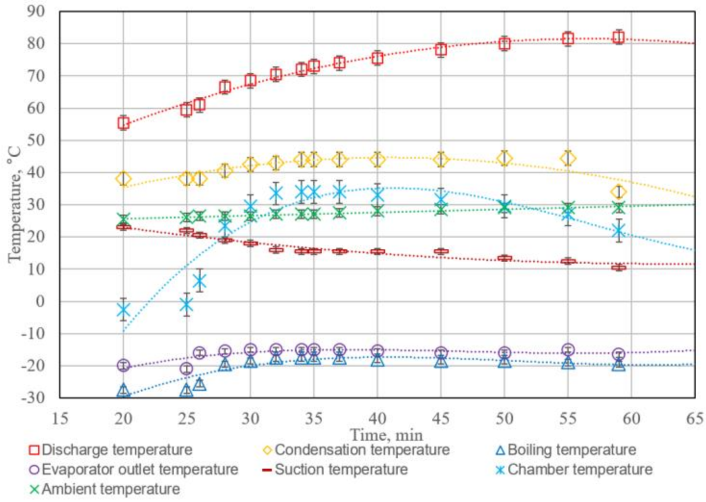


Figure 4 – Dynamics of temperature changes in the refrigeration cycle when a vessel with water at 60 °C is introduced

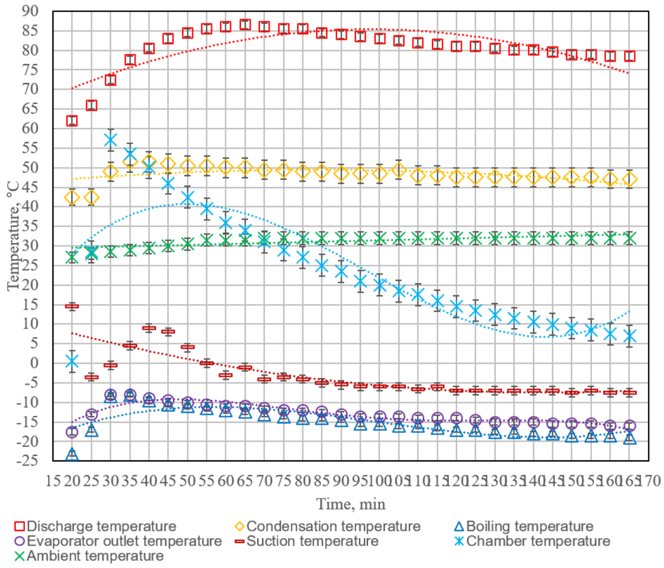


Figure 5 – Dynamics of temperature changes in the refrigeration cycle when a vessel with water at 80 °C is introduced

Analysis of the presented graphs allows for a comparative assessment of the temperature distribution within the chamber at different time intervals, as well as the identification of specific thermal behavior characteristics of the system under shock-loading conditions. These data serve as the basis for determining the degree of cooling uniformity, the efficiency of heat removal, and the rate of transition to the steady-state regime for each of the investigated modes.

Further comparison of the thermograms makes it possible to identify the most balanced operating mode, providing both an acceptable stabilization time and uniformity of the temperature field, which is a key criterion for evaluating the operational efficiency of the refrigeration system.

Analysis of the presented thermograms (Figures 3÷5) allows identifying characteristic features of the transient processes under different levels of thermal load. The duration of the transient processes directly depends on the initial temperature of the loaded element and determines the stability and uniformity of cooling.

In the 40 °C mode (Fig. 3), a rapid decrease in temperatures at the main control points is observed. By the 35th÷40th minute, the system reaches a quasi-steady state. However, local temperature differences between the central and peripheral zones of the chamber persist, particularly in the areas corresponding to sensors 1 and 11, indicating non-uniformity in the temperature field distribution.

In the 60 °C mode (Fig. 4), the cooling process occurs more uniformly despite the increased thermal load. The transient process is completed approximately by the 55th–60th minute, after which the temperature curves stabilize with minimal deviations. This indicates a balanced distribution of heat flows and efficient operation of the refrigeration system at this level of load.

The 80 °C mode (Fig. 5) is characterized by the maximum thermal load and, consequently, a significant increase in the duration of the transient process – up to 165 minutes. Temperature gradients between different zones of the chamber persist longer, indicating increased compressor load and reduced uniformity of cooling.

Comparison of the temperature diagrams shows that the nature of the shock load affects not only the duration of the transient process but also the dynamics of the main components of the refrigeration cycle. As the temperature of the loaded object increases from 40 to 80 °C, a more rapid rise in discharge temperature is observed, indicating increased compressor load. The boiling temperature changes less intensively, while the suction temperature remains elevated, reflecting reduced heat exchange efficiency in the evaporator. With increasing heating temperature, the difference between the discharge and suction temperatures grows, which is directly associated with higher energy consumption. Furthermore, the condensation temperature at 80 °C stabilizes significantly more slowly than at 40 °C and 60 °C, indicating condenser overload.

Thus, an increase in the level of thermal load leads to higher energy consumption, greater temperature gradients, and prolonged transient processes. Among the investigated modes, heating to 60 °C proved to be optimal, providing sufficient thermal load for evaluating the dynamic characteristics of the system while maintaining the transient period duration and cooling uniformity at an optimal level. Therefore, further experiments on the analysis of operating modes and fault diagnostics were conducted at this heating level.

The calculations performed in accordance with the methodology of Sakun A.A. [16] confirm the adequacy of the experimental data and allow a quantitative assessment of changes in cooling capacity under different levels of thermal load. Figure 6 shows the dependence of cooling capacity on time at three levels of thermal load, illustrating the nature of changes in system efficiency during transient modes.

Figure 6 shows the dependence of the cooling capacity of the refrigeration system on time at different levels of thermal load – 40 °C, 60 °C, and 80 °C. Each curve reflects the dynamics of the refrigeration cycle's efficiency during the transition from system start-up to the quasi-steady-state regime.

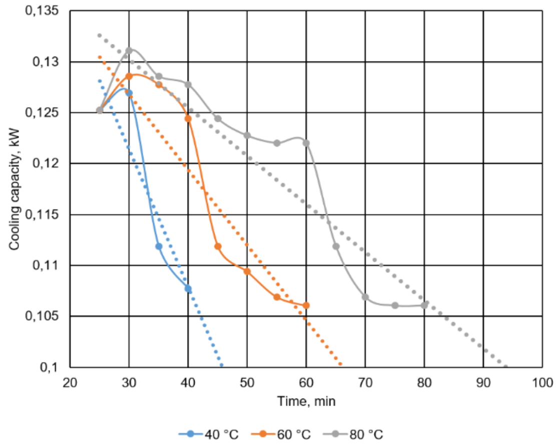


Figure 6 – Dependence of cooling capacity on time at different levels of thermal load

In the 40 °C mode, the highest and most stable cooling capacity is observed throughout the experiment. The curve exhibits a steep initial segment, indicating a rapid increase in efficiency after the compressor is switched on. By the 35th÷40th minute, the cooling capacity stabilizes at approximately 0.13 kW, indicating that the system has reached a steady operating regime under a moderate thermal load.

In the 60 °C mode, the curve is smoother: a gradual decrease in cooling capacity from 0.138 kW to 0.124 kW is observed by the end of the experiment (59th minute). This behavior indicates a more pronounced thermal load, which increases the compressor workload and reduces heat exchange efficiency in the evaporator. Nevertheless, the system demonstrates stable operation without sharp fluctuations, confirming its ability to adapt to the increased thermal input.

The most significant changes are observed at 80 °C. The curve shows a pronounced downward trend, with cooling capacity gradually decreasing from 0.133 kW to 0.106 kW by the end of the cycle (165 minutes). This indicates increased thermal inertia of the system and higher energy losses. In this mode, the compressor operates at maximum load, which is accompanied by an extended transient process and reduced efficiency of the entire cycle.

Approximating the obtained results as a linear relationship allows for assessing the intensity with which the system reaches a steady state after a disturbing thermal load in the cooled low-temperature circuit. The slope of the straight lines characterizes the rate of system stabilization: the smaller the slope, the longer the system takes to compensate for the thermal disturbance (as in the 80 °C mode). In this case, the increase in time until the start of stabilization amounted to 33 % for 60 °C and 50 % for 80 °C compared to the 40 °C mode.

Comparative analysis of the three modes shows that increasing the temperature of the loaded object leads to a decrease in actual cooling capacity and an increase in the duration of the transient process. At 40 °C, the system reaches a stable regime significantly faster, whereas at 80 °C, cooling becomes less intensive and more energy-consuming.

Thus, for further studies of the refrigeration system under various deviations from the nominal operating mode, the optimal thermal load level from the perspective of balancing power and transient duration is 60 °C, at which the refrigeration system maintains sufficient efficiency under a moderate thermal load.

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## ИССЛЕДОВАНИЕ ДИНАМИКИ ОТКЛИКА ХОЛОДИЛЬНОЙ СИСТЕМЫ В УСЛОВИЯХ РЕЗКОГО ТЕПЛОВОГО ВОЗДЕЙСТВИЯ


*В данной статье рассматривается оценка работы парокомпрессионной холодильной установки при воздействии шоковой тепловой нагрузки. Исследование проведено на модернизированном экспериментальном стенде «Холодильник-2» с системой цифрового мониторинга, включающей дополнительных 24 датчика DS18B20 и микроконтроллер STM32. Основной целью являлось сравнение поведения установки при внесении объекта с температурой 40, 60 и 80°C после выхода на квазистационарный режим. Проведён анализ температурных кривых, продолжительности переходных процессов и времени выхода на новый стационарный режим.*

*Дополнительно рассмотрены особенности распределения температур внутри морозильной камеры, а также влияние тепловой нагрузки на работу основных элементов цикла.*

*Научная новизна исследования заключается в комплексном рассмотрении переходных процессов, возникающих при резких тепловых воздействиях, с акцентом на их продолжительность и устойчивость системы. Практическая значимость работы связана с возможностью применения полученных результатов для оптимизации режимов эксплуатации холодильных установок, а также для проведения диагностики неисправностей в условиях, приближённых к реальным. В качестве оптимального выбран режим воздействия 60 °С, который обеспечивает баланс между продолжительностью переходного процесса и равномерностью распределения температур.*

***Ключевые слова:*** *холодильная установка, тепловая нагрузка, шоковое воздействие, температурные кривые, переходные процессы, холодопроизвводительность.*

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## КҮРТ ЖЫЛУ ӘСЕР ЕТУ ЖАҒДАЙЫНДА ТОҢАЗЫТҚЫШ ЖҮЙЕСІНІҢ ЖАУАП БЕРУ ДИНАМИКАСЫН ЗЕРТТЕУ

*Бұл мақалада бу-компрессиялық тоңазытқыш қондырғысының шоктық жылулық жүктеме жағдайындағы жұмысы қарастырылған. Зерттеу қосымша 24 DS18B20 датчигі және STM32 микроконтроллері бар цифрлық мониторинг жүйесімен жабдықталған «Холодильник-2» тәжірибелік қондырғысында жүргізілді. Негізгі мақсат – қондырғының квазистатикалық режимге шыққаннан кейін 40, 60 және 80°C температурадағы нысан енгізілген кездегі жұмысын салыстыру болды. Температуралық қисықтар, ауыспалы процестің ұзақтығы және тұрақтану уақыты талданды. Сонымен қатар, мұздатқыш камерасының ішіндегі температураның таралу ерекшеліктері мен циклдің негізгі элементтеріне жылулық жүктеменің әсері зерттелді.*

*Зерттеудің ғылыми жаңалығы – кенеттен жылулық әсерлер кезінде туындайтын ауыспалы процестерді кешенді талдау, олардың ұзақтығы мен жүйенің тұрақтылығына назар аудару. Жұмыстың практикалық маңыздылығы алынған нәтижелерді тоңазытқыш қондырғылардың жұмыс режимдерін оңтайландыруға және нақты жағдайларға жақын ортада ақауларды диагностикалауға қолдану мүмкіндігімен байланысты. Оптималды режим ретінде 60 °С таңдалды, ол ауыспалы процестің ұзақтығы мен температураның біркелкі таралуы арасындағы тепе-теңдікті қамтамасыз етеді.*

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*Received 17.10.2025*
*Revised 07.12.2025*
*Accepted 08.12.2025*