Modelling of single-stage refrigerating machine of provision chamber

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Abstract. The single-stage refrigerating machine model's review has been made. The analysis of these models and the possibility of its application are given. The model of a single-stage refrigerating plant of the provision chamber is developed. The results of simulation of the seawater heat sink of the refrigeration unit in various operating conditions are presented.

1. Introduction

The development of a vessel's refrigerating plant model is a difficult task in view of features of thermodynamic cycles of the refrigerator and the heat-exchanging equipment used in the modern shipbuilding. To research the processes in the refrigerating system of the transport vessel, it is necessary to develop a mathematical model. The mathematical model will consider a row of the external features influencing the operation of the refrigeration unit such as the parameters of environment, the mass in the refrigerating chamber, temperatures of cooling liquid in the condenser. The task of refrigeration unit simulation as a complex system of interdependent elements has not been solved sufficiently yet [1].

For models of the unified elements, the calculations of an adequate parameter range become correct in connection with a single definition of the adequate range and the multiplicity of use of these elements in case of design of different systems. The knowledge of the adequate parameter range allows one to choose correctly models of elements from among available and increase a calculation accuracy. In case of determination of the adequate range, it is necessary to choose the set of the input and output parameters corresponding to the considered properties in the model [2].

The increasing number of external factors enlarges the application of the model; however it increases a price of the determination process of the adequate range. The choice of a set of output parameters and the level of corresponding input parameters will be rather small, rather stable and make a standard set of output parameters.

At the first stage for model development, it is necessary to make the analysis of the existing models to define the basic principles of simulation.

The purpose of this article is the analysis of the existing models and the development of a mathematical model of the refrigeration unit of the provision chamber. The model has to consider a row of the outer features influencing the installation operation.

2. Analysis of the existing models

In Figure 1, the refrigeration unit used as the provision chamber of the vessel with output of heat in outboard water is shown.

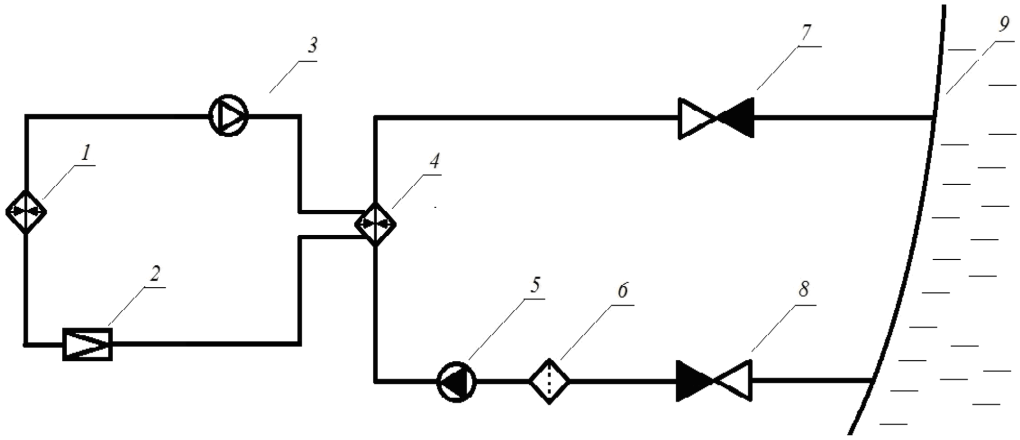

Figure 1. The scheme of output of heat in outboard water from the refrigerator installation:
1, 4 – heat exchanger; 2 – thermostatic expansion valve; 3 – compressor; 5 – seawater pump; 6 – filter; 7, 8 – nonreturn valve; 9 – vessel's shell

The basic principles applied when modeling refrigerators are given in publications [1, 3, and 9].

In publication [3] the problem of carrying out a numerical experiment is solved depending on compressor capacity. The compressor for the refrigeration unit is defined, and thermal capacity of the condenser is defined. The received solution of the specified tasks allows defining the set of the operating conditions in the form of dependence of refrigerating capacity of environment temperature. For simulation, the MatLab Refrigeration Utilities is used. The peculiarity of this model is its application to low capacity single-stage refrigerating plants.

In publication [4], simulation of the refrigeration unit of small productivity, based on the elementary circuit, is performed. The calculation of temporal dependences and the experimental temporal dependences of temperatures is given in the evaporator, the condenser and environment temperatures. Based on calculations, a task of optimum determination of the filled coolant amount is presented. The heat balance equation of processes in the refrigeration unit is assumed as a basis of a mathematical model to describe the main working cycle. The heat balance is presented in the form of heat rate equality of the capacity condenser and the capacities of the compressor and the evaporator:

$$Q_{cond} = Q_0 + N_k,$$

where Q_{cond} – the heat rate of the condenser, Q_0 – the heat rate of the evaporator, N_k – compressor power.

The equations of processes in the evaporator and the condenser are:

$$Q_0 = k \cdot F_{isp} \cdot (T_{kond} - T_{kam})$$

$$Q_{cond} = k \cdot F_{kond} \cdot (T_{kond} - T_z),$$

where k –heat transfer coefficient; F_{isp} – the heat exchange area of the evaporator, F_{kond} – the surface area of heat exchange area of the condenser. T_{kond} – coolant temperature in the condenser; T_{kam} – air temperature in the fridge chamber, T_z – temperature of outboard water.

The operating mode of the refrigeration unit is defined by interrelation of temperatures of the external environment and characteristics of system parts. Figure 2 shows a typical refrigerator cycle on the chart logarithm of pressure $lg(p)$ and refrigerant enthalpy I [8].

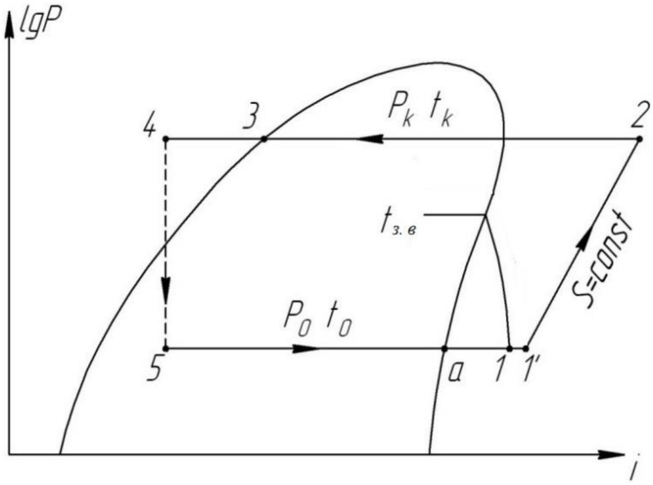

Figure 2. The typical refrigerator cycle

The thermal flux to the refrigerator is implemented through the surface of the fridge chamber walls and heat insulation is:

$$Q_{pr} = k_{org} \cdot F_{ogr} \cdot (t_{zin} - t_{kam}),$$

where k_{ogr} – heat transfer coefficient; F_{ogr} – fridge chamber walls area, t_{zin} – environment temperature; t_{kam} – temperature in the chamber, Q_{pr} – thermal current.

Thermal flux from the construction is:

$$Q_{pr1} = k_{org} \cdot F_{ogr} \cdot (T_{zin} - T_{kam}),$$

Thermal flux of cooled goods in the fridge chamber is:

$$Q_{pr2} = s_{pr} \cdot m_{pr} \cdot (T_{nach} - T_{zad})/t,$$

where k_{ogr} – heat transfer coefficient; F_{ogr} – fridge chamber walls area; s_{pr} and m_{pr} – specific heat capacity and mass of the cooled product; (T_{nach} – T_{zad}) – the difference of temperatures of the cooled chamber at the beginning and at the end of processing; t – freezing time.

There are two refrigeration unit operation modes: steady-state heat exchange and transient condition. The thermal balance mode (steady-state heat exchange) is characterized by a constancy in time of all variables, when thermal flux is equal to refrigerating capacity. For the transient condition, the equality is not satisfied, and the temperature in chamber T_{kam} is described by formula [5]:

$$\partial T_{kam}/\partial t=(Q_0-Q)/(s_{pr}\cdot m_{pr}).$$

The temperature in the fridge chamber is maintained by the periodic compressor operation [6, 10-13].

3. The modelling of the single-stage refrigerating machine

In the present research, the MatLab Simulink Refrigeration Utilities package is used for a creation model of the refrigeration unit [7]. According to the scheme in Figure 1, the mathematical model of the refrigeration unit has been created. Refrigerant R22 is applicated in the refrigeration unit. The model consists of the temperature indication unit (*Refrigerator Temperature*), the temperature setting mechanism (*Target Temperature*), the control unit (*Control*), the screw compressor unit (*Compressor*), the condenser unit (*Condenser*), the temperature-controlled valve (*Valve*), the fridge chamber unit (*Refrigerating Chamber*), the refrigerant parameters unit (*Two-Phase Fluid*). Operating parameters of the model are: an initial condition of temperature in refrigerator - 259 K, initial pressure on the input of the compressor - 0,2 MPa, on the output of the compressor - 0,95 MPa, the power of the compressor - 2,8 kW; the temperature of cooling water is 293 K, the condenser surface area is 22,6 m^2, the area of the fridge chamber is 12 m^2, mass of the cooled product – 50 kg. In the heat sink coefficient of outboard water, it is 3500 W/(m^2·K).

Figure 3 shows the developed mathematical model. The modeling allows obtaining surge characteristics of system parameters depending on initial parameters, such as the environment temperature, fridge chamber temperature and the parameters of the compressor load.

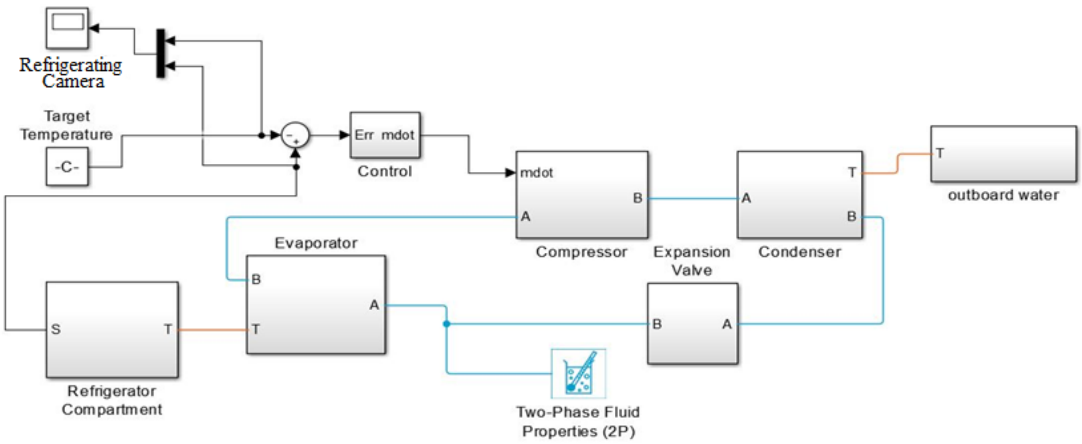

Figure 3. A scheme of Simulink model of the refrigeration unit

In Figure 4, the transient response of temperature of the fridge chamber in comparison with the set temperature (the block of the Target Temperature control point adjustment) of 259 K is shown (time of modeling is 3600 sec).

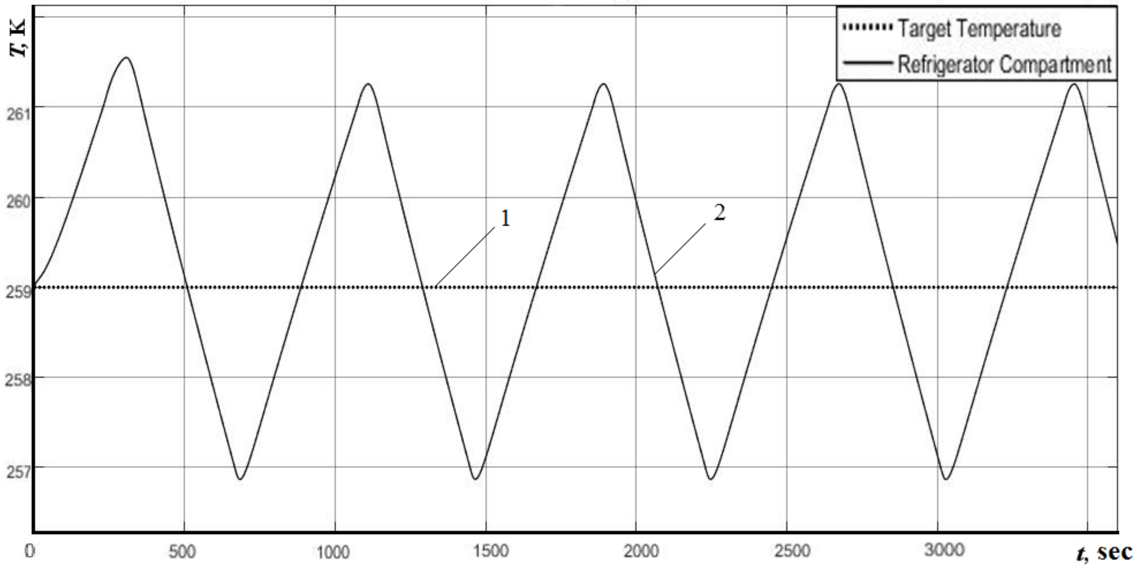

Figure 4. Dependences of a transient response of temperature in the provision chamber: 1 – set temperature; 2 – temperature in the chamber

The diagram of the evaporator temperature control is given in Figure 4. The evaporator temperature corresponds to regulation by the positional regulator in operation of the compressor. In the system, the hysteresis curve is set to be 2 K. Adding a mass load in the chamber and increasing the inside temperature to make it higher than 2 K, the compressor unit starts. The width of a hysteresis curve can be increase to reduce the number of switching of the compressor.

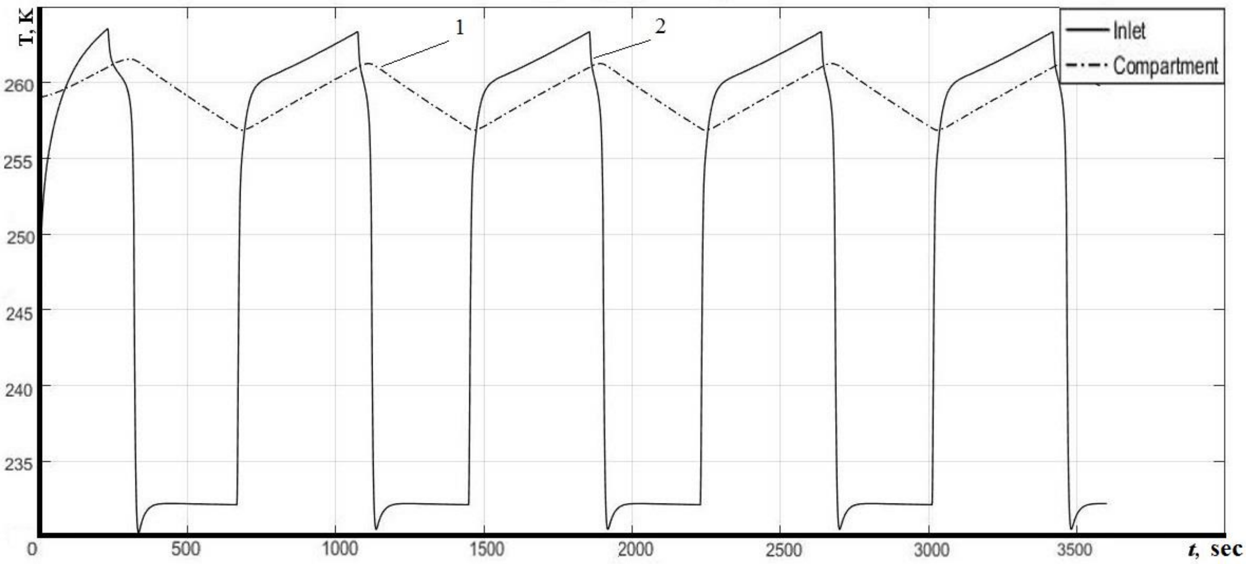

Figure 5. A diagram of a transient response of temperature in the evaporator: 1 – the set temperature; 2 – temperature in the evaporator

In Figure 5 the transient response of temperature in the evaporator in case of cooling system operation cycles is provided. At the beginning of operation, the evaporator of the refrigerator has the set temperature of 259 K. The diagram shows that the temporal amplitude of the transient response of temperatures in the evaporator is 480 seconds that correlates with results of previous simulation [4]. According to the diagram, the cycle in the evaporator has equal intervals and amplitudes and is also normalized for the set parameters.

The transient response of pressure in the compressor is shown in Figure 6. The compressor pressure increases retaining on a temporal interval of 480 seconds with increasing of capacity. On a temporal interval of up to 360 seconds, there is the non-uniformity of a pressure curve. It can be made to process a refrigerator compressor discharge in a nominal operation mode in installations such as admissible.

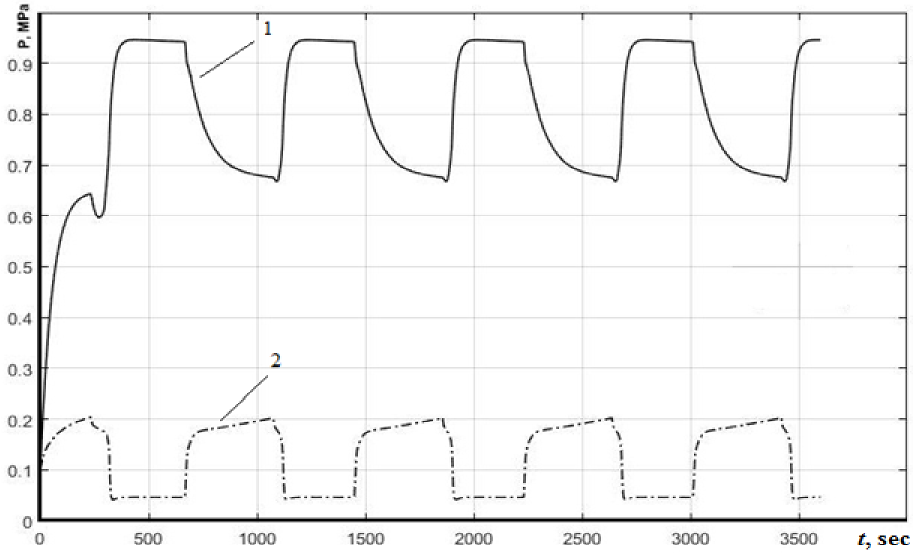

Figure 6. A diagram of a transient response of pressure in the compressor: 1 – outlet compressor pressure; 2 – inlet pressure compressor

Opening the temperature-controlled valve, the refrigerant consumption grows from 5 to 40 gram /sec and changes in the opposite direction when closing. Curve 1 in Figure 7 shows the refrigerator compressor operation at the time of refrigerant compression; curve 2 shows the operation of the temperature-controlled valve. The recurrence of the consumption repeats at regular intervals that specifies the set modes in the refrigerator unit.

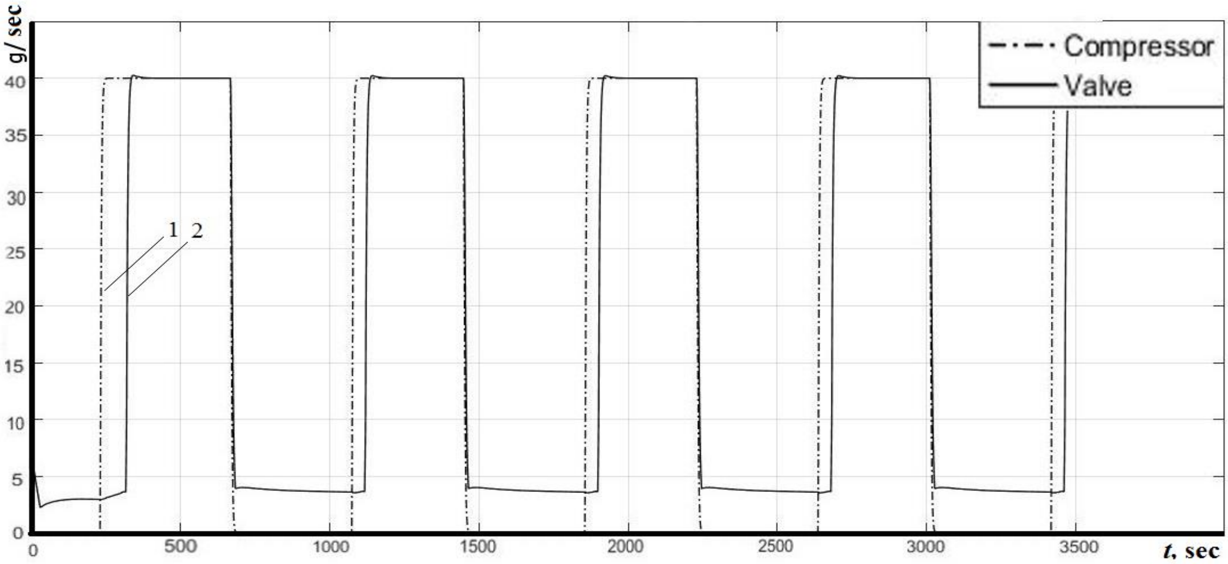

Figure 7. A diagram of a transient response of a refrigerant consumption: 1 – refrigerant consumption during the compressor operation at the time of refrigerant compression; 2 – refrigerant consumption during the operation of the temperature-controlled valve

In Figure 8, the diagram of a transient response of compressor power is shown. The cycles of power increasing depend on the requirement for the refrigerant amount for the refrigerating system. The temporary interval of compressor operation is 480 sec.

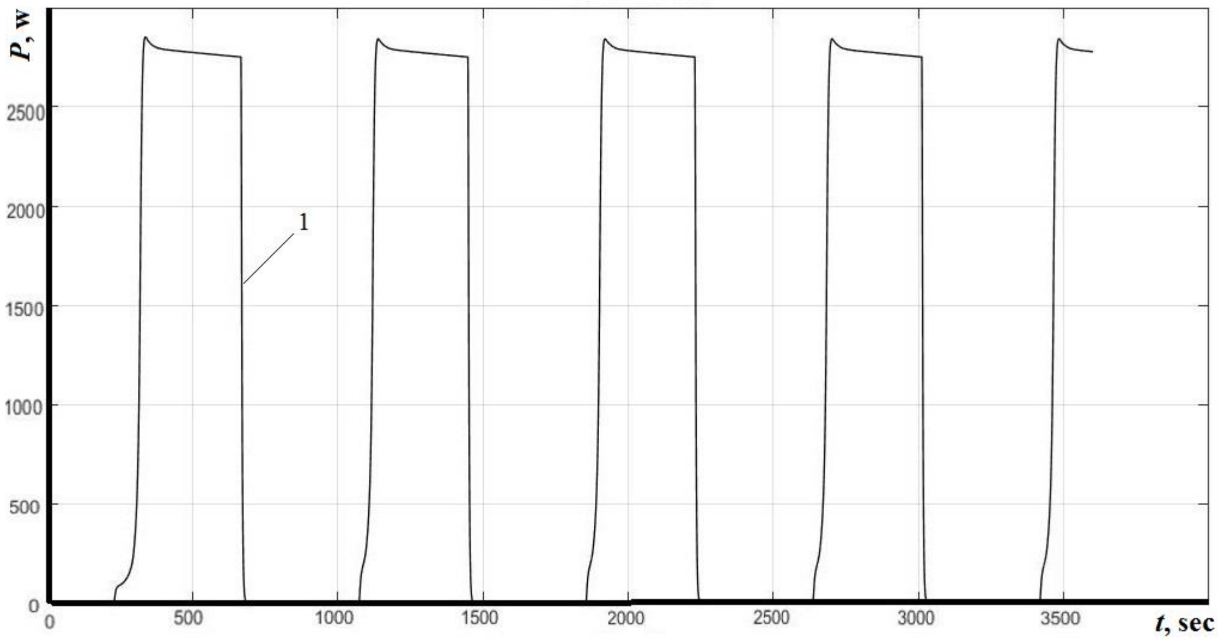

Figure 8. A diagram of a transient response of compressor power consumption

The diagram of the transient response of the fridge chamber temperature with loading mass of 50 kg is shown in Figure 9. A specific heat capacity of inner goods is 3500 J/(K•kg). The simulation of the fast freezing mode in the chamber is performed. The diagram shows the initial temperature of goods at 286 K and during 7000 sec, the chamber temperature increases. The refrigeration unit operates in a nominal operation mode with equal amplitudes of compressor unit switching.

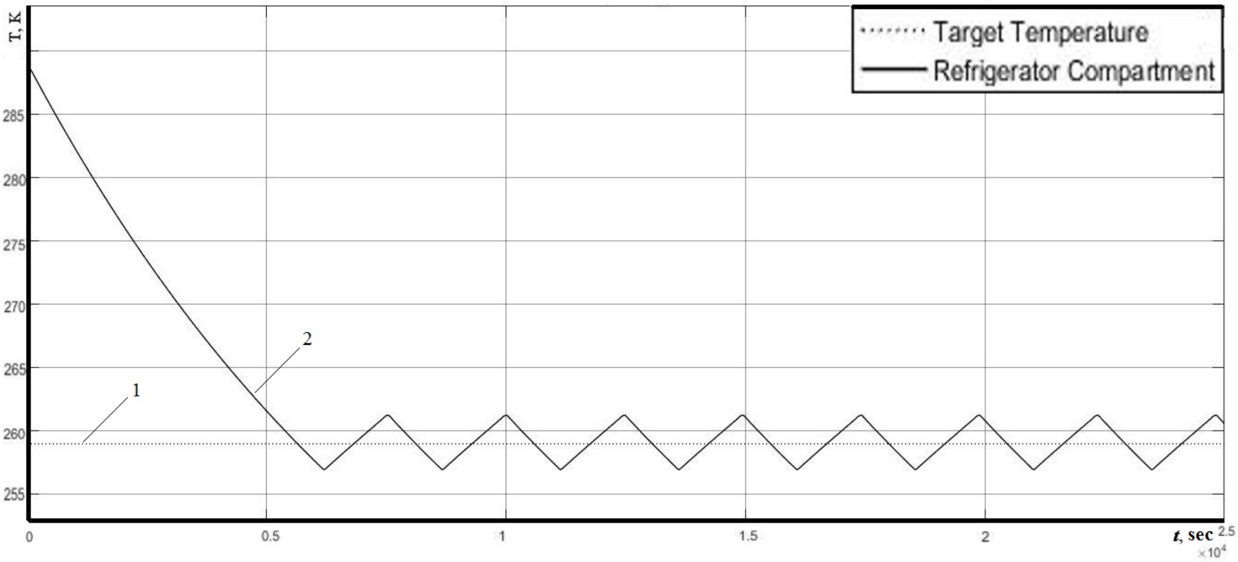

Figure 9. A diagram of a transient response at temperature regulation (loading mode): 1 – the set temperature; 2 – temperature in the fridge chamber

In Figure 10, the diagram of the transient response of the compressor pressure at cooling of the fridge chamber is shown. The compressor operates with nominal indices through 7200 sec after reaching the set temperature.

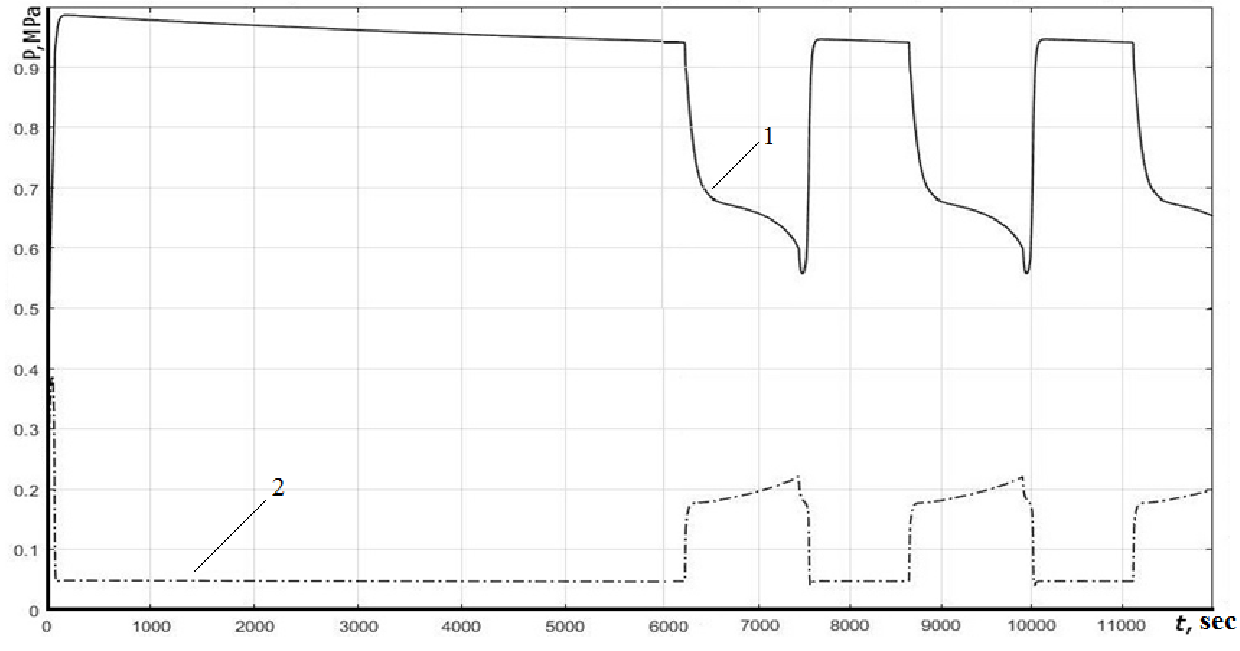

Figure 10. A diagram of a transient response of the compressor pressure: 1 – the compressor outlet pressure; 2 –the compressor inlet pressure

4. Conclusion

The performed analysis of the existing mathematical models of refrigeration units with the single-stage refrigerator indicates a narrow range of its application. The observed models allow one to research in particular processes only in selected nodes and plants of the refrigeration unit. Obtained results of study of the existing mathematical models give opportunities to make conclusion on its applicability in practice, feasible only with other detailed models.

The developed model considers features of the heat sink in outboard water that corresponds to the existing schemas of vessel refrigeration units of fridge chambers. The results received during the studies of the refrigeration unit correlate with results of other researches. Based on received results, it became possible to conclude about adequacy and extension of application of different types of refrigerator plants. The operation modes of the plant at different capacities of the fridge chamber are investigated. Operational characteristics of refrigeration units are designed with application of the specialized software for creation of the model. That gives the opportunities to upgrade and extend the solution of further tasks concerning the study of refrigeration units.

It is expedient to research further tasks of temperature regulation in the fridge chamber when using combined control of operation of the compressor and the temperature-controlled valve and increasing the efficiency of the heat sink of the refrigeration unit in outboard water.

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