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JUSTIFICATION OF THERMODYNAMIC EFFICIENCY OF THE NEW AIR HEAT PUMP IN THE SYSTEM OF REDISTRIBUTION OF ENERGY RESOURCES AT THE ENTERPRISE

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ABSTRACT

The article evaluates the energy resources of the components of the environment and the prospects for their use on the redistribution with the creation of local zones of cooling and heating. The physical basis of the principle and systems of redistribution and transformations of energy resources of environments with coverage of the role of compensation processes is given. The use of closed energy circuits with intermediate energy sources, which are subject to phase transitions of evaporation and condensation, and data of energy potentials of ambient air, which are practically achievable for use on this basis, is proposed. The article shows the advantages of arranging systems for redistribution of thermal potentials based on the use of phase transitions of material media. Determination of energy balances of energy redistribution systems is carried out with the indication that in the end, such a method is the most energy-efficient. Upon completion of technological tasks, local areas with different energy potentials and temperatures degrade in dissipation processes and transform to the level of environmental indicators. This means interfering with the environment only at the level of energy costs in compensation processes. The article shows the transition to secondary recovery systems of energy resources based on the use of primary energy sources in environmental transformations at the levels of increasing their energy potentials and providing phase transitions with appropriate mathematical formalizations. A regression analysis of the feasibility of using primary energy potentials is given. It is proved that in the heat pump due to the generated mechanical energy the heat return at the level of the lost one. The estimation of the general condition of processes at power effects is given. The offered air pump and system of realization of a refrigerating cycle are considered. The redistribution of energy potentials of natural, forcibly created environments or systems and the synthesis on this basis of powerful heat fluxes in combination with advanced control methods, allows you to control their values of thermodynamic parameters.

Keywords: energy circuits; recuperation; phase transitions; internal resources; heat pump; condenser

INTRODUCTION

The physical parameters of the globe, relating to the magnetosphere, atmosphere, lithosphere, and hydrosphere, correspond to the conditions of existence of the entire biological world and human society. In this definition, the energy component is no less important than the material, despite its differences from the coordinates, seasons, or time of day. After all, even under the harsh conditions of the Arctic and Antarctic, the air levels are quite far from absolute zero. Moreover, this corresponds to areas of human habitation with air temperatures above 0 °C.

The existence of the Earth's hydrosphere and lithosphere is accompanied by energy potentials created by interactions on a planetary scale. At the same time, the stabilization of the energy balance in this interaction ensures the existence of the biosphere under the accepted conditions. From this point of view, the authors **(Nochnichenko, and Yakhno, 2020)** believe that maintaining this balance or at least strict restrictions on its violation are crucial. Therefore, there is no alternative to the use of renewable resources and one of these areas is the use of technologies for redistribution of energy potentials of the environment based on heat pumps, air conditioners, refrigeration systems.

The properties of heat pumps provide **(Matsevity et all., 2014)** their significant use in connection with the possibility of transformation of energy potentials in a wide range of temperatures. However, the application of applied problems often requires the expansion of these intervals. In the global dimension, one-third of energy consumption is associated with the industrial sector ultimately consumed as heat.

Analysis of model approximations of medium types

A significant amount of modern research concerns the topic of opportunities for transformations of energy potentials. Research **(Kosmadakis, 2019)** on the prospects of recovery of low-temperature thermal waste is devoted to assessing the potential of industrial (high-temperature) heat pumps for waste heat regeneration **(Xu et al., 2019)**. In the paper **(Lei Wang et al., 2018)** it is presented that the expansion of the theoretical base is supplemented by experimental studies of the characteristics of the heat pump of the triple loop for heat recovery of exhaust air in winter. The authors **(Hyunjeong et al., 2017)** made a clear technical addition in search of energy-saving potentials. They pointed out that the use of heat pipes on geothermal sources is relevant.

It should be noted that in the work of the authors **(Wang et al., 2018)** the traditional ways in the technical representation of heat transfer processes logically supplement by options for heat recovery in drying plants of the food industry.

The authors **(Lim et al., 2019)** focused on absorption heat pumps in heat flow recovery studies simultaneously with the water-saving modification for a cogeneration system with a steam-gas combined steam cycle. Geothermal heat pumps are recognized as one of the promising technologies. According to the authors **(Cui et al., 2019)**, attention to this needs a feasibility study due to high capital investment and the cost of installation and technological support. In experimental researches, the problem of the creation of the system of dehumidification of fresh air with the use of the heat pumps completed with the heat exchangers in which the working surfaces covered with a dehumidifier is solved. The research **(Bin Hu et al., 2019)** is investigated the centrifugal heat pumps with the utilization of the fulfilled heat with considerable thermal power and high temperature of water supply.

Therefore, the rational use of heat pumps with simultaneous heating and cooling of local areas is carried out based on exergy analysis. Here, the prototype heat pump operates in three main modes. The authors **(Paul Byrne, and Redouane Ghoubali, 2019)** consider these regimes quite clearly, who noted that:

- the first – the heating mode which provides receiving of hot water with the use of heat available in ambient air;
- the second – the mode of cooling of cold water and heat removal to ambient air;
- in the third mode, hot water is supplied due to the heat taken away from the cold water.

Thus, the authors **(Woolley et al., 2018)** noted that the recovery of industrial thermal waste in a systematic approach is assessed at the level of limiting the negative effects on the environment.

Recent advances in heat pump systems **(Guo-Hua Shi et al., 2019)** involve the direct use of solar radiation, which is conducive to the environment through low-temperature environmental energy and solar radiation. It is shown that the integration of solar evaporators with photoelectric energy technologies in combination with thermal storage and the use of heat pipes is promising for use in different climatic conditions. Thus, thermal systems in which phase transitions are carried out with the relative ease of regeneration, remain relevant for theoretical and practical research.

Scientific Hypothesis

Defined in the form of phenomenological analysis of thermodynamic efficiency of air heat pump using the energy potential of the environment in the heat supply system and redistribution of energy resources and prospects for use in the food industry.

MATERIAL AND METHODOLOGY

Samples

The system of redistribution and transformations of energy resources of environments is considered. Theoretical and practical experience of thermodynamics specialists has allowed, among other things, to generalize the relationship between air heat capacity and temperature. Molar heat capacity at p = const, kJ / (kmol • K) is represented by the dependencies in the actual value in the interval 0-1000 °C:

$$c_{\mu p} = 28{,}7558 + 0{,}0057208t \tag{1}$$

and on average

$$\bar{c}_{\mu p}\Big|_0^t = 28{,}827 + 0{,}002708t\,. \tag{2}$$

Numerical values of heat capacities are given in Table 1, from which follows the possibility of certain comparisons.

Estimation of energy potential in 1 m^3 of air at a temperature of 303 K at a pressure of 1 bar, is:

$$Q_{pot} = c_p\, vT = 1.2971\ 1.0\ 303 = 393.0213\ kJ \tag{3}$$

Table 1 Heat capacity of air.

Temperature, °C	Heat capacity							
	Molar, kJ / (kmol • K)				Mass, kJ / (kg • K)		Volume, kJ / (m^3 • K)	
	$c_{\mu p}$	$c_{\mu v}$	$\bar{c}_{\mu p}\big\|_0^t$	$\bar{c}_{\mu v}\big\|_0^t$	$\bar{c}_p\big\|_0^t$	$\bar{c}_v\big\|_0^t$	$c_p\big\|_0^t$	$c_v\big\|_0^t$
0	29.073	20.758	29.073	20.758	1.0036	0.7164	1.2971	0.9261
100	29.266	20.951	29.152	20.833	1.0061	0.7193	1.3004	0.9295
200	29.676	21.361	29.299	20.984	1.0115	0.7243	1.3071	0.9362
300	30266	21.951	29.521	21.206	1.0191	0.7319	1.3172	0.9462

Cooling this volume of air to 272 K means heat transfer Q to the receiver. At the same time, we note that the same volume of air at -30 °C or 243 K has a potential of 315.1953 kJ. Thus, technological opportunities for the redistribution of energy potentials open up prospects for their transformation and use, due to the second law of thermodynamics.

Chemicals

Air is a mixture of gases. The composition of the air is not constant and varies depending on the area, region, and even the number of people around you. Air consists of about 78% nitrogen and 21% oxygen, the rest are impurities of various compounds. Its chemical formula is O2. Under normal conditions (temperature 0 °C, pressure 101.3 kPa) oxygen is in a gaseous state, with no mass of taste, odor, slightly heavier than air.

Instruments

The flow temperature at the pump inlet and outlet was determined, after which the temperature value was averaged. Several thermocouples were used to measure the flow temperature in the middle of the pipeline. The data of the primary temperature transducers were fed to the ADC, converted into a digital signal, and entered into the PC. Data registration interval - 10 s. Measurements were performed with chromel-kopel thermocouples, measuring device brand Expert (manufacturer Ukraine).

At regular intervals, the surface temperature t was measured. The surface temperature of the module was determined by a thermocouple embossed into the surface. At regular intervals, the air pressure was measured. Measurements were performed with a manovacuummeter OBMV1-1006f (manufacturer Ukraine). The value of pressure in the tables of properties of water vapor was determined by its temperature.

The determination of ambient air parameters was done by using a psychrometer brand VIT-2 (manufacturer Ukraine). There was a registration of air parameters, namely its temperature, humidity, moisture content, enthalpy. The measurement of these parameters was performed using the ADC module "Arduino" and a computer.

A digital humidity sensor SHT 10 was used to determine the parameters of the air coming from the pump. This allowed determining with high accuracy the characteristics of the air directly in the flow during the experiments. The program interface of the ADC converter is made in such a way that the change of air parameters from time to time is reflected in the form of graphical dependencies in the online mode. The use of such a scheme with the use of frequency control of the pump drive allowed to quickly intervening in the course of the experiment that simplifies its planning.

Laboratory Methods

The fluid flow simulation was performed using ANSYS CFD general-purpose computer software from ANSYS, Inc.

Software systems allow modeling and calculation of liquids and gases, heat and mass transfer processes, reacting flows. ANSYS CFD is fully integrated into the ANSYS Workbench environment, which is the basis of engineering modeling, it integrates all ANSYS tools and software.

The ANSYS Workbench environment provides general access to such tools as: communication with CAD-complexes, construction, and modification of geometry and calculation grid. The software package is widely used for modeling processes that take place in pumps, fans, compressors, gas, and hydro turbines, etc. The ANSYS CFD-Post postprocessor, which is part of the software package, can be used to create high-quality animations, illustrations, and graphics **(Bezbakh et al., 2009,; Basok, and Bazeev, 2017**; **Nochnichenko, and Yakhno, 2018)**.

Theoretical modeling of conditions of creation and reproduction of processes of redistribution of energy potentials of environment and recovery of secondary resources based on provisions and laws of technical thermodynamics is used.

The research of the process was carried out according to the Box-Benken plan, which allows obtaining the maximum amount of objective information about the influence of factors with the help of the smallest number of experiments.

Processing of the obtained experimental data set was performed according to well-known methods and statistical processing methods to obtain an empirical mathematical model:

$$Q_{ke} = f_Q(x_1; x_2; x_3)$$

using methods of correlation and regression analysis of the approximating function, which characterizes the influence of factors and their interaction on the optimization parameter, ie productivity.

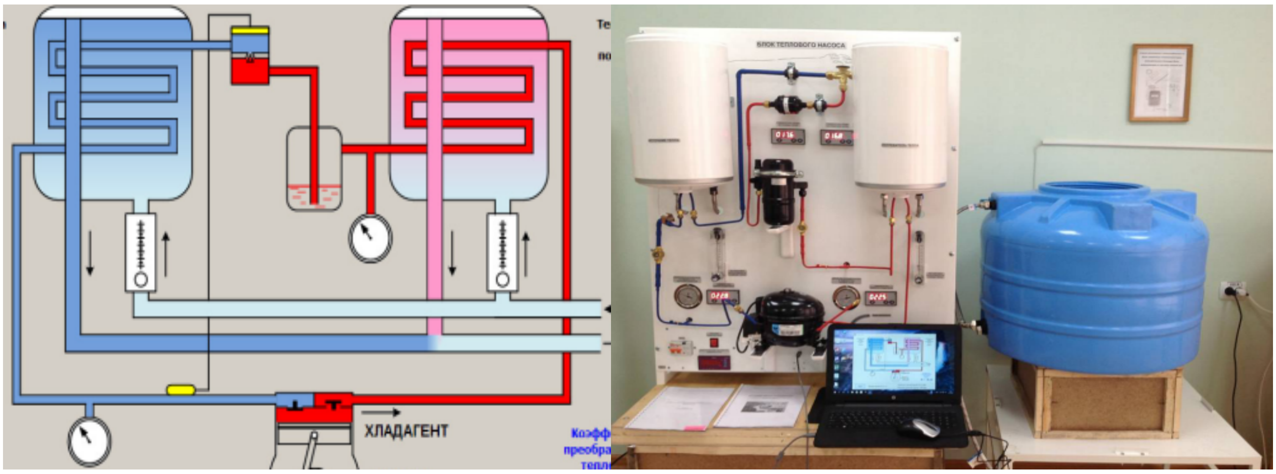
Based on the constructed regression equation, the contribution of each independent variable to the variation of the studied dependent variable is determined, ie the influence of factors on the performance indicator.

The experimental data set was processed using the Statistica-12 software package. The coefficients of the regression or approximating function equation, under the condition of orthogonality and symmetry of the plan-matrix of the planned factorial experiment, were determined according to the standard method according to known dependences.

The obtained results were statistically processed using the standard Microsoft Office software package.

Description of the Experiment

Theoretical and experimental research was performed fbased on the Problem Research Laboratory of the National University of Food Technologies. The study consisted of three parts. The first was to assess the energy potential of ambient air as the most accessible environment.



a *b*

Figure 1 software module (a) and General view of laboratory experimental setup (b).

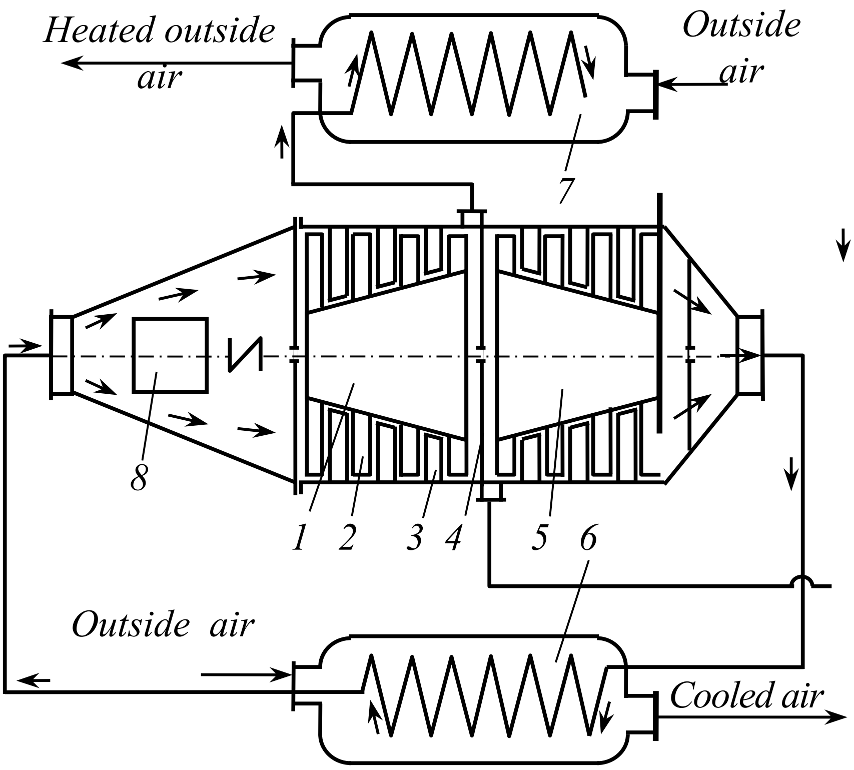


Figure 2 Air heat pump.

This part of the research is the basis for the creation of a modern air heat pump (a patent of Ukraine 17167) with the implementation of phenomenological studies relating to the redistribution of heat fluxes based on the second law of thermodynamics using a closed circulating air circuit.

The second part of the study concerns the thermodynamic features of achieving phase transitions of water as the main filler of food industry environments with the development of mathematical formalizations and estimation of energy consumption in the processes of heating the liquid phase and entropy transformations.

The third part is devoted to the implementation of phase transitions with the assessment of the energy potentials of the secondary pair. This creates a basis for the implementation of regenerative processes by increasing the pressures and temperatures in the compensation processes and subsequent condensation to obtain a liquid phase of H_2O in closed energy circuits.

In this article, we examine the first and second parts of the research, which substantiates our further direction of theoretically directed mathematical analysis.

Historically, humanity has received such opportunities after the creation of heat engines. In 1852, Lord Kelvin proposed new use of the heating machine for space heating. Kelvin called such a machine a heat pump, the task of which was to cool the cold outside air and transfer the received thermal energy at a higher temperature in the room. This unnatural process of heat transfer from a cold to a heated environment was carried out through the consumption of mechanical work. Each unit of mechanical work, brought to the ideal heat pump, before getting into the heated room "captured" 5 – 8 units of the heat of the outside air. Therefore, 427 k Gm of work at the inlet to the heat pump was converted into 6 – 9 kcal of heat at the outlet. The same kilocalorie formed by burning a certain amount of fuel is not supplemented by anything and remains one kilocalorie.

Burning some amount of fuel directly, bring in a heated room 1 kcal of heat. If the same amount of fuel will be burned in a heat engine, then only about 20%, equivalent to 85 kGm, will convert into mechanical work. If these 85 kGm are brought to the heat pump, it will provide 6 times more heat to the room, ie 6 • 85 = 510 kGm or 1,2 kcal. These ratios indicate the feasibility of using the primary energy potentials of the fuel in the circuit "heat engine - heat pump".

Thus, it is expedient to pay attention to equivalence in these thermodynamic transformations. Thus, the value of the coefficient of performance of heat engines is difficult or impossible to increase by 20%. In the heat pump due to the generated mechanical energy, heat returns to the level of lost.

The general structure and principle of operation of the model of the laboratory installation and the "Air Heat Pump" are shown in Figure 1 and Figure 2. The laboratory complex allows obtaining the dependence of the parameters of the heat pump installation on the temperature regimes of the heat supply and air conditioning system (Figure. 1 a, Figure 1b). In Figure 1a – the software module is given, and in Figure 1b – a general view of the laboratory experimental setup. The research aimed to establish the optimal parameters of the developed heat pump (Figure 2), which consists of a compressor 1 with blades 2, guides 3, partition 4, expander 5, heat exchangers 6 and 7, and a drive motor 8. It works as follows. The drive motor 8 provides rotational movement of the rotor of the compressor 1 and due to the interaction of the airflow with the blades 2 and the guide

Numerical data of energy costs and torque on the shaft of the electric drive depending on the load at a particular

Statistical analysis

It is worth recalling that a heat pump is an installation that converts low-potential natural thermal energy or heat from secondary low-temperature energy resources into the energy of higher temperature potential, which is already suitable for practical use. The transformations take place in the reverse thermodynamic cycle, and the transfer of energy from the lower temperature level to a higher one is performed due to a certain amount of mechanical (electrical) energy, which is externally supplied to the heat pump compressor and its design.

The algorithm for conducting experimental studies of the air heat pump, formalized in the form of a

the structural model scheme is shown in Figure 3. It involves determining the functional patterns of influence of individual input variables and their impact on the output

devices, 3 is its compression with increasing temperature. This compressed air enters the zone of separation of the internal volume of the pump and enters the heat exchanger 7, through which the external air flow. The latter absorbs thermal energy by cooling the compressed air. The cooled air is supplied to the expander 5, in which, expanding to a given final value of pressure, gives its energy. In this process, its temperature drops sharply to a temperature well below ambient temperature. Due to this, when in contact in the heat exchanger 6 with the flow of external air is heat transfer from the latter to the air circulating in a closed circuit. In the future, the cycle is repeated, and the cooled outside air is sent to further technological needs.

Pre-rough control of the compressor shaft speed of the compressor of the appropriate diameter was set using commands from the motor control panel of the control multisystem control and reading device Altivar 71 using Power Suite software version 2.3.0. The technical

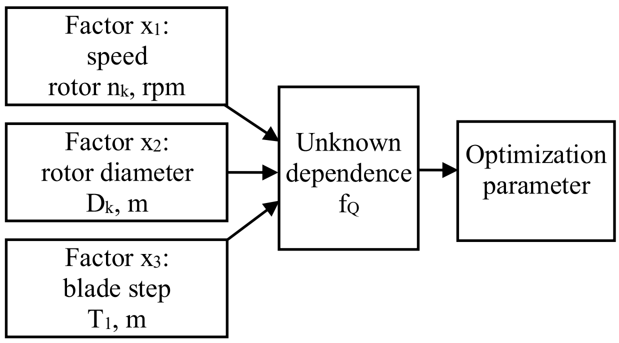


Figure 3 Scheme of the model of the planned experiment of the PFE 3^3 type.

capabilities of this device and software allow to smoothly change the speed of the motor shaft of the prototype laboratory installation in the range from 0 to 1300 rpm. The numerical value of the motor shaft speed (error within ± 1.5%) was recorded using a sensor type E40S6-10Z4-6L-5, which is connected simultaneously to the rotor of the motor and the multisystem device.

time of the experiment is displayed in the form of tabular data and graphical dependences on the PC monitor.

value, or optimization parameter. To verify the adequacy of theoretical research (theoretical model) of productivity Q_k, experimental studies of the model of the laboratory installation, which is shown in Figure 1 and Figure 2. To obtain an empirical regression equation characterizing the change in productivity Q_k depending on the parameters of the compressor rotor, implemented a planned three-factor experiment such as PFE 3^3.

The total number of experiments e N one repetition was determined by the formula:

$$Ne = P^k$$

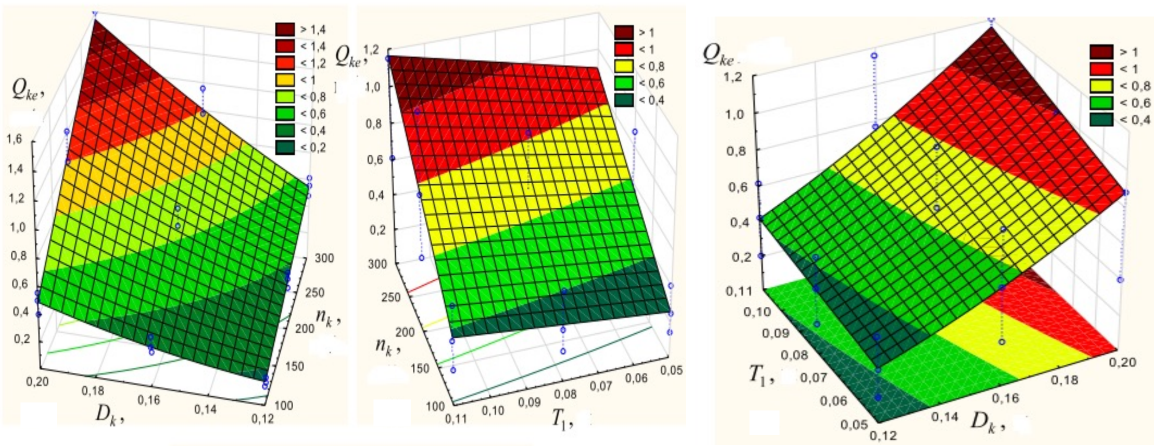
Where:

P – the number of levels of variation of the variable input factor;

k – the number of active variables of input factors in the experiment.

Table 2 The results of coding factors and levels of their variation.

Factors	Marking		Interval of variation	Levels of variation natural / coded		
	natural	coded				
Speed of rotation, n_k¢, rpm	X_1	x_1	100	100/-1	200/0	300/+1
Diameter D_k, m	X_2	x_2	0.04	0.12/-1	0.16/0	0.2/+1
Step T_1, m	X_3	x_3	0.03	0.05/-1	0.08/0	0.11/+1



(a) (b) (c)

Figure 4 Surface response changes in productivity in the form of functionality.

The experiments were performed in triplicate. The asymmetric plan-matrix of the planned three-factor PFE 3^3-type Box-Benkin experiment for three factors and three levels of factor variation had a total number of experiments equal to 27.

The independent variables were: the speed of the rotor of the compressor n_k, which was encoded by the index x_1, ie n_k; the diameter of the rotor of the compressor D_k, which is encoded by the index x_2, ie D_k; blade pitch T_1, encoded by the index x_3, ie T_1.

Structural model of a planned three-factor **(Krutov, 1989)** PFE-type experiment 3^3 shown in Figure 3.

Thus, to study the performance of Q_{ke}, an approximate mathematical model in the form of a functional dependence was chosen.

$$Q_{ke} = f_Q\,(x_1; x_2; x_3).$$

When compiling the plan-matrix of experiments, coded notations of upper (+1), lower (-1), and zero (0) levels of variation by factors were introduced **(Krutov, 1989)**, ie a three-factor experiment was performed at three levels of variation by input factors or a planned PFE 3^3 type experiment was implemented.

The results of coding of variable input factors, the upper and lower level of variation of each factor, and the interval of its variation are given in Table. 2.

Because during the experiments independent variable input factors, ie n_k are inhomogeneous, ie they all have different physical units and different orders of arithmetic numerical values of units, they were led to a single system of calculations by switching from the entered notation coded values to real (natural) values. Made a randomized plan matrix of the planned three-factor experiment type PFE 3^3.

After estimating the statistical significance of the coefficients of the regression equation and checking the adequacy of the mathematical model of the logarithmic function, we obtained a regression equation that characterizes the functional change in productivity in natural quantities **(Krutov, 1989)**.

$$Q_{ke}=0.81+0.61\ln(n_k)+1.33\ln(D_k)+0.31\ln(T_1) \quad (4)$$

With the probability level p = 0.95 and the value of the t-alpha criterion equal to 2.053, the following statistics were obtained: coefficient of multiple determination D = 0.893; multiple correlation coefficient R = 0.945; standard deviation of the estimate s = 0,150; Fisher's F-test is 64,212. The coefficient D is significant with the probability level P = 1.00000. The regression equation (4) characterizes the change in the performance of the air heat pump depending on the design and kinematic parameters within the following limits of change of input factors: speed nk (from 100 to 300 rpm); diameter Dk (from 0.12 to 0.2 m); blade pitch T1 (from 0.05 to 0.11 m). The functional change in productivity depending on the change in Qke factors is directly proportional - with increasing speed, diameter and pitch, the value of productivity also increases.

According to the regression equation (1), the response surface of the functional change in the productivity of Qke in the form of a functional is constructed:

$Q_{ke}= f_Q(n_k; D_k)$ *(Figure 4, a);*
$Q_{ke}= f_Q\,(n_k; T_1)$ *(Figure 4, b);*

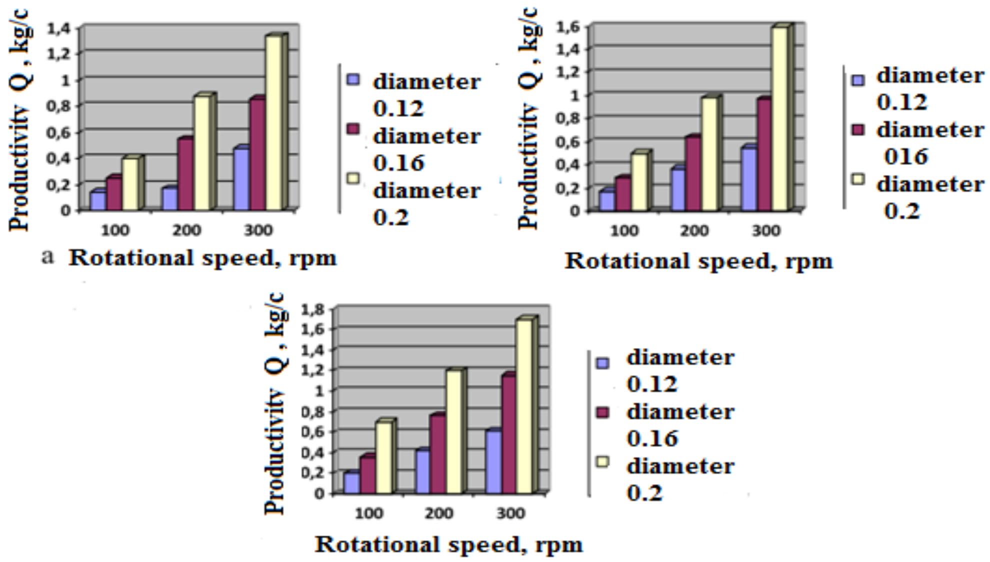


Figure 5 The diagram of change of productivity Qke of the heat pump. Note: a, b, c – T1 = 0.05; 0.08 and 0.11 m.

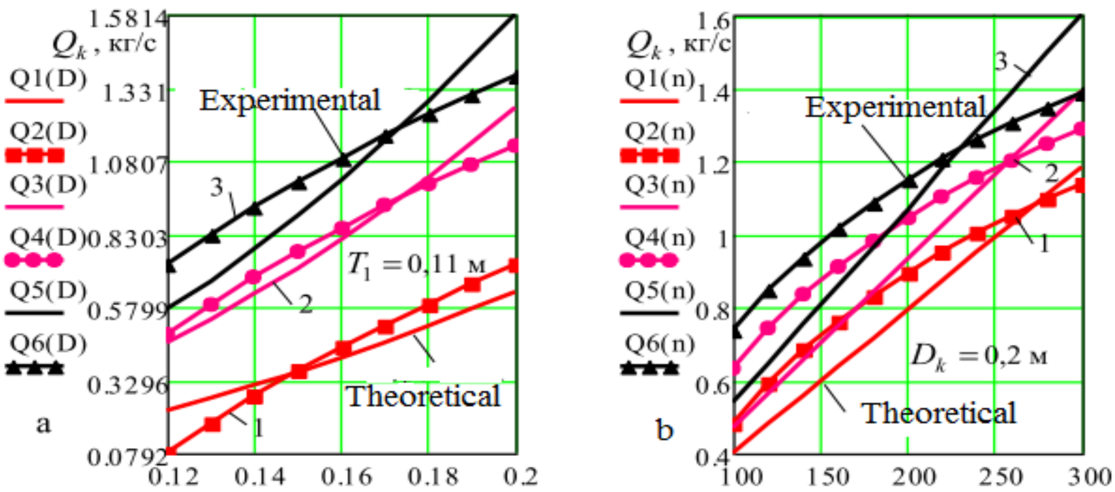


Figure 6 Dependence of change in productivity Qe as a functional:a – $Q_k = f_{Qk}$ (D) , 1, 2, 3 – in accordance, n_k= 100; 200; 300 rpm; b – $Q_k = f_{Qk}$ (n_k), 1, 2, 3 – in accordance, T_1 =0,05; 0,08; 0,11 m.

$Q_{ke} = f_Q (D_k;T_1)$ Figure 4, c).

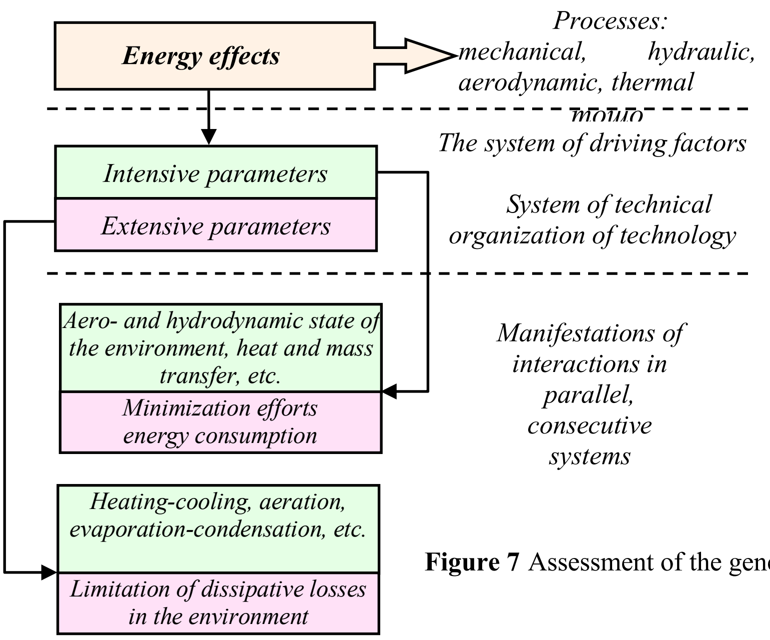


Figure 7 Assessment of the general state of processes in energy effects.

The dominant factors that have a significant functional impact on the increase in productivity Q_{ke} are the speed nk and diameter D_k, which is characteristic of the graphical interpretation of the response surface, and this is the regulation of energy potential, ie temperature.

Figure 5 represents a diagram of the change in the productivity of the Q_{ke} heat pump, based on the obtained average results of experimental studies with three repetitions of each numbered factor field experiment according to a randomized plan matrix of the planned experiment type PFE 3^3.

Based on the graph-analytical analysis (Figure 5) it can be stated that the nature of the functional change in the productivity Q_{ke} of the heat pump. It is obtained for the limit values of the corresponding points of the a three-factor experiment type PFE 3^3 compositional plan is quite adequate model $Q_{ke} = f_Q$ (x_1; x_2; x_3)= $Q_{ke} = f_Q$ (n_k; D_k; T_1), Figure 4, Figure5, which is also characteristic of the dependence, which is shown in Figure 6.

The discrepancy between the experimental values of the performance Q_{ke} of the pump obtained according to the regression equation (4) and the experimental values of the performance Q_k (graphical dependences of Figure 7) is in the range of 5 – 10%.

RESULTS AND DISCUSSION

This feature of energy transformations is based on the second law of thermodynamics with an indication of the need to use compensation systems by increasing the temperatures and pressures of energy sources in closed circuits.

An important advantage of the heat pump is that it implements "reverse" processes in the modes of heating and cooling of the premises as an ideal air conditioner.

The technical implementation of heat pumps and refrigeration machines based on the Carnot reverse cycle, which is the only achievement of humanity in the implementation of the principle of energy redistribution in existing parallel systems.

Returning to condition (3) we obtain an estimate of the heat flux dissipated from the cooling medium:

$$Q' = c_p v' \left(T_{(\text{п})} - T_{(\text{к})} \right) = c_p v' \left(t_{(\text{п})} - t_{(\text{к})} \right), \text{kW},$$

Where:

v' – volumetric flow of the gas phase supplied to the evaporator as part of the heat pump, m^3 / s;

$T_{(n)}$, $T_{(\text{к})}$, $t_{(\text{п})}$ and $t_{(\text{к})}$ – initial and final absolute temperatures and temperatures in degrees Celsius.

Similarly, it is possible to determine the energy potentials of the liquid phases of lakes, rivers, seas and oceans, which are largely used.

The study **(Nikitin and Krylov, 2012)** estimates the ratio of redistribution of energy flows, according to which from 60 to 70% of energy costs related to the circulating circuits.

Understanding this situation in a significant number of cases **(Mandryka, 2017)** prompted attempts to use this energy component in favor of energy resources. It should be noted that the kinematic parameters of the gas-liquid medium are estimated to be approximately stable. Their transfer to the regimes characteristic of transitional processes should be assessed as a promising direction of intensification of energy resources.

Another direction **(Sniegkin et al., 2008)** concerns the use of secondary energy resources that accompany most industrial technologies. Their energy potentials elate to the solid and liquid phases of the input raw materials, to which the potentials of the vapor phases and gases are added in the transformation processes. The latter applies to a significant number of technological processes and individual complexes. Solving the problems of recovery of secondary energy resources is most appropriate to solve in parallel-synchronized flows. This largely applies to thermal systems in which phase transitions are carried out due to the relative ease of regeneration in them.

In cases of asynchronous situations, there is a need to use energy-saving storage devices. However, the positive results for parallel system designs are quite achievable even in mechanical systems in which transients are generated. In this case, in addition to energy effects, it is possible to regulate the movement of machines with restrictions on total dynamic loads.

In the general list of processes that take place in food, chemical, microbiological and other technologies, there are mechanical, hydraulic, aerodynamic, thermal interactions or various combinations of them (Figure 7). Manifestations of such interactions are in series and parallel systems with corresponding intensive and extensive parameters, based on driving factors, aero- and hydrodynamic states of environments, heat, and mass transfer surfaces, means of increasing energy potentials, energy loss compensators, and so on. The technical organization of technologies in general and at the level of individual processes require the interaction of material, energy, and information flows, the task of which is to achieve appropriate technological effects related to heating-cooling, evaporation-condensation, formation of concentrated media, gas-saturated systems, aeration, etc. At the same time, efforts to minimize energy costs and limit dissipative losses to the environment at a certain level of opportunity in the implementation of these provisions remain fundamental. Assessing the general condition, we turn to the example of the features of only one component of convective heat transfer.

During convection, heat is transferred during the mixing of cold and warm layers of liquids or gases, and therefore this process is inextricably linked with the mechanical motion of liquid and gas flows. Their theoretical basis relates to the relevant sections of hydro- and aerodynamics, but the level of complexity, even for simple cases in mathematical formalizations, is so significant in combination with thermal processes that it has led to limitations in the relevant scientific interests. However, it is convection in heat transfer mechanisms in heating systems, technological devices, electric drives, brakes, compressors, refrigeration units, etc. in terms of significance that led to the development and solution of applied problems.

Most of them concern the determination of heat transfer coefficients, which may depend on the thermal conductivity of the media, viscosity, density, heat capacity, kinematic parameters, and geometry of the media volumes. The effects of all these parameters are combined by the phenomenon of the boundary layer. The imaginary shirt creates the main barrier to heat transfer, which barriers that most effectively overcome in the modes of phase transitions of boiling and condensation due to the activation of heat transfer coefficients. An additional positive effect of the phase transition concerns the production of a coolant with a thermodynamic parameter supplemented by the heat of vaporization.

Phase transitions open additional possibilities of transformation of parameters of pressure and temperatures that allow overcome natural prohibitions which features are formulated by the second law of thermodynamics. In the classical definition, this is achieved by supplementing the closed or partially closed circuits with a *compensatory process* of mechanical compression or the introduction of additional thermal potential with increasing pressure and temperature of the coolant circuit. As a result, such transformations in the reversed Carnot cycle, it is possible to transfer heat from less heated media and bodies to more heated ones, and the purpose of such transformations may relate to the problem of cooling (heating) the local zone. In the first case there is a use of the refrigerating machine, and in the second - the heat pump.

However, in addition to information on the creation of Lord Kelvin air heat pump with the transformation of energy potentials of air flows due to the relationship between pressure and temperature, we note the consequences of continuing attempts to create their modern structures, which we consider in this paper.

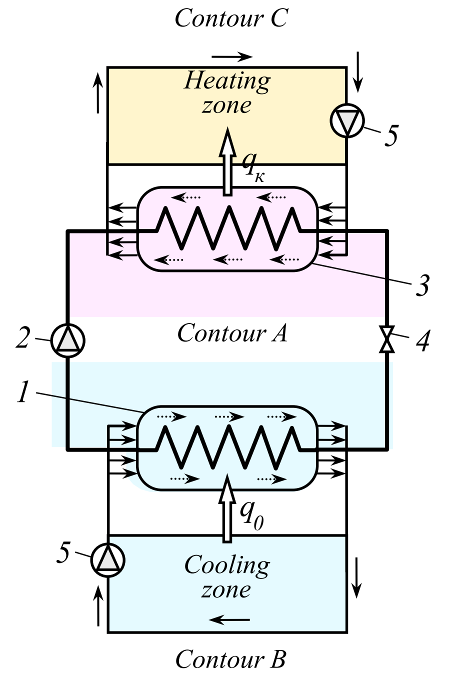


Figure 8 System of realization of a refrigerating cycle: 1 – the evaporator; 2 – compressor; 3 – capacitor; 4 – throttle; 5 – fan.

This applies to the development of the patent of Ukraine 17167 "Air heat pump" (Figure 2).

The creation of initial energy potentials in such systems is carried out using primary energy sources. The latter in most cases relate to the resources of the generated vapor phase, electricity, energy of hydraulic systems, compressed air systems, or chemical energy of incoming raw materials. The presence of the latter is a constant factor in any technology, according to which the energy potential of recycled raw materials should be preserved as much as possible. However, the appropriate set of energy-material transformations provide by the influences of external energy flows due to which the set temperatures of technological processing of environments are reached. It can be carried out without achieving the modes of phase transitions or with their implementation. Consider the transformation of the energy potentials of airflows due to the relationships between the design parameters of the pump and the process.

System of realization of energy potentials

The potential of devices for increase of energy efficiency and intensification of processes of a mode of phase transitions and generation of steam, gas phase, or steam-gas mixes is high enough. Development of new designs of heat exchangers, evaporators, the definition of rational modes of their operation is possible only based on the data received at comprehensive researches of the processes proceeding in devices.

It is expedient to refer to the peculiarities of the cycles of refrigeration units or heat pumps from the point of view of creating analogies for systems of industrial devices in which there are modes of phase transitions and generation of steam, gas phase, or steam-gas mixtures. The existence of a closed circuit in the refrigeration cycle involves the combination of an evaporator as a steam phase generator (Figure 8), a compressor, a condenser, and a choke operating in synchronized parallel modes with the appropriate thermodynamic parameters.

In the closed circulation circuit A of the refrigerant, phase transitions occur due to the supply of heat flow q_0 from the cooling zone with circuit B and the removal of heat flow q_k from the condenser in circuit C. Depending on the technological tasks, circuits B and C can be closed or open.

This leads to the conclusion that the total energy balance of circuit A is supplemented by the energy consumption $\ell_к$ of compressor 2, which meets the condition:

$$q_к = q_о + \ell_к, \tag{6}$$

and the whole system in balance calculations must take into account power consumption in the circuits B and C. The decision of technical problems is achieved in one of the circuits B or C, or both simultaneously. It is important that the arrangement of energy-material connections of circuits B and C following the evaporator and condenser can be realized due to convective air flows of the medium, which are formed in response to the existence of a gravitational field. This solution is present in the installation of most domestic and industrial refrigeration systems and systems.

Cooling and heating zones can exist as local, but in cases where they are open, it means that they are interconnected through the environment, and technical systems of refrigeration systems, heat pumps, and air conditioners *act as programmable energy redistributors*. Important is the ratio of the potentials of the synthesized energy flows in the direction from zone B to zone C and the potential of the compensation processes, which can be up to 5 – 10 units. This means the possibility of creating powerful energy-intensive systems using compensatory processes, the limited structure of which is the ultimate negative result of the impact on the ecosystem. The last statement is because

the synthesized heat fluxes at the end of technological processes are dissipated with the equalization of temperatures following the law of the most probable state. To prevent further negative effects on the environment the power supply of the electric drive of the compressor-compensator deserves attention. The use of modern systems for the transformation of world energy into electricity in such cases would practically solve the
problems of energy security in a maximum way.

Thermodynamic analysis of energy resources.

A scientifically based analysis of energy processes is essential for an active energy-saving policy. Modern laws of thermodynamics **(Annex 49 summary report IEA ECBCS. –Fraunhofer IBR. -2011)** include the study of the properties of energy in its transformations in two approaches to efficient use: energy and exergy. Such approaches involve the use of two thermodynamic characteristics of energy - quantity and quality: quantity - in energy, both - in exergy.

Thus, the authors **(Kudelya, and Dubovskyi, 2020)** consider the possibility of obtaining work when the characteristics of the system (pressure, temperature, velocity, chemical composition, and potential energy of the system) differ from the characteristics of the state (parameters) of the environment. This possibility is completely lost when the system and the environment are in balance and calm concerning each other.

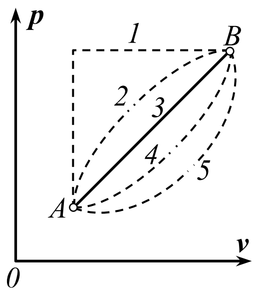


Figure 9. Dependence of p = p (v) in thermodynamic transformations parameters.

The magnitude of the work, as a quantitative measure of energy quality, is included in the equation of energy balance (First law of thermodynamics), and the condition of convertibility S gene ≥0 - in the equation of entropy balance (Second law of thermodynamics). Therefore, the authors **(Ebrahimi, 2012)** propose the use of low-potential heat in optimizing the generation of electricity taking into account the depth temperatures and heat exchange of wells with side rocks. In this case, the Rankine cycle was chosen as the theoretical basis for the calculation of a heat engine with distributed parameters.

The calculation of authors **(Domschkea, 2017)** based on the total energy consumption for main gas transportation for a multi-threaded network, which includes compressor stations, heat exchange areas with the environment, bridges, and branches

Modeling and optimization of gas flow through the pipeline network by the authors **(Domschkea, 2017)** used a hierarchical model based on one-dimensional isothermal Euler equations of fluid dynamics. Therefore, in the works **(Liu, et al., 2017; Orga, et al., 2017; Pouladi, 2017)** based on the analysis of the topological structure of the heating network, its hydraulic and thermodynamic parameters, a method of counting the heat flow of the network was developed. Taking into account the external heat inflow in the sections of pipelines minimizes the total heat consumption and improves the management of technological processes.

Based on the above, the physical state of the system is determined by the values of two variables out of three, namely pressure, volume, and temperature.

It is known that the physical state of the system is determined by the values of two variables out of three, namely pressure, volume, and temperature. There is a functional connection between these three parameters. In what follows, we will consider the pressure p and the volume v as independent variables, and then we will display this relationship in the form:

$$T = f(p,\ v). \tag{7}$$

The set of values of p and v determines the position of a point on the plane p-v. Each such point corresponds to a certain value of temperature T (Figure 9).

Differential

$$dT = \frac{\partial f}{\partial p} dp + \frac{\partial f}{\partial v} dv \tag{8}$$

is a complete differential. By changing the state of the system from the parameters at point A to the parameters of point B, the temperature at point B can be determined in the form:

$$T_B = f(p_B, v_B). \tag{9}$$

Determining the values of the work performed by the system as a result of changing its state during the transition of parameters from point A to point B and, considering the process inverse, we reflect the dependence:

$$W_{A-B} = \int_{v_A}^{v_B} p\, dv. \tag{10}$$

The graphical interpretation of the given integral is the plane under the transition curve on the p-v diagram. Since the transition from point A to point B can be done with different trajectories, it means that these areas will be different. Their area is to some extent determined by the design parameters and speed of the drive. It follows that the value of W depends on not only the coordinates of points A and B, but also on the selected transition trajectories. It is logical to assume that the amount of heat perceived in this transition of the system also depends on that, but the difference between the amount of perceived heat Q and energy W does not depend on the shape of the transition trajectory. The conclusion about the constancy of the difference Q – W, which corresponds only to the state of the system at points A and B, indicates a change in the internal energy u:

$$\Delta u_{A \to B} = (Q - W)_{A \to B} = F(p_B, v_B) - F(p_A, v_A). \tag{11}$$

In another form, expression (11) has the form:

$$du = dQ - dW = \frac{\partial u}{\partial p} dp + \frac{\partial u}{\partial v} dv. \tag{12}$$

For the case of a closed trajectory from point A we obtain a curvilinear integral from du, then we have:

$$\int_{v_A}^{v_A} du = u_A - u_A = 0. \tag{13}$$

The written curvilinear integral is called the circulation and is denoted by a symbol $\oint_{(\ell)}$,

Where:

ℓ – closed curve.

Bringing the heat flux Q to the medium means corresponding changes in the value of entropy. The latter is determined only by the variables that characterize the physical state of the system, and in the transition from point A to point B changes in entropy do not depend on its trajectory.

Herewith

$$\Delta s_{A\to B} = \int_A^B \frac{dQ_{зв}}{T}, \tag{14}$$

Where:

$dQ_{зв}$ – the amount of heat passing through the system boundaries during the reverse process.

In the elementary process we have:

$$ds = \frac{dQ_{зв}}{T}; \quad dQ_{зв} = T\,ds\,. \tag{15}$$

Replacement of values dQ i dW provided (12) leads to the form:

$$du = T\,ds - p\,dv, \tag{16}$$

in which there are point functions and complete differentials.

Integration (16) leads to the value of u as a function of the variables s and v in the form:

$$u = f_u(s, v), \tag{17}$$

or, disclosing condition (17), write:

$$du = \left(\frac{\partial u}{\partial s}\right)_v ds + \left(\frac{\partial u}{\partial v}\right)_s dv, \tag{18}$$

and by comparison with condition (16) we obtain:

$$\left(\frac{\partial u}{\partial s}\right)_v = T \;\; i \;\; \left(\frac{\partial u}{\partial v}\right)_s = -p\,. \tag{19}$$

If condition (19) is known for a mass of any homogeneous liquid, then the parameters T, p and u can be calculated for any physical state of the medium, which is determined by the independent variables s and v. Therefore, the performance of the heat pump sets the value of the internal energy **u** of the process.

Methods for determining the temperature field of a low potential energy source

The paper **(Oosterkamp, Ytrehus, and Galtunget, 2016)** is aimed at analyzing the influence of extreme temperature conditions on heat transfer between a low-potential energy source of soil massifs and an underground pipeline. One- and two-dimensional models were used to calculate thermal conductivity. It is shown that the accuracy of soil temperature forecasting deteriorates when using air temperatures to assess the marginal condition of the soil surface. It is proposed to take into account the effect of heat accumulation, as well as the actual temperature of the gas in the pipeline for more accurate efficiency of heat transfer prediction.

Therefore, the calculation of the temperature field of a low-potential energy source in the zone of influence of the compressor rotor diameter and the blade pitch reduced to solving the equation of nonstationary thermal conductivity.

In a cylindrical coordinate system characteristic of a heat pump, the equation has the form **(Lykov, 1967)**:

$$\frac{\partial t}{\partial \tau} = a\left(\frac{\partial^2 t}{\partial r^2} + \frac{1}{r}\frac{\partial t}{\partial r} + \frac{1}{r^2}\frac{\partial^2 t}{\partial \theta^2} + \frac{\partial^2 t}{\partial z^2}\right)$$

Where:

t – the ambient temperature, °C;

τ – hour, s;

a – thermal conductivity, m^2/s;

r is the radial coordinate, m;

θ is the polar angle (the angle between the radius vector r and the x axis).

This is a three-dimensional problem, but given the shape and length of the rotor relative to the radius of impact, as well as the heterogeneity of the blades, it can be reduced to two-dimensional with a sufficient degree of accuracy. For this problem statement, taking into account the symmetry of the temperature field, it is proposed to make a simplified solution, provided that τ>; 0 до rp< r< rк **(Rudenko, 2012)**:

$$\frac{\partial t}{\partial \tau} = a\left(\frac{\partial^2 t}{\partial r^2} + \frac{1}{r}\frac{\partial t}{\partial r}\right)$$

Where:

rp – average rotor radius, m;

rк – radius of the contour of influence, m.

Simplifying the task by switching from a three-dimensional to a two-dimensional model eliminates heat flow along the rotor axis. However, the heat flow in the vertical direction, despite its small orders, must be taken into account due to its continuity in time, even when the heat pump is stopped. To solve the problem, we introduce an amendment that compensates for bulk sources and heat fluxes (environment). Then equation (2.2) will take the following form **(Rudenko, 2012; Sniegkin et al., 2008)**:

$$\frac{\partial t}{\partial \tau} = a\left(\frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial r^2} + \frac{1}{r}\frac{\partial t}{\partial r}\right) + \frac{g_v}{c}$$

Where:

t – ambient temperature, °C;

r – time, s;

a – thermal conductivity, m^2 /s;

r – is the radial coordinate, m;

qv-sources and heat runoff due to heat fluxes of the environment and heat release through the surface, W / m^3;

c – heat capacity, J / (m^3 • °C).

The paper **(Biletsky, 2013)** presents the concept of calculating the mode parameters of gas transportation through the network of gas wells, and the authors **(Romaniuk, et al., 2019)** reveal the features of calculating electricity losses in systems. The heat exchange between the transported gas and the external environment at each of the sections of the pipeline network is not taken into account. The problem of cork and hydrate formation in the pipeline is not considered. The calculation of electricity losses does not fully reflect the effects of the external environment, heat fluxes.

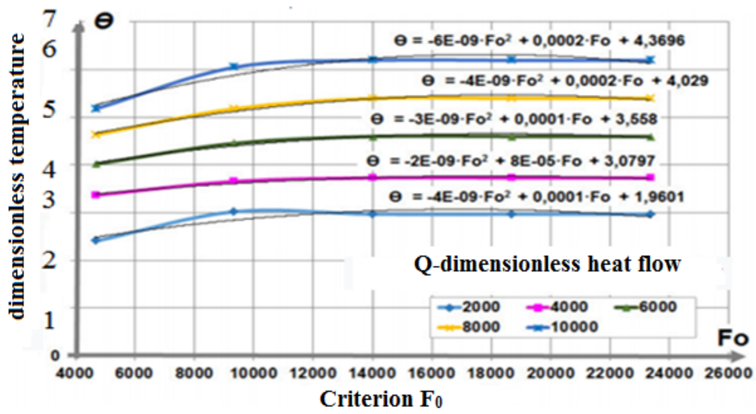


Figure 10 The results of the calculation of the function from the defining parameters.

Therefore, the set of factors: background temperature of low potential energy source (t_{fon}, °C), ambient temperature, heat runoff (qv, W), thermophysical characteristics, the intensity of incident solar radiation, are the basic data in the calculations. The set of factors: background temperature of low potential energy source (t_{fon}, °C), ambient temperature, heat runoff (qv, W), thermophysical characteristics, the intensity of incident solar radiation, are the basic data in the calculations.

Execution of the technical and economic analysis is reduced to the definition of the temperature of the heat carrier selected from the heat pump that in turn, is defined by the created temperature. The second feature is the need to assess the operating conditions of the heat pump in the worst, in terms of the coefficient of thermal transformation, conditions. This corresponds to the time period of completion of the heating (cooling) cycle.

The known similarity criteria do not fully reflect the studied phenomena, in connection with which the following dimensionless complexes are proposed in the research work: relative heat flux (Q), modified dimensionless temperature (Θ), and criterion Fo.

The temperature field of a low-potential energy source is described by a dimensionless function **(Rudenko, 2012)** with three dimensionless parameters:

f = (Fo, Θ, Q), (1)

Where:

Fo –Fourier criterion,

Θ – dimensionless temperature,

Q – relative heat flux.

Considering the active load on the rotor with blades, which perturbs the temperature field factor, we propose to introduce the relative heat flux (Q), which is accepted in the research work to calculate the formula:

$Q = g_{na}/g_{fon}$

(2)

Where:

q_{na} – specific heat flux per unit area of the rotating rotor with blades, heat load on the pump in a certain period of operation, W / m²;

q_{fon} – background heat flux (specific, per unit area of the environment), W / m²

The operating parameters of the heat pump depend on the difference between the generated temperature and the ambient temperature.

The Fo criterion was formed by a known formula (**Lykov, 1967**). The determining size is proposed to take the radius of the rotor:

$F_0 = \frac{a\,\tau}{r_p^2}$,

Where:

a - thermal conductivity coefficient equal to a =λ/cρ m²/s;

λ - thermal conductivity, W / m °C;

ρ – air density, kg / m³;

c_p - heat capacity of air, J / (kg × °C);

τ - characteristic time of change of external conditions, s; r_p - characteristic body size (rotor radius), m.

The complex nature of the mutual influence of the defining parameters does not allow to formalize an unambiguous solution, in connection with which the traditional approach to the type of criterion equation as a static dependence is used. The generalizing equation for single-stream operation can be described as a regression:

$\theta = \kappa_1 F_0^2 Q + k_2 Q F_0 \ldots + k_n F_0 Q$

Where:

$k_{1,2 \ldots n}$ – determining factors.

The results of the calculations are well approximated by second-order polynomials. Applying the methods of statistical processing, the criterion equation is obtained:

$\theta = -5\ 10^{-9} Q F_0^2 + 2\ 10^{-8} F_0 Q + 0.0003\ Q + 5.1$

The results of the calculation of the temperature at the outlet of the partition as a function of the defining parameters in the dimensionless form are presented in Figure 10 **(Saprykina, 2016)**. This allows you to predict the temperature change of a low-potential energy source operating in the cyclic (seasonal) mode without reversing the heat flow.

CONCLUSION

The process of supplying and discharging heat to a low-potential energy source is a function of time and space. The temperature field is formed by the design parameters of the pump. Analysis of performance data and these formed temperature fields showed the predominance of heat flux in the radial direction and a small amount of heat flux in the axial direction. Nevertheless, due to the design, the formation of heat flow and heat dissipation from the circuit are stabilizing factors that provide a quasi-stationary state.

The phenomenological analysis of the materials given in researches allows noting perspective directions of use of the closed power circuits in the following list:

- Technologies of redistribution of energy potentials of the environment based on heat pumps, refrigeration units, and air conditioners;
- Recuperative transformations of heat fluxes of industrial environments based on thermodynamic connections between pressures and temperatures of gas and steam phases;
- Technologies of creation and transformations of steam, gas, and steam-gas streams with the application of modes of adiabatic phase transitions;
- Creation of technologies based on use of dynamic systems in which continuous processes of heating, endurance, and cooling of streams of environments for use of primary potentials in the closed system without initial streams with the subsequent compensation of losses in the environment with the subsequent transition to dynamic modes are realized;
- In cooling systems of environments in large volumes of technological devices based on the use of cooling jackets or external heat exchangers, an important disadvantage is the gradual reduction of temperature differences on heat exchange surfaces and restrictions on heat recovery. Avoidance of such shortcomings is associated with the transition to a dynamic system with constant temperature differences.

According to the results of theoretical and experimental studies, taking into account thermodynamic analysis, the temperature field of a potential energy source, the main rational parameters of the heat pump rotor are set. So, diameter - 0.2 m; step of the first turn of the blade - 0.11 m; step increment - 0.03 m; the number of blades that are installed between one a pair of adjacent turns - 4 pcs; rotor speed - 300 rpm.

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