Розглянуті основні можливі напрямки вирішення завдання підвищення енергетичної ефективності абсорбційних холодильних приладів, показана перспективність та напрямки вдосконалення систем автоматичного керування ними. Представлений аналіз впливу теплової потужності в генераторі на процеси тепломасообміну в елементах абсорбційного холодильного агрегату і енергетичну ефективність абсорбційного холодильного приладу. Виділено п'ять характерних режимів роботи генератору

Ключові слова: абсорбційні холодильні прилади, енергетична ефективність, система автоматичного керування, теплова потужність

Рассмотрены основные возможные направления решения задачи повышения энергетической эффективности абсорбционных холодильных приборов, показана перспективность и направления совершенствования систем автоматического управления ими. Представлен анализ влияния подводимой тепловой мощности в генераторе на процессы тепломассообмена в элементах абсорбционного холодильного агрегата и энергетическую эффективность абсорбционного холодильного прибора. Выделено пять характерных режимов работы генератора

Ключевые слова: абсорбционные холодильные приборы, энергетическая эффективность, система автоматического управления, тепловая мощность

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SEARCHING FOR THE ENERGY EFFICIENT OPERATION MODES OF ABSORPTION REFRIGERATION DEVICES

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1. Introduction

At present, there is a wide variety of technologies of canning to provide for the prolonged preservation of food products. Many of them are connected to thermal treatment or to the use of different natural and artificial preservatives [1, 2]. However, it is a common knowledge that in the first case, the ingredients valuable for human organism are destroyed in the products, and in the second – human organism accumulates the substances that negatively influence the health. That is why the use of artificial cold is a priority direction in the production of ecologically safe food products with a prolonged period of storing. Not a single technology except cooling is capable of prolonging the period of storing the products and simultaneously maximally preserving their initial properties [3, 4].

According to the known classification of the methods of canning of foodstuffs [1], the cooling is based on the principles of anabiosis – suppression of vital activity of living products and their pests (microorganisms) with the help of action of external factors. Low temperature makes it possible to sharply inhibit the vital functions of a microorganism and in so doing to artificially prolong the period of storage of foodstuffs with their initial quality. At the provision of optimal conditions for storage, the foodstuffs after cooling preserve practically all original properties and differ insignificantly from the fresh ones. This special feature of refrigeration preservation method is especially valuable taking into account the seasonality of harvesting and production of the majority of foodstuffs. It should also be noted that the energy costs for cooling and storage of food products in the cooled form are considerably lower than with other methods of canning.

According to the estimation of the International Institute of Cold (IIC) [5], the total losses of all food products in the world amount to 25 %. Wherein, the share of perishable products comprises more than half of the overall world production. That is why the application of cold has the defining role in the provision of quality and sufficiency of food for population, as well as in the reduction of losses of agricultural raw materials and foodstuffs on the way from producer to users. Important role in this case belongs to continuous refrigeration chain.

Continuous refrigeration chain is the totality of the means of refrigeration equipment and technologies, as well as organizational measures, which ensure necessary modes of refrigeration processing and storing of agricultural raw materials and products along the way of their movement. It includes refrigeration systems in the places where the raw materials are collected, refrigeration capacities of the processing enterprises, transporting refrigerators, distribution cooled terminals, commercial refrigerators, home refrigerators. As many years of experience show, the largest deviation from the recommended and optimal modes in terms of storage and energy consumption occurs in the home refrigerators. This is linked to a considerable extent to the subjective human factor and the lack of control systems that could remove it.

For the production of artificial cold at homes, the compression and absorption refrigeration devices are mainly used now (CRD and ARD). The main segment of the market for home refrigeration equipment belongs to CRD [6]. This is connected with the fact that CRD have an important advantage – higher energy efficiency. At the same time, ARD have a number of such unique qualities as:

1) working body of ARD is an ecologically safe water-ammonium solution with hydrogen;

2) the absence of moving elements and, as a result, no noise, high reliability and long-lasting performance resource;

3) the possibility of using different sources of thermal energy – both electric and nonelectric;

4) the capacity to work with the poor quality sources of electric energy at circuit voltage from 160 to 250 V;

5) minimal base price in comparison with the compression analogs.

The factors enumerated above demonstrate large potential of using ARD provided their main shortcoming is eliminated. Thus, an increase in the energy efficiency of home ARD is a relevant task. Solving this problem will allow ARD to successfully compete with the compression analogs and to take up a worthy place in the market of household refrigeration equipment.

2. Literature review and problem statement

The ARD set-up includes absorption refrigeration unit (ARU), which realizes pumpless absorption-diffusion refrigeration cycle. The working body of ARU consists of natural components – water-ammonium solution (WAS) with the addition of inert gas (hydrogen, helium or their mixture).

Comparatively low, in comparison with the compression analogs, energy efficiency of household ARD is predetermined by the specific character of physical processes, which take place in the implementation of pumpless absorption-diffusion refrigeration cycle with gravitational flow of the components of the working body [7]:

1) by the necessity of conducting the process of dephlegmation for cleaning the vapor of the refrigerant – ammonia;

2) by the presence of low intensive diffusion processes of the heat-mass transfer in the elements of ARU at evaporation and absorption;

3) by the presence of heat losses into environment from the elements of a generator unit.

Contemporary research and designs, which make it possible to decrease energy consumption in household refrigeration devices of absorption type, are carried out in three directions:

– improvement of thermodynamic cycles, modes of operation and constructions of the ARU elements [8–10];

– rational use of artificial cold [11, 12];

– improvement in the modes of operation, means and systems of the ARD control.

The designs, executed within the framework of the first two directions, may be realized exclusively at the stage of the design of a refrigeration device since they imply a change in the construction of ARU, whereas those in the third direction can be realized both at the stage of designs and in the process of operation.

The authors, based on the experience of our own studies, as well as on the analysis of designs of the leading world manufacturers of household refrigeration equipment, consider the latter direction as the most promising in terms of reducing the energy consumption by ARD.

The majority of contemporary models of household refrigeration devices both of absorption and compression types are dual chamber refrigerators with a freezer or one chamber refrigerators with a low-temperature compartment. Traditionally, starting from the middle of the XXth century, absorption refrigerators are produced with one-, two- and three-section electric heaters. They are equipped with positional control systems with a capacity of automatic or manual temperature control in the refrigeration chamber by turning off the thermal power supplied to the heater or its switch to a lower value when reaching the set temperature.

Attempts to increase energy efficiency of ARD by the improvement of heating element were undertaken by the Swiss firm «Sibir» in the 60's of the XXth century [6]. They used a two-section electric heater (main section – 110 W, the section on hold – 40 W) with constantly supplied thermal power, which made it possible to decrease the energy consumption by the dual chamber absorption refrigerator «Sibir» E–225 by 20 %. However, after a number of tests on other models, the universality of this method was not proven.

Subsequently, constant competition in the market for household refrigeration equipment among the manufacturers of compression and absorption refrigerators forced the latter to search for more efficient ways of reducing energy consumption.

Improvement of the methods of the ARD control has proven to be one of the most effective directions. A number of studies were carried out, connected with the search for the optimal magnitude of the thermal power, supplied to the ARU generator in a two-position mode, while installing additional thermal insulation on the dephlegmator [6]. Contemporary studies in this direction are connected with papers [13, 14], the main focus in which is the solution of the problem of ARD energy-efficiency when operating over a wide range of temperatures of the surrounding air.

It is known [6] that ARD as well as other refrigeration devices are designed, in the first place, for maintaining the assigned level of cooling in the cooled chambers under "tough" operating conditions (for Ukraine, it is 32 °C). And while for the compression analogs reduction in the outside air temperature to 10 °C (at a lower temperature there is a danger of mechanical breakdown in the moving elements of compressor at its start because of oil thickening) increases the energy efficiency of a refrigeration device, this situation is ambiguous for the absorption models.

In ARD, similar to the compression analogs, the reduction in the outside air temperature contributes to the decrease of heat flows to the cooled chambers and improves conditions for the removal of the waste heat of refrigeration cycle into environment. However, in ARU favorable conditions for the heat removal from the heat dissipating elements negatively affect the supply of ammonia from the generator to the capacitor – additional condensation of ammonia vapor occurs in the dephlegmator. In order to decrease this negative influence, it is proposed [13] to regulate the composition and pressure of a working body in ARU, as well as to install a special protective coating in the lift section of the ARU dephlegmator [14].

However, in the field of improving the systems of automatic control (SAC) of ARD, there are an insignificant number of designs as the specialists in the area of automation have focused their attention on the problem of increasing the energy efficiency of ARD only recently.

At present, the ARD set-up uses the simplest (standard) SAC. Such SAC ensure only stabilization of the temperature in the refrigeration chamber θ_{rc} based on the information about its current value at work under tough operation conditions, due to a change in the magnitude of the thermal power supplied to the generator unit. In this case, the algorithms of regulation, similar to the compression refrigerators, where this is dictated by design features, are positional.

Let us examine in more detail the structure of a standard SAC of ARD and all impacts that influence the process of temperature control in a refrigeration chamber.

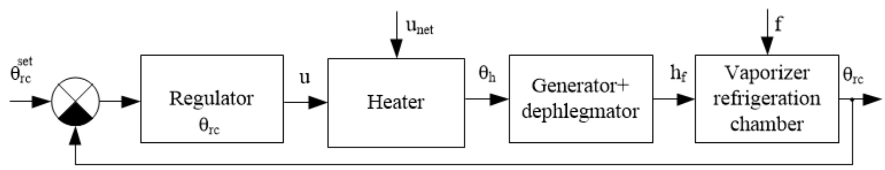


Fig. 1. Structural scheme of standard SAC of ARD

Structural scheme (Fig. 1) demonstrates two groups of perturbations:

a) controlled perturbation is the network voltage (u_{net}) that feeds the electric heater and the information about the magnitude of which may be used in the control algorithm;

b) uncontrolled perturbations f, the information about which cannot be used in the control algorithm.

The uncontrolled perturbations include:

a) heat flows from the products, loaded into the chambers, with ambient temperature;

b) heat flows from the outside air through the walls of refrigeration chamber;

c) operational heat flows (at opening the door, from the illumination lamp, irrational arrangement of products in the working volume of the chamber);

d) heat flows from the infiltration of the outside air through the thinnesses of the doors design.

Furthermore, the scheme (Fig. 1) highlights temperature of the surface of the heater (thermosyphon) θ_h and the level of vapor-liquid front in the lift section of the dephlegmator h_f.

The qualitatively new development of designs in the field of improving SAC of ARD has started relatively recently. Studies [15, 16] demonstrated that in order to realize energy-efficient modes of the ARD operation [6], the top priority task is improving the quality of implementation of the existing function of the regulation θ_{rc}, and after that, the transition to realization of new functions. Thus, several promising ways were proposed [15, 16] of improving the positional control algorithms, which make it possible to increase dynamic accuracy of stabilization θ_{rc} in the neighborhood of its set values.

The simplest variant of improving SAC of ARD is the introduction into the positional regulation algorithm of integrating and differentiating components, vibration linearization of relay element by the coverage of the relay with inertia feedback. It is assumed that the application of such variants of the improvement of the structure of SAC of ARD will make it possible to reduce the amplitude of temperature fluctuations in the refrigeration chamber θ_{rc} to 0,2 °C and, practically, 0 °C, respectively.

The introduction of vibration linearization of the relay allows increasing the resource of workability of both the electric heater and the ARU generator, since at a temperature exceeding 190 °C, the process of corrosion of the material of the wall of the ARU generator intensifies dramatically [17].

In SAC with the vibration linearization, the situation when θ_h exceeds the level of 190 °C is possible only at the starting modes of ARU while amplitude of the θ_h fluctuations substantially decreases but remains significant nevertheless. In this case, reduction in the resource of the heater elements occurs as a result of its frequent temperature deformations. The solution to this problem is the use of SAC of cascade structure [16], where the temperature of the surface of the heater θ_h is used as the internal variable of regulation.

The advantage of the proposed ways of improving SAC of ARD consists in maintaining a simple and cheap execution device – a two-position relay. However, in this case further improvement of SAC of ARD requires cancelling a standard electromechanical direct action controller and realization of a new regulator in digital or analog variant.

Thus, a large number of papers [6–16] are devoted to solving the problem of increasing the ARD energy efficiency, connected, in particular, to the development of efficient modes of operation of ARD, to the methods of their control, as well as the systems of automatic control (SAC). The prospect of such directions of improvement of ARD consists, in the first place, in the universality – possibility of application both in the new ARD models and in those already put into practice. In this case, in contrast to the compression analogs, the ARD control can actually be accomplished only with the change in the supplied thermal power to the ARU generator. This requires comprehensive study of the influence of the supplied thermal power to the modes of operation of ARU and ARD, to which, within the framework of the studies conducted earlier, was given insufficient attention.

3. Aims and objectives of the research

The objective of the work is the analysis of the influence of the thermal power, supplied in the ARU generator node, on the operating modes and energy efficiency of ARD over a wide range of the outside air temperatures.

To achieve the set aim, the following tasks were to be solved:

– to study design features of the generator and their influence on the normal functioning in the composition of ARD;

– to conduct experimental studies of the ARD performance and its separate elements under conditions of "tough" operation (increased air temperature of environment 25...32 °C) at different values of the magnitude of thermal power supplied to the ARU generator.

4. Materials and methods of the research into the influence of thermal power supplied in the ARU generator unit on the operating modes and energy efficiency of ARD

4. 1. Equipment, used as the examined sample, as well as for the experimental studies

As the object of the study we used the modernized one-chamber, with the low-temperature compartment (LTC), ARD "Kiev-410" of the Ash-160 type (Ukraine, Vasilkovskiy Plant of Refrigerators, Fig. 2). The overall working volume of the refrigeration chambers is 160 dm^3, the LTC volume is 16 dm^3. The original modernization [18] is due to the installation of the L-shaped thermal pipes, which connect the ARU vaporizer, placed beyond the limits of working volume, with the LTC side walls. The thermal pipes are charged with ammonia and have axial incision.

Comparative analysis revealed that in the modernized design, the energy consumption, in comparison with the contemporary analogs, is reduced: RV400 Electrolux (Sweden) – by 7,5 %; EKS160A Electrosuisse (Italy) – by 37 %.

For conducting experimental studies on the influence of thermal power supplied in the generator unit on the work of ARD and its elements, we used automated working place (AWP) [19]. AWP consists of the following elements:

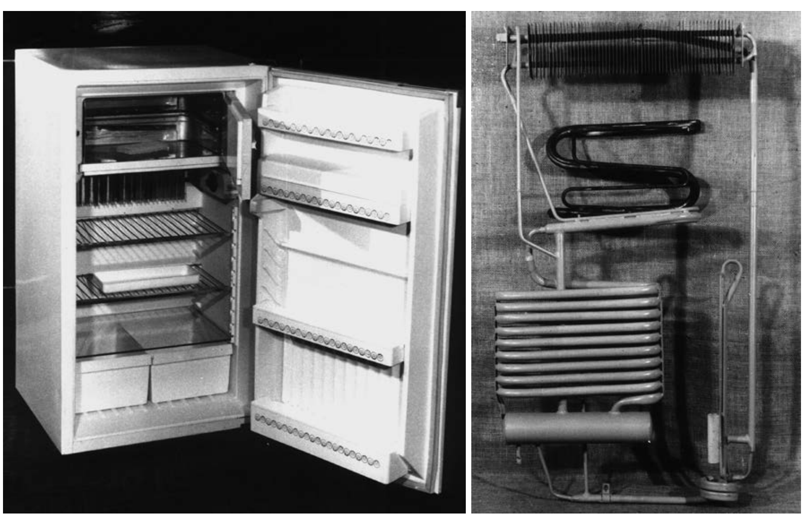
– the data acquisition board PCI-1710 with the terminal board PCLD-8710 by Advantech;

– the 16-channel normalizing converter for information input from the thermal resistors Pt 1000 to the board PCI-1710;

– a set of reference resistors;

– the measuring transloading converter of alternating current E850–M1;

– the execution unit for smooth control of power – the single-phase semiconductor relay RM 1E23V25 by Carlo Gavazzi;



a *b*

Fig. 2. One-chamber ARD with LTC "Kiev-410" of the Ash-160 type: *a* — general view of refrigeration device; *b* — ARU

– the DC power unit PS by ABB for RM 1E23V25;

– the PC Pentium 4,2 GHz with installed SCADA-system by Advantech DAQView for processing and visualization of the obtained information [20].

4. 2. The method of experiment

For studying the static properties of ARD with the help of AWP we organized automated experiments, which may be considered as the obtaining of quasi-static characteristics. Their essence consisted in the change, with preliminary selected constant velocity, of value of the power supplied to the ARU generator node and registration of the change in temperatures in the ARD control points during it. The range of change in power is from 60 W to 220 W. The temperatures of interest in the control points: θ_1 – at the output from thermosyphon, $\theta_2...\theta_{11}$ – along the length of dephlegmator, θ_{12} and θ_{13} – in the middle and at the output of capacitor, respectively, θ_{14} – on the edge of vaporizer.

Each experiment on obtaining the quasi-static characteristics was conducted for the duration of approximately 48 hours.

Initially, as a result of automated experiment, we obtained a set of quasi-static characteristics of ARD by the channels "thermal power, supplied to the ARU generator – temperatures of the surface of the ARU elements in control points" for the examined ARD. At the following stage we obtained the ARD quasi-static characteristics by the same channels, but under other conditions of the work of the lift section of the ARU dephlegmator:

1) at intensive heat removal from the surface of dephlegmator to environment with the aid of an air fan, of the 3 W power;

2) in the quasi-adiabatic mode – with the thermal insulation of dephlegmator along its entire height.

The thermal insulation and the blowout of dephlegmator by the fan made it possible to simulate different environmental conditions: at a reduced temperature (10...12 °C) and an increased (32...35 °C) air temperature.

5. Results of research into the influence of the thermal power supplied in the ARU generator unit on the operating modes and energy efficiency of ARD

5. 1. Design features of the generator and their influence on the ARU performance

In modern constructions of ARU, a generator is executed in the form of pumping thermosyphon – a pipe of inside diameter ≈4,0 mm [21]. In its lower part, filled with strong WAS, the thermal power is supplied. Numerical values of the thermal power in the heating zone are selected to provide for the process of vaporization in the mode of the upward flow of vapor–liquid mixture (VLM) in the internal part of capillary [21, 22].

In the lift or transport part of the generator (of length 0,35...0,45 m), at a constant heat supply, a dynamic vapor–liquid pillar is formed, which consists of the particles of liquid WAS, captured when lifting by the vapor bubbles, and the vapor bubbles. Ammonia vapor is found predominantly in the vapor phase while the liquid phase is a weak WAS with a mass fraction of ammonia at 0,10...0,15 [21].

The selection of inside diameter and height of the lift part of the generator is carried out by the designers of ARD by the thermal load in accordance with the theory of "The rise of fluid with the aid of its own vapors" [22], as well as based on designing experience. The above mentioned values of inside diameter and height of the lift part of a generator correspond to the calculated mode of jet flow at supply of thermal power from 40 to 110 W. In the range of indicated mode and design parameters, the mode of operation of the pumping thermosyphon is ensured with the production of vapor and lifting the liquid to the set height.

From this range, for different constructions and operating modes, it is possible to find the optimal ratios between the mass of the lifted liquid and the mass of the obtained vapor – mass coefficient of the thermosyphon supply b.

In the case of increasing the inside diameter at the constant thermal load and height of the lift part of the generator, the mode of jet flow with the capture of particles of the liquid will not be realized. In this case, there appears the nucleate boiling regime with the lifting of the separate bubbles of vapor, practically without lifting the liquid.

In the case of decreasing inside diameter of the generator one may observe a reverse picture – the ejection of liquid occurs with an insignificant volume of vapor, i. e., the mode of operation of the pumping thermosyphon is not realized either.

The height of the lift part of the generator determines hydraulic resistance during the VLM flow and heat losses to environment.

That is why, under these conditions, a generator with minimal height of the lift part is the most preferable.

At the same time, the height of the lift part of the generator determines the conditions of work of the ARU absorber, which in modern constructions is a serpentine tube heat exchanger [4, 5], along whose internal surfaces a weak WAS moves by gravity, while a flow of the saturated hydrogen-ammonium steam-gas mixture (SGM) rises by countercurrent to it.

By design, a serpentine absorber in space is found between the input-output of a thermosyphon and actually the height of the lift part of the generator determines the surface of heat- and mass exchange in the process of absorption and, to a considerable extent, refrigerating capacity of the ARU vaporizer.

5. 2. Results of experimental research into the ARD performance and its separate elements at different values of magnitude of the thermal power supplied to the generator

Our conducted experimental research into ARU at three different conditions of heat removal from the surface of a dephlegmator (Fig. 3) made it possible to select 5 standard modes of work of the ARU generator (Fig. 4).

First, these are two boundary modes, connected with a non-start of generator – I and V. Let us denote the mode I as "non-start of generator, type I" and the mode V as "non-start of generator, type II".

Mode I lies in the range of thermal loads of a generator from 0 W to 35...40 W. It is characterized by the fact that amount of supplied heat is insufficient for the formation of the steam bubble, capable to eject liquid WAS out of the lift part of the generator. In the zone of heat supply, an immovable steam bubble is formed, and above it, in the lift part of the generator, there is a pillar of liquid WAS. The supplied heat is transferred by thermal conductivity to the elements of construction of a generator node and is scattered into environment. In the mode I, the ARU cycle is not realized because of the lack of WAS circulation between the generator and the absorber.

Mode V occurs in the course of supplying the thermal load in the generator 180...190 W and larger. It is characterized by draining the zone of heat supply, connected with the crisis of boiling. High overheating in the zone of heat supply and in the feeders blocks the supply of strong WAS to the generator. The boiling of strong WAS actually occurs in a rectifier. Resultant vapor enters the dephlegmator and then the capacitor, where it is liquefied and flows to the vaporizer. Because of the blocking of the liquid in the horizontal elbow of the rectifier, the work of absorber stops and, correspondingly, the steam-gas contour between the vaporizer and the absorber is not realized. Because of this, the ammonia that enters the vaporizer does not evaporate but it flows to the tank of absorber. Refrigeration cycle under this mode is not realized either.

Optimal ratio (b_{opt}) between the amount of lifted liquid and the volume of obtained vapor occurs in the mode III in the range of supplied thermal power from 70...80 W to 100...110 W. In this case we observed maximal refrigerating capacity of the ARU vaporizer and, correspondingly, the maximal values of thermal coefficient of the ARU cycle are attained [6, 13–15].

The middle part of the range of thermal power of the ARU generator corresponds to optimal, from the point of view of energy efficiency, values at ambient temperatures of 24...26 °C.

b_{opt} is shifted towards lower values (70...80 W) at the reduction in the air temperature to 18...20 °C.

b_{opt} passes towards larger values (100...110 W) at temperatures of 32...35 °C.

Such displacement of the values of b_{opt} is connected with the change in the conditions of the ARD work, i. e., with the change in the heat flows to the cooled chambers and in the heat release conditions to environment. These results, obtained in the process of experimental research [6, 13–15], are confirmed by theoretical analysis of the cycles of both pumpless and pump ARU [13].

Thus, from the point of view of energy efficiency of realization of the ARU cycle, it is expedient to change the value of the supplied thermal power in the ARU generator in accordance with the change in the ambient air temperature.

Mode II lies at the side of lower, in comparison with the optimal mode III, values of the supplied thermal power. Its range is from 35...40 W to 70...80 W. In this mode, there predominantly occurs the pumping of the WAS liquid phase by the lowest possible volume of vapor. Under these working conditions, a smaller volume of ammonia vapor enters the capacitor and then the vaporizer, which leads to the reduction in refrigerating capacity.

At the lower generation of vapor, the flow of weak WAS is not cleaned to the concentration of 0,15...0,18 at the input of the absorber. However, due to high multiplicity of circulation between the generator and the absorber of WAS, the absorber manages the tasks of cleaning SGM, which is supplied from the vaporizer. Refrigerating capacity of the vaporizer and energy efficiency of the ARU cycle in the mode II diminishes at the decrease in the value of the supplied thermal power in the generator from 70...80 W to 35...40 W.

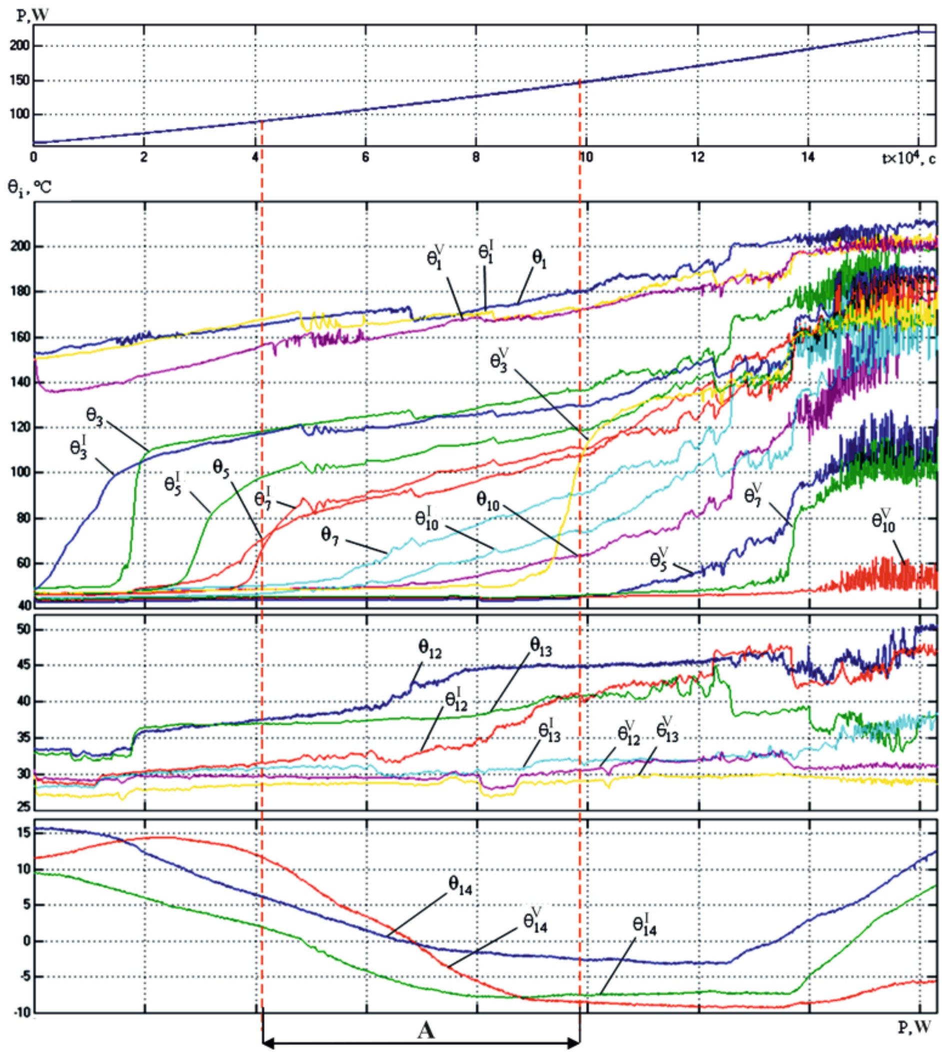


Fig. 3. Comparison of the quasi–static characteristics of dependencies of temperatures of the surface of the ARU elements in control points on the thermal power, supplied to the generator, at different conditions of the work of the lift section of a dephlegmator: θ_i – temperatures without a change in the conditions of heat removal to environment, θ_i^V – with intensive heat removal with the aid of a fan, θ_i^I – with the thermal insulation along entire length of the lift section of a dephlegmator, A – the range of power, within which the optimal value of thermal coefficient of the ARU cycle is attained

P, W	Mode	b	
above 180...190	Non–start of generator, type II	b=0	V
100...110 – 180...190	Volume of obtained vapor exceeds optimal value	$b<b_{opt}$	IV
70...80 – 100...110	Optimal ratio between amount of lifted liquid and obtained vapor	b_{opt}	III
35...40 – 70...80	Amount of lifted liquid exceeds optimal value	$b>b_{opt}$	II
0 – 35...40	Non–start of generator, type I	$b=\frac{0}{0}$	I

Fig. 4. Ranges of the working modes of the ARU generator

From the point of view of controlling ARD in the positional mode, the mode II may be considered as a "waiting" mode when turning off the basic (nominal) thermal power. The "waiting" ARU mode ensures minimal generation of vapor and circulation of the solution so that the inert gas, hydrogen, is pushed out of the larger part of the lift section of the dephlegmator. In this mode, ARU is, so to speak, in the "standby regime" for rapid start of capacitor and vaporizer at the transfer to a larger thermal power, supplied in the generator.

Mode IV is to the side of larger, in comparison with the optimal mode III, thermal power in the generator – from 100...110 W to 180...190 W. The mode IV is characterized by predominant production of vapor rather than the amount of the pumped liquid WAS, i. e., $b<b_{opt}$. The multiplicity of circulation of the liquid WAS flow between the generator and the absorber is minimal but weak WAS is depleted by ammonia lower than the optimal values to 0,10...0,12. In this case, in spite of the minimal consumption of circulating weak WAS, its high absorbing potential makes it possible to efficiently solve the problems of cleaning the saturated SGM, which enters the absorber from the vaporizer.

Under this mode, the steam flow contains a significant volume of water vapor and the dephlegmator manages to clean the steam flow, which enters the capacitor and then the vaporizer, only at low temperatures of the outside air (10...15 °C).

At the lower boundary of thermal power, refrigerating capacity of the vaporizer is still sufficiently significant. With an increase in the thermal power, water starts to enter the vaporizer and insufficiently cooled weak WAS enters the absorber. Both these factors lead to the reduction in refrigerating capacity.

Thus, the operating mode IV is characterized by low energy efficiency because of significant amount of evaporated water. Paper [6] demonstrates that the steam flow with increased content of water vapor possesses the higher specific volume than the flow of vapor of pure ammonia. Such a flow can much faster extrude inert gas from the dephlegmator and start the vaporizer. The mode IV may be recommended as the "accelerated" at the ARU start [1, 10], but in the course of its realization, it is necessary to remember the limitation of temperature of the heating surface of the tube of thermosyphon by the value of 180...190 °C because of the danger of occurrence of process of active corrosion.

6. Discussion of results of the research into influence of the thermal power supplied in the ARU generator node on the operating modes and energy efficiency of ARD

Let us further analyze the influence of thermal power in the generator on the working modes of the rest of the ARU elements.

At the first stage of analysis it should be noted that all the elements of ARU are designed for the work with nominal thermal power in the generator with a certain reserve by the heat transfer surface. Under the nominal regime, all the elements of ARU should be guaranteed to perform their functions:

a) rectifier – to conduct partial cleaning of the steam flow, supplied from the generator and to preheat strong WAS before its entering the lower part of the generator;

b) dephlegmator – to conduct complete cleaning of ammonia vapor from water vapor with the outlet of phlegm to the rectifier;

c) capacitor – to conduct liquefaction of the steam flow of ammonia and partial subcooling of liquid;

d) vaporizer – to produce artificial cold in the process of contact interaction between the flow of liquid ammonia with the flow of purified inert gas – hydrogen;

e) absorber must provide for the cleaning of saturated SGM, supplied from the vaporizer, with simultaneous bringing of weak WAS to the state of strong WAS;

f) liquid heat exchanger (LHE) must provide for the preheating of flow of strong WAS, entering the generator node, with simultaneous subcooling of the flow of weak WAS, which passes from the generator to the input of absorber.

Let us examine the peculiarities of the working modes of the basic elements of ARU at the deviation of thermal power in the generator from the nominal value to the larger (mode IV) and lower (mode II) sides.

Rectifier. With an increase in the supplied thermal power in the generator (mode IV), the consumption of strong WAS at the input of the rectifier decreases. Simultaneously, the consumption of the VLM grows, which passes from the downflow section of dephlegmator to the lift one. Because of the increased speed of the VLM flow and lowered speed of the flow of strong WAS, the temperature in the rectifier in the process of interaction of flows rises. The increase in temperature in the rectifier shifts equilibrium in the liquid WAS towards the smaller equilibrium concentrations of ammonia. Accordingly, in the rectifier, the cleaning of ammonia vapor is not done in full, but in this case ammonia is additionally evaporated out of strong WAS and a more heated WAS enters the generator's input.

Reduction in thermal power in the generator (mode II) increases the consumption of strong WAS at the input of rectifier and reduces the amount of the entering vapor. Equilibrium temperature is shifted to the area of increased concentrations of ammonia. In this case, a deeper cleaning of the VLM flow will be carried out before it enters the input of the lift section of dephlegmator, but the insufficiently heated strong WAS will enter the generator's input.

It should be noted that the rectifier is located in the thermal insulation jacket and is minimally subjected to the action of ambient air temperature. A rectifier is made by design with maximally possible size with the purpose of increasing the surface of interaction between the fluid and steam flow in the bubbling mode. Only hydraulic resistance of vapor flow is the limitation.

Dephlegmator. At high values of thermal power, supplied in the ARU generator, the larger flow of steam mixture enters its output with increased content of water vapor. Thermal mode of the work of dephlegmator is complicated, especially at elevated ambient air temperatures (28...32 °C). In this case, dephlegmator is not capable to fulfill its function and insufficiently purified ammonia enters the input of capacitor and then the vaporizer.

At low values of ambient air temperature (10...15 °C), dephlegmator is capable to clean the ammonia vapor. At the same time, when working under these conditions with the nominal or lower thermal power, supplied in the generator (mode III and II), a partial condensation of ammonia vapor occurs, which decreases refrigerating capacity of vaporizer and energy efficiency of the ARU cycle.

Dephlegmator is designed to solve the problem of complete removal of water vapor from ammonia vapor under operating conditions at a temperature of ambient air of 32 °C when working in the nominal mode of heat supply.

Capacitor. Even at the increased thermal power, supplied in the ARU generator, the capacitor, fabricated originally with a certain reserve by the surface, solves the problem of liquefaction of ammonia vapor. But the subcooling of condensate cannot be achieved at high ambient temperature.

Vaporizer. At the increase in thermal power, supplied in the ARU generator, the amount of liquid ammonia that enters the vaporizer increases. However, since the consumption of weak WAS decreases, the absorber is not capable to clean the circulating SGM. Insufficiently purified SGM starts entering the input of vaporizer. Vaporization conditions deteriorate and a part of liquid ammonia flows into the tank of absorber (receiver of strong WAS). This mode is characterized by low energy efficiency of the ARU cycle and observed at comfortable and elevated ambient temperatures.

At reduced ambient temperatures the absorber can solve the problem of cleaning SGM. But in the majority of practical cases, at a low temperature of the outside air, the heat flows to the cooled chambers are reduced and thermal load of the vaporizer is also reduced. Accordingly, a part of liquid ammonia again does not participate in the process of evaporation and goes into the receiver.

The only case, when the mode of increased thermal power, supplied in the generator, becomes energetically efficient, is the loading of a large volume of heated products into the chambers, but ARD in this case must be located under conditions of reduced ambient temperatures.

At the reduction in thermal power, the vaporizer receives a lower amount of liquid ammonia. It is guaranteed to evaporate but refrigerating capacity is reduced. The energy efficiency of the ARU cycle is reduced accordingly. This effect is less felt at reduced ambient temperatures and is more demonstrated at elevated temperatures. This situation is explained by the effect of ambient temperature on the absorbing capacities of absorber.

Absorber. At the increased thermal power, supplied in the generator, a lower amount of liquid WAS circulates through the absorber, at the lowered – vice versa. In the first case, a weaker (by ammonia) WAS enters the input, in the second – stronger.

Low temperatures of ambient environment are favorable for the process of cleaning SGM in the absorber, high – do not contribute to it. Absorber is designed with a certain reserve by the surface and it allows, with larger or lower efficiency, solving the problems of cleaning SGM even under unfavorable conditions of the ARD work.

LHE. At the increased thermal power, is reduced the circulation both of weak and strong WAS is reduced. Weak WAS with the elevated temperature comes to the input. At the reduced thermal power, supplied in the generator of ARU, the circulation of solutions in LHE increases, and weak WAS with reduced temperature comes to the input of LHE.

Since LHE is made for realization of a certain average nominal mode, then at increased thermal power its efficiency will increase, and at the decreased power, it will be reduced.

The advantages of the conducted research include:

a) classification and analysis of directions of increase of energy efficiency of ARD, substantiation of the relevance of intensification of the studies in the field of improving the modes of operation, methods and systems of control of ARD;

b) the study of the features of construction of boilers-generators and description of their influence on the normal functioning in the composition of ARD without reference to the concrete model;

c) the analysis of influence of thermal power, supplied to the generator, on the processes of the heat mass exchange and the modes of operation of ARD, substantiation of the presence of 5 different modes of the work of generator (Fig. 4): the most energetically efficient (III), "waiting" (II), "accelerating" (IV) and non-working modes (I, V).

The work's shortcomings may include the following:

a) experimental studies were conducted only under conditions of elevated ambient temperatures at 25...32 °C, whereas variations may be observed at the lowered values;

b) the experiments were conducted for the concrete ARD model ("Kiev-410", the Ash-160 type) and results for other models can be different.

The given research can be used for designing the absorption refrigeration apparatuses of household and special usage, as well as in the related industries when developing the energy-efficient methods and designing the energy-efficient systems of control.

The conducted research is useful for designers of systems of automatic control of ARD.

7. Conclusions

1. Based on analysis of the processes of heat mass exchange and the modes of flow of vapor-liquid water-ammonium mixture in the ARU generator-thermosyphon, we showed the influence of numerical values of the height of the lift part of the generator on energy characteristics of a standard ARU. It is ambiguous – on one side, an increase in height leads to the increase of hydraulic resistances at the motion of theVLM flow and heat losses, on the other hand, there appears a possibility of increasing the surface of the heat mass exchange in the absorber.

2. We obtained a set of quasi-static characteristics of the work of modernized one-chamber ARD "Kiev-410" with NTO of the Ash-160 type along the channels "thermal power supplied to the ARU generator – temperatures of the surface of the ARU elements in control points" at different conditions of heat removal from the external surface of the dephlegmator (nominal, intensive heat removal, thermal insulation along entire length of dephlegmator). This made it possible to conduct the simulation of different conditions of environmental effect on the thermal modes of ARD and ARU.

3. As a result of conducted studies of modernized one-chamber ARD "Kiev-410" with LTC of the Ash-160 type, we selected 5 types of the working modes of generator: optimal by energy efficiency (III), "waiting" (II), "accelerating" (IV) and two non-working modes (I and V). It was shown that at modes I and V refrigeration cycle of ARU is not realized. Mode II may be used by designers when developing energy-saving ARD with positional algorithms of control as the "waiting" mode, which ensures the state of "readiness" for rapid start; mode IV – as the " accelerating" at the start of ARU from non-operating state to the rapid attaining of the working load.

4. The conducted research and analysis of its results make it possible for the designers of household ARD to create energy-saving models that efficiently work in a wide range of ambient temperatures from 10 °C to 32 °C.

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