

Ministry of Education and Science of Ukraine
**ODESSA NATIONAL ACADEMY OF
FOOD TECHNOLOGIES**

International Competition of
Student Scientific Works

**BLACK SEA
SCIENCE 2020
PROCEEDINGS**



ODESSA, ONAFT 2020

Ministry of Education and Science of Ukraine
Odessa National Academy of Food Technologies

International Competition of Student Scientific Works

BLACK SEA SCIENCE 2020

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4. POWER ENGINEERING **AND ENERGY EFFICIENCY**

THERMODYNAMIC ANALYSIS OF PERIODIC OPERATION AMMONIA-WATER ABSORPTION REFRIGERATION UNITS IN ATMOSPHERIC WATER GENERATION SYSTEMS

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Abstract. *The usage of heat absorption water-ammonia refrigeration units in atmospheric water generation systems is considered. A basic design of periodic operation AWRU is described. A method for thermodynamic calculations and analysis of AWRU PO cycles and modes of operation is presented. Specific refrigerating capacity depending on the composition of water-ammonia solution, the temperature of the heating source, the ambient temperature of the environment is calculated. It is shown that increasing the temperature of the heating source from 65°C to 95°C leads to minimum temperature in the cooling zone decreasing from 7°C to -17°C. Low-temperature ambient air at 25°C enables attaining the maximum value of refrigerating capacity of AWRU PO by increasing the proportion of ammonia in the initial composition from 0.3 to 0.5, and this enables lowering of the heating temperature from 95°C to 65°C.*

Key words: *ammonia-water absorption, periodic operation refrigerator, thermodynamic analysis, atmospheric water generation.*

NOMENCLATURE

t	temperature,	(°C),
P	pressure,	(Pa)
h	heating, heated,	
m	mass,	(kg)
w	cooling, cooled	
Δm	transferred mass,	(kg)
a	absorption	
X, x	fraction of NH ₃ ,	(kg/kg)
r	heat of evaporation,	(kJ/kg)
Q	cooling capacity,	(kJ)
beg	at the beginning	
q	specific cooling capacity,	(kJ/kg)
A	ammonia (NH ₃)	
WAS	water-ammonia solution	
B	water	
AWRU	absorption refrigeration unit	
(x)	in liquid	
PO	periodic operation	
(y)	in vapor	
G-A	generator-absorber	
A-E	absorber-evaporator	
0	useful capacity	

y fraction of NH_3 in vapor, (kg/kg)
ob an object

1. INTRODUCTION

It is a common knowledge that one of the most valuable resources in the future of our planet is going to be fresh water, and the demand for water resources is already one of the main factors in global logistics of contemporary world, and this trend will only grow in the foreseeable future. One of the developments in water production technology is mechanical air dehumidification — condensation of water vapor on the surfaces with a temperature below the dew point. In this case, there are great prospects for the methods associated with the work of independent generators of cold — chillers that are guaranteed to provide the temperature below the dew point temperature. A necessary condition for operation of compression refrigeration machine is the availability of electrical energy. At the same time, the majority of countries facing water scarcity are limited in energy resources, too. Often the readily available source of energy in there is the sun. [Alekseyev V.V., Chekarev K.V. 1996.]

In this regard there have been developed original schemes of absorption water-ammonia refrigeration units of periodic operation (AWRU PO) based on solar collectors, which differ with autonomy and independence from the sources of electrical energy, and unlike heat-analogues (steam jet and lithium-bromide absorption) can be operated with air cooling of their heat-dissipating elements. [Pearlstein B.H. 2008.]

2. A METHOD OF CALCULATION FOR AWRU PO CYCLE

A scheme of flows in AWRU PO during different phases of its work is shown in Figure 1. In the initial time, when AWRU PO zones are at the same temperatures equaling ambient temperature, the composition of the working fluid (WAS) is the same in both zones. In the charging period, the heat flux Q_h arrives to the AWRU PO generator (left part in Fig.1.a) at the temperature t_h . The absorber-evaporator (right part in Fig.1.a) is at ambient air temperature (t_w) and removes the absorption heat Q_a .

During the charging period (Figure 1.a), there occurs the movement of mostly lower boiling component (ammonia) from the generator-absorber (G-A) into the absorber-evaporator zone (A-E). Herewith a temperature in G-A is increased from ambient temperature toward the temperature of the heating medium (t_h), the rate of change is slightly influenced by the initial composition of WAS. At the end of the evaporation process, the temperature in the G-A is at its maximum, the pressure in the system is also at maximum, and the temperature in A-E can be assumed constant and equal to t_w . At the same time, the maximum proportion of ammonia in the WAS is in the A-E, and the minimum — in the G-A.

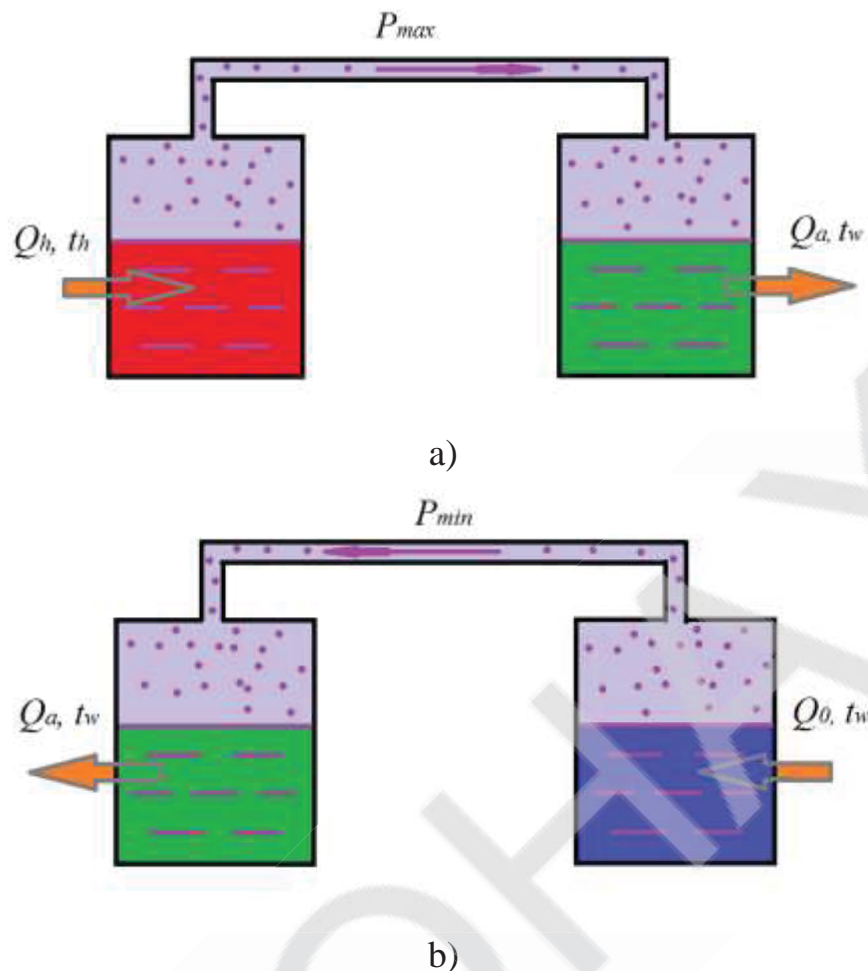


Figure 1. The diagram of the heat and mass flows inside the operating AWRU PO
 a) — operation during the charging phase; b) — operation during the cooling phase

In the cooling phase (Figure 1.b), the heat flow from the heat source is blocked, and the outside air is supplied to the outer surface of the G-A, leading to its cooling to ambient environment temperatures. Due to the equilibrium shift in the WAS, when the temperature in the G-A is lowered, the system moves into a state of reduced pressures. In the internal volume of AWRU PO, the system pressure falls to the minimal (in the initial time) value P_{min} . At this point, saturated with ammonia WAS in the A-E starts to boil with heat removal from the outside air flow. Upon cooling of WAS, a thermal flow Q_o from the environment into the G-A appears due to the temperature difference, that flow is a refrigerating capacity of the AWRU PO. The generated vapor of ammonia is absorbed in the G-A zone with a heat of absorption Q_a transferring to the environment with the corresponding temperature t_w . In this process, there is a monotonic increase of pressure with a corresponding increase of temperature in the A-E zone. The air flow that washes over the outer surface of the A-E is cooled to temperatures below the dew point, and the water condensate devaporates out of it. The cooling process takes place until the establishment of thermal equilibrium in zones G-A and A-E.

For the practical implementation of such a device, it is necessary to estimate its specific cooling capacity q_o when operating under different climatic conditions, with the prospect of maximal utilization in the arid tropical zones of the planet. This

refrigerating capacity is determined by the amount of heat, removed from air while it cools below the dew point temperature, relatively to refrigerant's mass. In connection with this, the initial data must include temperature and humidity of atmospheric air and the potential maximum temperature of the heating source t_h .

At the initial stage of the calculation, there was specified an initial equilibrium composition of WAS, denoted as x_{beg} (in the liquid phase) and y_{beg} (vapor phase). When calculating, the volumes of WAS in G-A and A-E zones are assumed equal. Considering equal temperatures of all system elements $t_w^{G-A} = t_w^{A-E}$ before operation, the composition of the phases are defined as:

a) for the liquid phase:

$$x_{G-A}^{beg} = \frac{m_{G-A(x)}^A}{m_{G-A(x)}^A + m_{G-A(x)}^B} = x_{A-E}^{beg} = \frac{m_{A-E(x)}^A}{m_{A-E(x)}^A + m_{A-E(x)}^B} \quad (1)$$

b) for the vapor phase:

$$y_{G-A}^{beg} = \frac{m_{G-A(y)}^A}{m_{G-A(y)}^A + m_{G-A(y)}^B} = y_{A-E}^{beg} = \frac{m_{A-E(y)}^A}{m_{A-E(y)}^A + m_{A-E(y)}^B} \quad (2)$$

where m is the mass of solution components, kg; A — ammonia, B — water.

During the charging period (Figure 1.a), some mass of ammonia vapor and water vapor transfers from the zone G-A to the zone A-E. The maximum possible value of the proportion of ammonia in the liquid phase in the A-E is determined by the following relationship:

$$x_{A-E}^{max} = \frac{m_{A-E(x)}^A + \Delta m_{(x)}^A}{m_{A-E(x)}^A + \Delta m_{(x)}^A + m_{A-E(x)}^B + \Delta m_{(x)}^B} \quad (3)$$

Respectively, the mass in the G-A proceeds to decline:

$$x_{G-A}^{min} = \frac{m_{G-A(x)}^A - \Delta m_{(x)}^A}{m_{G-A(x)}^A - \Delta m_{(x)}^A + m_{G-A(x)}^B - \Delta m_{(x)}^B} \quad (4)$$

where $\Delta m_{(x)}^A$ and $\Delta m_{(x)}^B$ — respectively, the mass of ammonia and water in the liquid phase, transferred from G-A to A-E, kg.

The values of x_{G-A}^{min} and the values of x_{G-A}^{max} are linked by their thermodynamic parameters — pressure and temperature.

The aim of the thermodynamic calculation of AWRU PO is to define the operating range with the estimation of specific cooling capacity, which determines the performance of installation for the atmospheric water generation by mechanical dewatering (ensuring the temperature of wall and air contact area is below the dew point).

The calculation was carried out for a range of regime parameters:

a) the temperature of the heating source (generator wall) $t_h = 65 \dots 95^\circ\text{C}$;

b) the temperature of the "cold source" (ambient air temperature) $t_w = 25 \dots 45^\circ\text{C}$;

The water-ammonia solution (WAS) is used as the working fluid. The calculations assume the maximum operating temperature in the cooling area to be $t_{ob} = 10^\circ\text{C}$.

3. THE RESULTS OF CALCULATION AND THEIR ANALYSIS

The analysis of received results shows that with the ambient air temperature rising, the minimum pressure in the system P_{\min} (for a fixed WAS composition in the area of generation) increases, moreover the increase is higher for larger values of ammonia fraction in G-A (X_{\min}). This suggests that the increase in ambient air temperature and pressure rise in the system means the temperature in the cooling area increases too, i.e. the cooling capacity of AWRU PO decreases. This dependency is even more noticeable at higher numerical values of X_{\min} .

The analysis of the dependency in Figure 2 shows that with increasing temperature of the heating source, the temperature in the cooling zone is reduced. Thus, when $t_h = 65^\circ\text{C}$, $t_{ob} = 7^\circ\text{C}$, but when $t_h = 95^\circ\text{C}$, $t_{ob} = \text{minus } 17^\circ\text{C}$. The composition of WAS in the generation area has only a little effect on the minimum temperature in the cooling zone, as illustrated in Figure 3.

To assess the cooling capacity of AWRU PO there was conducted the calculation of current operating parameters of WAS in operating zones during the processes of charging and discharging. Using the formulas (3) and (4), and neglecting the amount of ammonia in the vapor phase, we obtain the dependencies of current parameters (primarily the temperature in A-E zone) during the discharge period.

To estimate the specific cooling capacity of AWRU PO in the range of real modes of operation (the cooling area temperature is not above 10°C), there was carried out a calculation of average integral values of the heat of vaporization of ammonia (r_{cp00}) for the operation period of "charge-discharge". The value of r_{cp00} is depending on the pressure and temperature.

During the operating period, the specific cooling capacity is calculated from the mass of evaporated ammonia $\Delta m_{(x)}^A$ with the equation:

$$q_0 = \Delta m_{(x)}^A \cdot r_{cp00} \quad (5)$$

The Figure 4 represents the obtained dependencies of the AWRU PO specific cooling capacity, calculated by formula (5). Analysis of the curves in Figure 4 shows that the cooling capacity increases with the temperature of the heating source, as expected. Thus, when $t_w = 25^\circ\text{C}$ and $X_{\min} = 0.3$, at t_h growth from 65 to 95°C , the value of q_0 changes from 650 to 2800 kJ. When $t_w = 35^\circ\text{C}$, the value of q_0 is increased from 50 kJ to 1200 kJ. When ambient air temperature is $t_w = 45^\circ\text{C}$, the operating mode of AWRU PO cannot be implemented at temperatures of the heating medium below 95°C .

At low ambient air temperatures, sufficiently high cooling capacity can be achieved by increasing the amount of ammonia in WAS in the generation-absorption area (X_{\min}). Thus, similar values of $q_0 = 2650$ kJ when $t_w = 25^\circ\text{C}$ can be obtained at $t_h = 95^\circ\text{C}$ and $X_{\min} = 0.3$, as well as at $t_h = 65^\circ\text{C}$ and $X_{\min} = 0.5$.

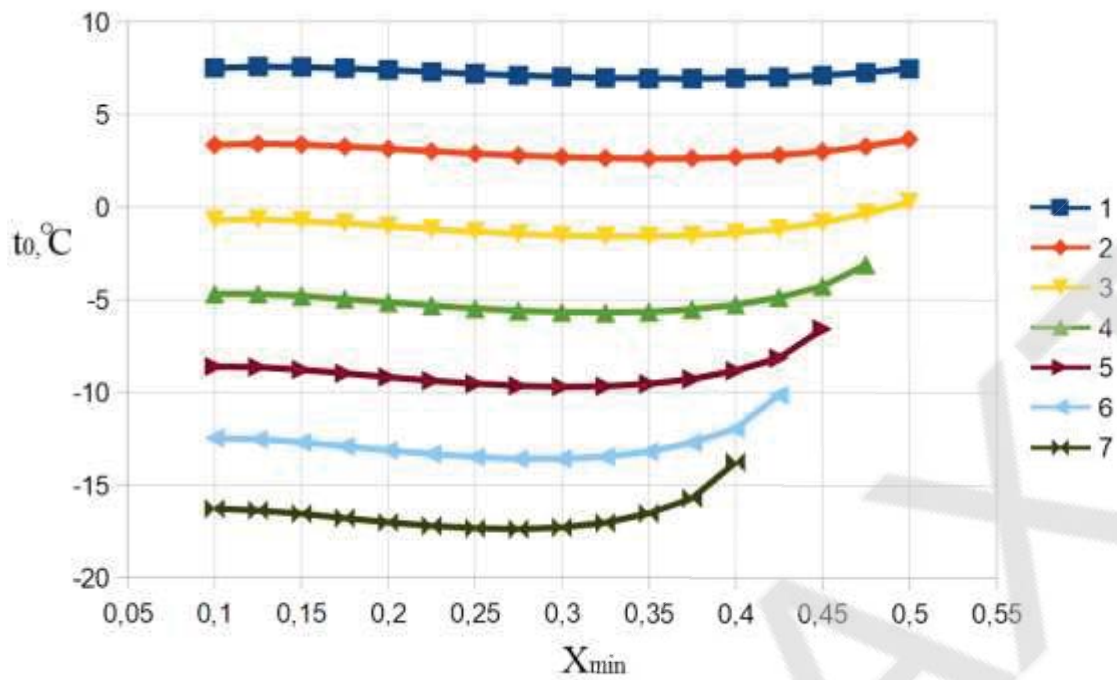


Figure 2.a

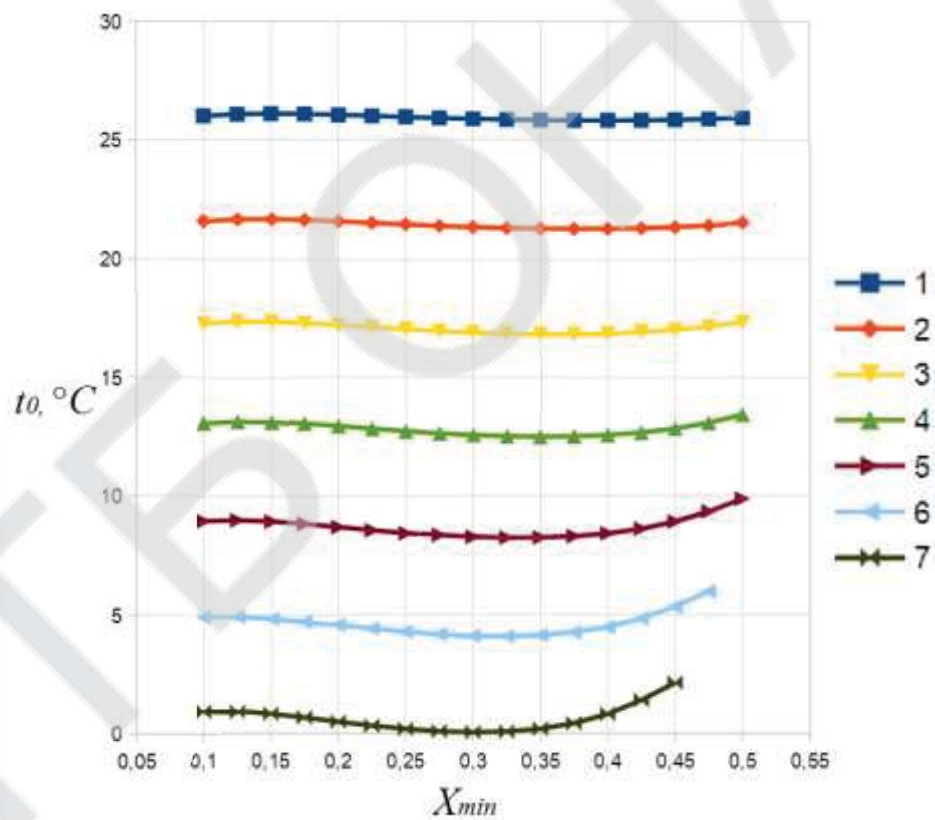


Figure 2.b

Figure 2. The minimal temperature in the cooling zone depending on the composition of WAS in the generation zone and the temperature of heating source at the fixed ambient temperature: a) $t_w = 35^\circ\text{C}$; b) $t_w = 45^\circ\text{C}$; 1, 2, 3, 4, 5, 6, 7 — the temperature of heating source, respectively 65, 70, 75, 80, 85, 90, 95 °C

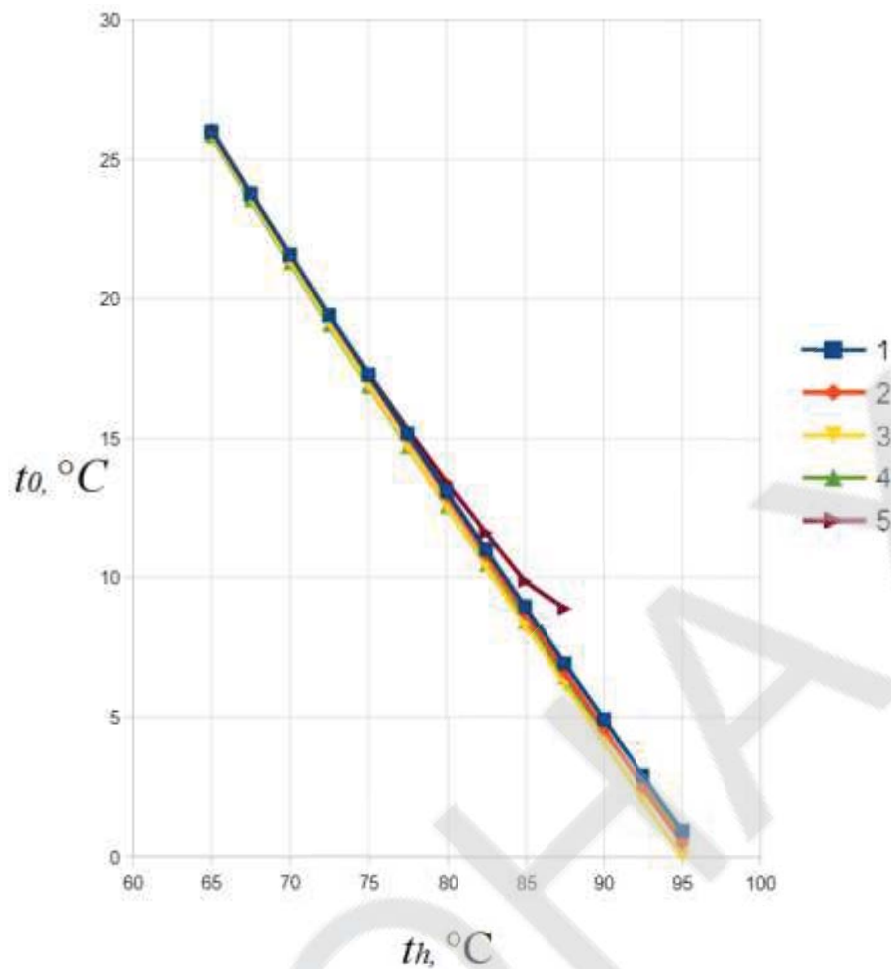


Figure 3. The minimal temperature in the cooling zone depending on the temperature of heating source and the composition of WAS in the generation zone at the fixed ambient temperature $t_w = 35^\circ\text{C}$; 1, 2, 3, 4, 5 — the composition of WAS with minimal fraction of ammonia x_{\min} , respectively 0.1, 0.2, 0.3, 0.4, 0.5

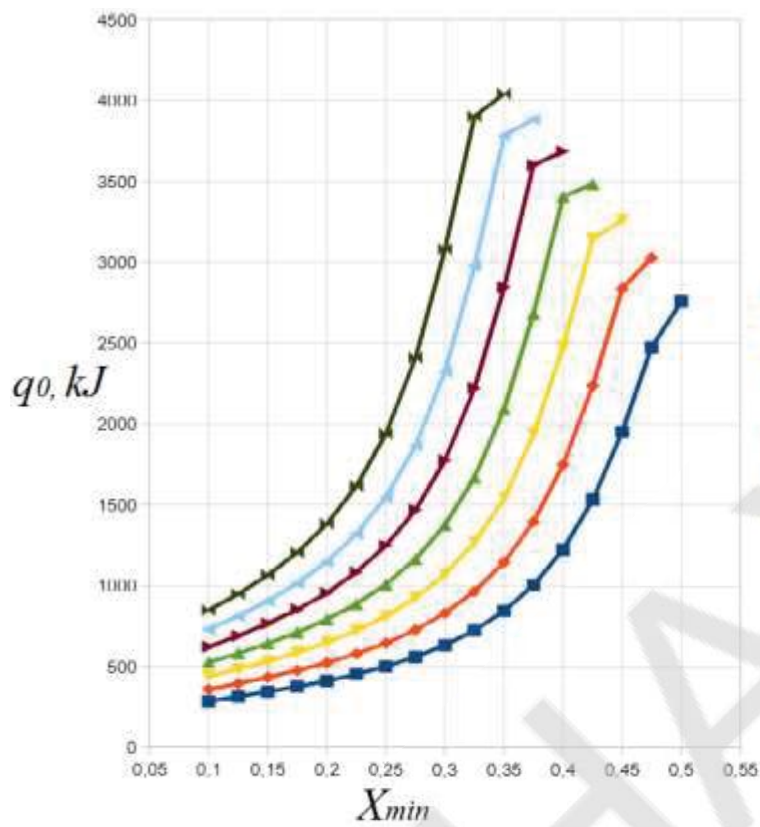


Figure 4.a

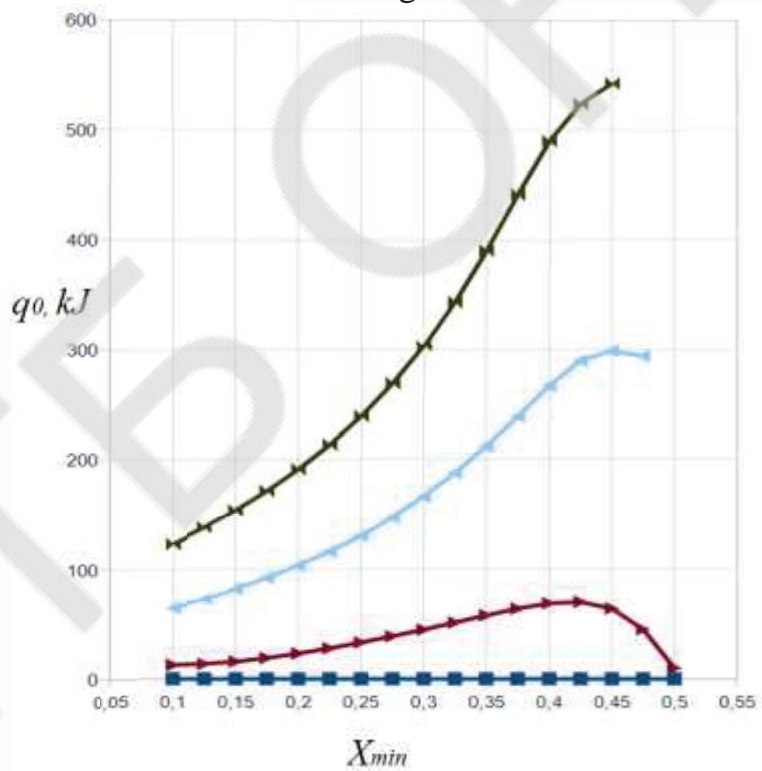


Figure 4.b

Figure 4. The specific cooling capacity of AWRU PO, depending on the mixture composition in the generation zone and the temperature of heating source, at the constant ambient temperature: a) $t_w = 25^\circ\text{C}$; b) $t_w = 45^\circ\text{C}$; 1, 2, 3, 4, 5, 6, 7 — the temperature of the heating source, respectively 65, 70, 75, 80, 85, 90, 95 °C

4. CONCLUSIONS

1. By increasing the temperature of heating source, the proportion of ammonia in the G-A zone is reduced, allowing to obtain higher potential capacity of absorption process during the cooling phase, i.e. to increase the specific cooling capacity of AWRU PO and the performance by water extraction from the air. Since the temperature rise of the heating source from 65°C to 95°C, minimal temperature in the cooling area decreases from 7°C to minus 17°C.

2. When the ambient air temperature increases, the specific cooling capacity of AWRU PO decreases, and this tendency is especially noticeable at higher ammonia fraction in the generation area.

3. The performed estimation of specific cooling capacity of the AWRU PO has shown that it increases along with the temperature of heating source, and at lower ambient air temperatures, this trend is more obvious.

4. At low ambient air temperature, the maximal values of specific cooling capacity of the AWRU PO can be obtained, by increasing the amount of ammonia in the generation area.

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