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DESIGNING ENERGY-EFFICIENT HARDWARE AND TECHNOLOGICAL STRUCTURE OF ABSORPTION REFRIGERATION UNITS FOR AMMONIA PRODUCTION

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The object of research is the equipment and technological design of absorption refrigeration units (ARUs) for the technological system of secondary condensation of large-scale ammonia production. Improving the energy efficiency of ARU is an urgent problem in the general process of reducing operating costs for natural gas in these industries as a whole.

Based on the results of analytical studies, the feasibility of combining absorption-refrigeration and vapor-ejector cycles was substantiated, which ensures a decrease in the boiling temperature of a weak water-ammonia solution in the cube of the generator-rectifier and an increase in the condensation pressure in the ARU cycle. Under such circumstances, it becomes possible to increase the concentration of the refrigerant due to the rectification of steam with a part of the liquid refrigerant without using a pump with the removal of the dephlegmator from the ARU circuit.

Experimental studies and material-thermal calculations of ARU cycles were carried out to determine the basis of comparison and the proposed version of the ARU scheme. It has been proven that the new technological design of ARU provides an increase in cooling capacity from 3.22 MW to 3.6 MW (by 12 %), the thermal coefficient from 0.527 to 0.551 (by 4.6 %), a decrease in the circulation ratio from 7.77 to 7.1 (by 8 %), and a decrease in the secondary condensation temperature by 2.5 °C.

It is shown that for the proposed version of the technological design of ARU, there is a change in specific costs – an increase in electricity by 1.48 kWh/t NH_3 and a decrease in natural gas by 0.41 nm^3/t NH_3. Taking into account existing cost indicators for natural gas and electricity, the application of the proposed technology ensures a decrease in annual operating costs by USD 185,000, and therefore an increase in the economy of ammonia production as a whole

Keywords: ammonia synthesis, absorption-refrigeration unit, heat disposal, energy efficiency of ammonia production

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1. Introduction

The expected growth of the world population to 9.6 billion by 2050 [1] makes it necessary to constantly increase the yield of grain agricultural crops, which is ensured by the introduction of nitrogen-containing mineral fertilizers into the soil.

The main raw material for these fertilizers is synthetic ammonia, the global production of which is mainly carried out in synthesis units with a capacity of more than 450,000 tons per year [2].

A feature of the equipment and technological design of modern large-tonnage ammonia synthesis units is their energy efficiency. One of the manifestations of such energy technology was the use of absorption refrigeration units (ARUs) as part of the technological system of secondary condensation. The principal technological function of ARUs is the cooling of circulating gas (CG), and their operation is ensured by the utilization of low-potential heat of material flows in the boilers of the generator-rectifier. As these flows, converted gas (CG) with a temperature of 137 °C from the carbon monoxide conversion department and steam-gas mixture (SGM) with a temperature of 125 °C from the gas condensate dispersal department are used [3]. This approach to some extent helps improve the energy efficiency of ammonia production.

The functioning of ARU is under the constant influence of external disturbances, which is due mainly to the use of air-cooling devices as condensers both in their composition and at the previous stage of primary condensation. In connection with this, the stability of the ARU operation is disturbed. At the same time, the main indicators of ARU efficiency vary within quite wide limits: cooling capacity from 2.44 MW to 3.25 MW; thermal coefficient from 0.42 to 0.51; CG cooling temperature (temperature of secondary condensation) from –8 °C to +5 °C [3]. An increase in the latter even by 1 °Cleads to a decrease in the energy efficiency of ammonia production due to an increase in the annual consumption of natural gas in the additional steam boiler by 307.3 thousand nm^3 [4].

Therefore, reducing the temperature of secondary condensation requires the construction of an energy-efficient hardware and technological design of ARU, which becomes especially relevant in the general process of reducing the energy costs of ammonia production.

2. Literature review and problem statement

The energy efficiency of the ARU cycle is largely determined by the thermal coefficient, which is the ratio of the cooling capacity Φ_0 to the spent heat Φ_g in the generator-rectifier [5]. A characteristic feature of ARU operation is the inversely proportional dependence of the cooling capacity, the heat coefficient η, and the temperature of secondary condensation Θ_{2C} on the multiplicity of solution circulation f [5]. However, given the existing equipment and technological design, the value f, in turn, follows an inversely proportional dependence on the temperature of the atmospheric air Θ_{ar} [3, 6], which makes it impossible to simultaneously increase the values of η and Φ_0 and decrease the value of Θ_{2C}.

The occurrence of such a situation is clearly illustrated by such a concept as the multiplicity of circulation of solutions f, which largely characterizes the work of ARU [7]. The value f is determined by the ratio of the difference in ammonia concentrations in the water-ammonia vapor from the dephlegmator (rectifier) ξ_{df} and weak solution ξ_a to the degassing zone, which is the difference in ammonia concentrations in strong ξ_r and weak ξ_a water-ammonia solutions. In accordance with this, the value of f decreases with the growth of the value of the degassing zone. An increase in the latter, in turn, is associated with an increase in the concentration ξ_r, which increases with an increase in the pressure in the absorber. The increase in this pressure occurs due to the increase in the pressure in the evaporator, the increase of which is due to the increase in CG temperature Θ_{1C} at the evaporator inlet, that is, the external heat load. Under this condition, the boiling temperature in the evaporator increases and, despite the increase in Φ_0 due to the decrease in the value of f, the temperature Θ_{2C} increases.

The value of the circulation multiplicity can also be reduced with a decrease in the concentration ξ_{df} due to a decrease in the pressure in the rectifier generator. The latter is largely determined by the pressure in the air-cooling condenser, which decreases as the temperature of the ambient air decreases. Therefore, in order to reduce the value of ξ_{df}, it is necessary to reduce the pressure in the condenser, which is impossible under the conditions of increasing temperature Θ_{ar}. In addition, a decrease in the concentration ξ_{df} will lead to an increase in the boiling temperature of the refrigerant in the evaporator, to reduce which the intensity of phlegm drainage must be increased. Thus, under the existing ARU scheme to reduce the temperature Θ_{2C}, it is impossible to ensure a simultaneous reduction of condensation pressure, boiling of the refrigerant in the evaporator and an increase in the concentration of ξ_{df} to the evaporator under the conditions of an increase in the temperature of the atmospheric air.

Overcoming such a contradiction, as shown in works [8, 9], can be implemented by using a jet compressor between the rectifier generator and the condenser. The proposed scheme will ensure an increase in pressure in the condenser, which will allow intensifying the refrigerant condensation process at a higher temperature Θ_{ar}. At the same time, there is a possibility of a decrease in the pressure in the generator-rectifier, which will cause a decrease in the boiling temperature of the weak water-ammonia solution in the cube of the generator-rectifier and the heat load on the absorber. The process of increasing the condensation pressure contributes to an increase in the temperature of the refrigerant from the condenser to the evaporator, which negatively affects the specific cooling capacity, and therefore the temperature of secondary condensation. Under such circumstances, in order to increase the specific cooling capacity, it is necessary to ensure additional subcooling of the liquid refrigerant [10], which in turn will lead to an undesirable increase in operating costs. However, it is possible to remove the dephlegmator from the ARU circuit and obtain a refrigerant of very high concentration due to the rectification of steam with a part of the liquid refrigerant from the condenser receiver. With such a solution, there is no need to use a pump, which occurs with a generally accepted technological design process [11].

The operation of the jet compressor is ensured by working ammonia steam. The production of this steam in the steam generator and its condensation in the cycle of the steam ejector technological system (STS), as is known, is associated with additional energy costs. However, in the literature [8, 9] there is no information on the substantiation of the economic feasibility of the application of all the technical solutions discussed above. Under such circumstances, it becomes necessary to carry out material-thermal calculations of the refrigeration cycle to determine the target indicators of energy consumption for the ARU condensers and the STS steam generator. The shortcoming of the existing material-thermal calculation algorithms [3, 11] is the lack of consideration of the hydrodynamics of the rectifier generator, which does not allow determining the actual pressure distribution, and therefore the vapor and solution concentrations along its height. Underestimation of this distribution leads to miscalculations in the determined multiplicity of the circulation of solutions and the thermal coefficient of ARU. Thus, the final determination of the hardware and technological design of the refrigeration system requires separate research, improvement of the method of material-thermal calculation of the combined cycles of ARU and STS and a detailed technical and economic analysis of the economic feasibility of the technical solutions discussed above.

3. The aim and objectives of the study

The purpose of our research is to design an energy-efficient equipment and technological structure of refrigerating systems for the secondary condensation module, which combines the functioning of the absorption-refrigeration and steam-ejector technological cycles. As a result, under conditions of increased external heat load on the technological devices of ARU, the possibility of increasing its cooling capacity and lowering the secondary condensation temperature is ensured. This will make it possible to improve the energy efficiency of ammonia production by reducing the consumption of natural gas.

In order to achieve the set goal, it is necessary to solve the following tasks:

– to investigate the performance indicators of ARU according to industrial operation data to establish a comparison base;

– to determine the material low-potential heat flows in the synthesis unit to ensure the operation of STS and finally formulate technical solutions for the construction of the equipment and technological design of ARU;

– to determine the efficiency indicators for the newly built equipment and technological design of ARU, taking into account the hydrodynamics of the generator-rectifier, and perform a technical and economic justification regarding the feasibility of its use.

4. The study materials and methods

Based on the results of our literature review, the main directions for increasing the cooling capacity of ARU as an object of research include:

– obtaining practically pure refrigerant due to the application of the steam rectification scheme with part of the liquid refrigerant from the condenser receiver under high pressure;

– carrying out the process of condensation and generation-rectification at different pressures with the installation of a jet compressor between them;

– additional subcooling of the liquid refrigerant after the condenser in the water cooler;

– rejection of the steam dephlegmating scheme with a strong solution before it enters the solution heat exchanger.

Analysis of the proposed technical solutions shows that their implementation is due to additional energy costs to ensure the operation of the jet compressor with working ammonia steam and the air condenser in the STS cycle, as well as the liquid subcooler with cooling water. Determining the economic feasibility of applying the technical solutions listed above requires establishing a comparison base. For this purpose, the mode of operation of ARU was chosen, which provides the highest refrigerating efficiency under the conditions of increased atmospheric air temperature (Θ_{ar}=30 °C). At the same time, the material-thermal calculation of the cycle and cooling capacity of ARU according to both options (basic and proposed) was carried out using the algorithmic software described in [3]. This algorithm is additionally supplemented with the results of mathematical modeling of the absorber, evaporator, and hydrodynamics of the generator-rectifier operation.

The target indicators for the proposed version of the ARU hardware design were previously determined. The concentration of ammonia at the outlet of the dephlegmator, and therefore from the condenser, was taken at the equilibrium level, which is confirmed by real industrial experimental data. The condensation pressure was taken at 1.6 MPa, which ensures an increase in the condensation temperature to 40.3 °C. At this level of temperature under conditions of increased temperature Θ_{ar}, the efficiency of the condensation process will also increase. Carrying out the rectification and condensation processes at different pressures, respectively at the level of 1.435 MPa and 1.6 MPa, will allow the supply of a part of the liquid refrigerant (ammonia) from the condenser to the rectifier without the use of a pump. The pressure value at the level of 1.435 MPa at the outlet of the rectifier is due to the need to reduce the pressure in the cube of the generator-rectifier to the level of 15.5 MPa, the boiling temperature to 118 °C, and the concentration of the weak solution to 0.308 kg/kg. Under such conditions, the solution degassing zone will increase and the efficiency of the heat exchange process in the generator will increase. At the same time, the pressure value at the point of entry of the solid solution to the generator and the pressure difference in the generator cube and at the outlet of the rectifier, which is due to hydrodynamics, were calculated according to the equation given in [12]. Removal of steam from the dephlegmator scheme with a strong solution will result in a decrease in the temperature of the weak solution at the absorber inlet to a value of no more than 43 °C (67 °C according to the project) and a decrease in the heat load on the absorber.

Under such circumstances, it will be possible to have an excess of cooling water for use in a water subcooler. The use of an excess of this water will ensure a decrease in the temperature of the refrigerant after the condenser to a value of no more than 33 °C, and therefore an increase in the specific cooling capacity in the evaporator. In addition, according to existing data of mathematical modeling of the absorber, the amount of absorbed refrigerant will increase to 11.5 t/h [13].

CG consumption at the entrance of the secondary condensation system (618.5 thousand nm^3/h) and its composition (H_2 – 55.92 % vol., N_2 – 18.64 % vol., Ar – 6.0 % vol., CH_4 – 9.89 % vol., NH_3 – 9.55 % vol.)) were taken in accordance with the primary condensation temperature of 30 °C. The value of such a temperature is most characteristic according to the data of industrial operation in the spring and summer period. The productivity of the ammonia synthesis unit was taken at the level of 55.63 t/h, which is most typical for the existing AM-1360 series ammonia production. The cooling capacity of ARU, the amount of drained phlegm from the evaporator, the boiling temperature of the refrigerant in the evaporator and secondary condensation were established based on the results of mathematical modeling. At the same time, the modeling process was carried out taking into account the equation for the heat transfer coefficient from the circulating gas, which was actually determined based on experimental data, in accordance with the algorithm described in [4]. The temperature of the solid solution at the entrance to the generator-rectifier was determined depending on its concentration and pressure by the method of successive approximations in connection with its arrival in the state of wet steam.

5. Results of investigating efficiency indicators of absorption-refrigeration units

5. 1. Building a base of comparison regarding the performance indicators of ARU according to the data of industrial operation

Based on the results of experimental studies and the execution of material-thermal calculations, the basic mode of comparison was determined for the current (existing) ARU scheme. The main parameters of the nodal points of this mode are given in Table 1; the results of summarizing its heat balance are given in Table 2.

Given in Table 1, the results characterize the best operating mode under conditions of increased external thermal load on the devices, which is confirmed by the lowest cooling temperature of the central heating system at the level of 1.6 °C under such conditions.

Table 1

Main indicators of ARU efficiency according to the data on industrial operation

The state of the material flow	The best operating mode according to the existing scheme			
	Temperature, °C	Pressure, MPa	Concentration, kg/kg	Consumption, t/h
Strong solution at the generator inlet	106	1.6	0.396	82.774
Strong solution at the outlet of the absorber	35	0.29	0.396	82.774
Weak solution at the output of the generator	122	1.68	0.304	72.054
Liquid refrigerant from a solution heat exchanger	49	1.68	0.304	72.054
Liquid refrigerant from the condenser	35	1.58	0.998	10.72
Liquid refrigerant from a water subcooler	–	–	–	–
Liquid refrigerant from a steam subcooler	30	1.58	0.998	10.72
Refrigerant vapor at the condenser inlet	50	1.58	0.998	10.72
Phlegm from the condenser	–	–	–	–
Refrigerant vapors at the outlet of the steam subcooler	10	6.29	1.0	10.62
Refrigerant vapors at the evaporator outlet	–4.1	0.29	1.0	10.62
Phlegm from the evaporator	–4.1	0.29	0.808	0.1
Circulating gas to the evaporator	16	23.49	0.08714*	168.512
Circulating gas from the evaporator	1.6	23.49	0.10544*	168.512

*Note: * – concentration of ammonia condensate*

Table 2

Summarizing results of ARU heat balance according to industrial operation data

Device name	Amount of heat			
	Supplied		Discharged	
	Specific q, kJ/kg	Total Φ, MW	Specific q, kJ/kg	Total Φ, MW
Rectifier generator	2049.2	6.1	–	–
Evaporator	1095.5	3.22	–	–
Absorber	–	–	2009.4	5.96
Condenser	–	–	1157.6	3.43
ARU as a whole	3144.7	9.23	3167.0	3.39

The Table 2 results even more testify to the validity of choosing this mode as the basic one, which is due to the maximum achievable value of cooling capacity of 3.22 MW (3.14 MW according to the project). At the same time, the reliability of those values of the parameters of the nodal points of the ARU cycle that are given in Table 1 are confirmed by the convergence of its heat balance.

5. 2. Determination of low-potential material heat flows to ensure the operation of STS jet compressor

Our analysis of the material flows of ammonia production made it possible to establish that the task of obtaining working steam for the STS jet compressor can be most effectively solved only through recycling. Spent water vapor from a natural gas compression turbine in the amount of 18 t/h with a temperature of up to 90 °Cand a pressure of 0.04 MPa was chosen as such flow. Due to the disposal of the spent water vapor in the STS steam generator, it becomes possible to reduce the load on the air condensers, the operation of which is provided by three fans with an electric drive, the total consumer power of which is 348 kW. At the same time, the total consumption of the possibly obtained working steam M_{WS} with a pressure of 3 MPa, t/h, due to the disposal of the spent steam M_{SS} in the amount of 18 t/h in the STS steam generator is determined by the equations:

$$M_{SS} = 3.6 \times \Phi_{SG} / \left(i_{SV}^{IN} - i_{WK}^{OUT} \right); \quad (1)$$

$$\Phi_{SG} = M_{WS} \left(i_{WV} - i_K \right) / 3.6, \quad (2)$$

where Φ_{SG} is the heat flow of the steam generator, kW; i_{SV}^{IN}, i_{WK}^{OUT} – enthalpy of the spent water vapor at the input and water condensate output of the steam generator, kJ/kg, respectively; i_{WV}, i_K – enthalpy, respectively, of working ammonia vapor and ammonia liquid at the outlet of the condenser, kJ/kg.

According to the results of calculations based on equations (1), (2) taking into account the numerical values of enthalpies, the $M_{\Pi P}$ value will be more than 30 t/h. In accordance with the technical solutions listed above and the determined source for ensuring the operation of the jet compressor, the hardware and technological design of ARU can finally be represented in the form of the diagram shown in Fig. 1.

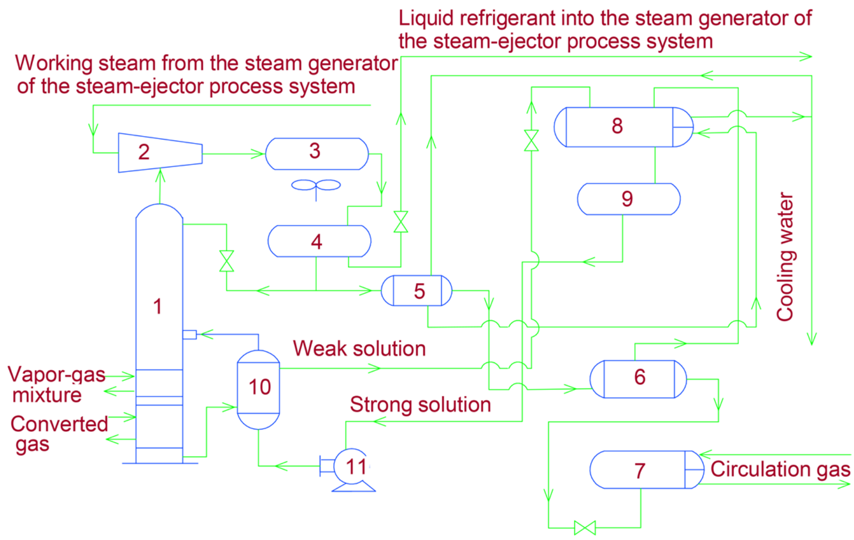

Fig. 1. Hardware and technological design of the absorption-refrigeration unit: 1 – generator-rectifier; 2 – jet compressor; 3, 4 – a module of air-cooling condensers in the cycle of the absorption-refrigeration unit and the steam-ejector technological system with a receiver; 5, 6 – water and steam supercooler, respectively; 7 – evaporator; 8, 9 – absorber with receiver; 10 – solution heat exchanger; 11 – pump of solid solution

The hardware and technological design of ARU formed in this way is subject to justification regarding the economic feasibility of its use.

5. 3. Determining efficiency indicators of the constructed equipment and technological design of the absorption-refrigeration installation

For the proposed version of the hardware and technological design of ARU (Fig. 1), the following indicators were additionally determined: consumption of working steam and steam of the injected refrigerant; steam consumption for air condensers and phlegm from the condenser receiver to the rectifier; specific heat of the rectifier and condenser. A list of indicators should be provided.

The amount of working steam M_{WS}^{D} with a pressure of 3 MPa from the STS steam generator to the jet compressor of each ARU was set according to the following equation [14]:

$$M_{WS}^{D} = M_{y}^{D}/u, \tag{3}$$

where M_{y}^{D} is the consumption of refrigerant steam injected from the rectifier of the ARU, t/h; u=1.73 is the injection coefficient of the jet compressor, calculated according to the algorithm sufficiently tested under practical conditions [14].

The increase in the consumption of working steam M_{WS}^{D} and refrigerant M_{K}^{D} on the condensers of each ARU was calculated according to the following formulas:

$$M_{y}^{0} = M_{WS}^{D} + M_{K}^{D}; \tag{4}$$

$$M_{K}^{D} = M_{F}^{K} - \left(M_{y}^{S} - M_{y}^{x}\right); \tag{5}$$

$$M_{F}^{K} = M_{y}^{x} X, \tag{6}$$

where M_{K}^{D} is the additional consumption of steam for the ARU condenser over the design load, t/h; (M_{y}^{S} =12 t/h) – steam consumption load on the condenser of each ARU according to the project, the condensation of which is provided by air cooling fans with an electric drive, the consumer power of which is 400 kW; M_{y}^{x} – consumption of refrigerant vapor from the ARU condenser to the water subcooler, t/h; M_{F}^{K} – flow rate of phlegm from the receiver of the ARU condenser, t/h; X is the mass fraction of liquid to be supplied in the form of phlegm from the receiver of the ARU condenser for rectification. At the same time, the value of X was calculated according to known formulas [6, 15]:

$$X = q_R/q_K; \tag{7}$$

$$q_R = (1+R)i_1^1 - i_5 - R i_1^0; \tag{8}$$

$$R = \left(\xi_5 - \xi_1^1\right)/\left(\xi_1^1 - \xi_r\right); \tag{9}$$

$$i_1^1 = f\left(t_1^1; \xi_1^1; P_1\right); \tag{10}$$

$$i_1^0 = f\left(t_1^0; \xi_r \xi; P_1\right); \tag{11}$$

$$q_K = i_5 - i_6, \tag{12}$$

where q_K is the specific heat of condensation, kJ/kg; q_R – specific heat of the rectifier, kJ/kg; R is the mass fraction of phlegm in the rectifier; i_1^1 – enthalpy of the solution after the generator, kJ/kg; i_1^0 – enthalpy of the solution at the beginning of boiling in the generator, kJ/kg; P_1 – steam pressure after the generator, MPa; i_5 – enthalpy of refrigerant vapor from the rectifier, kJ/kg; i_6 – enthalpy of liquid refrigerant at the outlet of the subcooler, kJ/kg; ξ_5, ξ_1^1, ξ_r – the concentration of refrigerant vapor from the rectifier, vapor after the generator, and solid solution, respectively, kg/kg.

The results of material and thermal calculations for the proposed version of ARU, taking into account formulas (3) to (12), are given in Table 3.

The reliability of the obtained indicators regarding the mode parameters according to the proposed scheme of equipment and technological design of ARU is confirmed by the convergence of the heat balance of the supplied and removed heat in the devices, the results of which are summarized in Table 4.

Table 3

Parameters of nodal points according to the proposed scheme of hardware and technological design of ARU

The state of the material flow	Operating mode according to the proposed scheme			
	Temperature, °C	Pressure, MPa	Concentration, kg/kg	Consumption, t/h
Strong solution at the generator inlet	96.5	1.46	0.4056	81.5
Strong solution at the outlet of the absorber	35.9	0.29	0.4056	81.5
Weak solution at the output of the generator	118.4	1.55	0.3082	70
Liquid refrigerant from a solution heat exchanger	43	1.55	0.3082	70
Liquid refrigerant from the condenser	40	1.6	0.9997	11.5
Liquid refrigerant from a water subcooler	33	1.6	0.9997	11.5
Liquid refrigerant from a steam subcooler	27	1.6	0.9997	11.5
Refrigerant vapor at the condenser inlet	50	1.6	0.9997	14.87
Phlegm from the condenser	40	1.6	0.9997	3.37
Refrigerant vapor at the outlet of the steam subcooler	6	0.29	1.0	11.477
Refrigerant vapor at the evaporator outlet	–6.35	0.29	1.0	11.477
Phlegm from the evaporator	–6.35	0.29	0.8537	0.023
Circulating gas to the evaporator	16	23.49	0.08714*	168.512
Circulating gas from the evaporator	–0.9	23.49	0.10745*	168.512

*Note: * – ammonia condensate concentration*

Table 4

Agreed results of the thermal calculation of ARU according to the proposed scheme

Name of the device	Amount of heat			
	Supplied		Removed	
	Specific heat q, kJ/kg	Total heat, MW	Specific heat q, kJ/kg	Total heat Φ, MV
Rectifier generator	2049.2	6.54	–	–
Evaporator	1126.9	3.6	–	–
Absorber	–	–	1720.6	5.48
Capacitor	–	–	1426.6	4.54
Water subcooler	–	–	34.1	0.11
ARU as a whole	3176.1	10.14	3181.3	10.13

Determining the consumption of spent water vapor M_{WV} to obtain working ammonia vapor M_{WS}^{D} in the steam generator was calculated according to the formulas:

$$\mathrm{M}_{WV} = 3.6 \times \Phi_{SG} \Big/ \left(i_{SV}^{IN} - i_{WK}^{OUT} \right); \tag{13}$$

$$\Phi_{SG} = M_{WS}^{D} \left(i_{WV} - i_{K} \right) / 3.6, \tag{14}$$

where Φ_{SG} is the heat flow of the steam generator, kW; i_{SV}^{IN}, i_{WK}^{OUT} – enthalpy of spent water vapor at the input and water condensate output of the steam generator, respectively, kJ/kg; i_{WV}, i_K – enthalpy, respectively, of working ammonia vapor and ammonia liquid at the outlet of the condenser, kJ/kg.

Calculations according to equations (13) and (14) ensure the determination of the additional electricity load for the condensation of working steam and its reduction for the condensation of spent steam. The results of our calculations for the existing and proposed variants of the hardware and technological design of ARU are summarized in Table 5.

It should be noted that operational indicators given in Table 5 are summarized for two ARUs.

Table 5

Generalized results regarding electricity consumption for the existing and proposed variants of the technological design of ARU

Indicator name	Hardware and technological design options	
	Existing	Proposed
Consumption of working steam to the jet compressor, t/h	0	17.2
Consumption of spent steam for air condensers, t/h	18	10
Consumption of ammonia steam for condensers, t/h	21.44	46.94
Power consumption for condensation of spent water vapor, kW	348	193
Power consumption for ammonia vapor condensation, kW	800	1200
Consumption of circulating water for cooling the absorber, t/h	840	700

6. Discussion of results of investigating the energy efficiency of the designed equipment and technological structure of the absorption-refrigeration unit

The proposed version of the equipment and technological design of ARU (Fig. 1), unlike the existing one, is distinguished by the presence of a jet compressor between the rectifier and the condenser, a water subcooler, and the absence of a dephlegmator.

Comparison of indicators according to the existing and proposed schemes of ARU, given in Tables 1–5, indicates an increase in the specific cooling capacity from 1095.5 kJ/kg to 1126.9 kJ/kg in the proposed version of the scheme. Such an increase and decrease in the boiling temperature in the evaporator to –6.35 °C is due to an increase in the concentration of the refrigerant from 0.998 kg/kg to 0.9997 kg/kg. The presence of these positive conditions is ensured by its additional rectification with liquid ammonia from the receiver of the ARU condenser without the use of a pump. Due to the increase in the concentration of the refrigerant, the consumption of drained phlegm from the evaporator decreases by almost 5 times. At the same time, despite the overall increase in heat load on the rectifier generator from 6.1 MW to 6.54 MW, the volume of refrigerant increases from 10.92 t/h to 11.1 t/h. This is due to a decrease in the boiling temperature of the solution in the generator-rectifier cube from 122 °C to 118 °C and, as a result, an increase in the average temperature difference during the heat exchange process by 2 °C. Under this condition, taking into account the design indicators of the heat exchange surface of 2480 m^2 and the average heat transfer coefficient for the upper and lower parts of the generator of 300 W/m^2K, the total amount of supplied heat will increase and will be 300*2480*9=6.69 MW (where 9 °C is the new average difference temperatures). This amount of heat is quite enough to obtain 11.5 t/h of refrigerant vapor. Therefore, even with the constancy of the specific heat of the generator-rectifier, the decrease in the temperature of the weak solution in the generator cube helps increase the cooling capacity from 3.22 MW to 3.6 MW (almost by 12 %). Also, the circulation ratio decreases from 7.72 to 7.1 (by 8 %) and the thermal coefficient increases from 0.527 to 0.551 (by 4.6 %). At the same time, at operating plants, this indicator does not exceed the value of 0.45 at the boiling temperature in the evaporator of –6 °C [16]. The increase in cooling capacity contributes to the reduction of the secondary condensation temperature from 1.6 °C to –0.9 °C. At the same time, at the entrance of the absorber, its specific heat load decreases from 2009.4 kJ/kg to 1720.6 kJ/kg. Such a change is caused by a decrease in the temperature of the weak solution from 49 °Cto 43 °C, its consumption – from 72 t/h to 70 t/h, and the temperature of the refrigerant vapor – from 10 °C to 6 °C. As a result of this reduction, the amount of absorbed refrigerant will increase from 11.22 t/h to 11.5 t/h. In addition, there is no need for the existing water consumption of 420 t/h, which cools the absorber. The possibility of reducing this amount of water is due to a decrease in its total thermal load from 5.96 MW to 5.48 MW, that is, by almost 18 %. Under such conditions, it becomes possible to use the remainder of this water, about 70 t/h, in a water subcooler to cool the refrigerant to a temperature of no more than 33 °C.

An increase in condensing pressure from 1.435 MPa to 1.6 MPa is provided by a jet compressor. With such a small compression difference, the injection ratio will be quite high and, as already noted, is 1.72 units. With this value of u, 8.6 t/h of working steam with a pressure of 3 MPa is enough for each ARU to inject 14.87 t/h of refrigerant steam from the rectifier generator. Due to this, the total consumption of steam per unit of condensers in the ARU and STS cycle will increase, taking into account two ARUs, to 22.94 t/h. The increase in steam consumption for condensation requires, according to data in Table 5, installation of an additional air-cooling condenser with a power consumption of about 400 kW.

As a result of the disposal of the spent steam with a temperature of about 90 °C and a pressure of 0.04 MPa of the natural gas compression turbine in the STS cycle, it is possible to obtain working steam in the amount of 17.2 t/h for two ARUs. Due to such disposal, the load on air condensers with water vapor is reduced by 8 t/h. At the same time, the consumption power of electricity to drive the fans will decrease from 348 kW to 193 kW, i.e., by 155 kW. Therefore, the total costs due to the increase in electricity consumption in the spring-summer period (6 months) will increase by 0.669 million kWh. Lowering the temperature of the secondary condensation by 2.5 °C helps reduce the load on the circulation compressor and the compression compressor of the fresh nitrogen-hydrogen mixture. Under such circumstances, the consumption of natural gas in the additional steam boiler will be reduced for the same period by 184.4 thousand nm^3, which ensures the drive of the steam turbine with steam at a pressure of 10 MPa. Taking into account the currently existing price of natural gas for Ukrainian enterprises of 50 UAH/m^3 and the price of electricity 3.17 UAH/kWh, the total annual operating costs of ammonia production will decrease by UAH 7 million (USD 185,000).

Our results were obtained using mathematical models of the hydrodynamics of the generator-rectifier, absorber, and evaporator. Identification of the processes in these devices was performed on the database of industrial operation of ARU, which confirms the reliability of our indicators.

The advantage of the proposed hardware-technological design of refrigeration systems is the possibility to ensure, under conditions of increased external heat load (spring-summer period), a decrease in the temperature regime of central heating cooling, an increase in their energy efficiency and ammonia production in general. The developed ARU technology can be implemented in ammonia synthesis units with a productivity of 1360 t/day in the presence of disposed material resources with a temperature level even below 100 °C. The results build on the knowledge on designing energy-efficient technological cooling systems through the disposal of low-potential heat with ultra-low temperature potential.

Further research will focus on determining wider utilization possibilities of using low-potential heat to reduce the energy intensity of chemical production.

7. Conclusions

1. Based on our experimental studies and performed material-thermal calculations, the basic mode of operation of ARU was chosen, which provides the maximum achievable energy efficiency under conditions of increased external heat load. We have quantitatively established indicators of such energy efficiency, namely cooling capacity of 3.6 MW, heat coefficient of 0.551 units, and secondary condensation temperature at the level of almost –1 °C.

2. Based on the results of analysis of the existing technological design of the ammonia synthesis unit, a source was determined to ensure the operation of the STS steam generator, which was chosen as the low-potential heat of the flow of spent water vapor of the natural gas compression compressor turbine. Exploiting this heat with an ultra-low temperature potential of up to 90 °C will ensure the operation of the jet compressor, which combines the work cycles of ARU and STS. Due to such a choice, conditions were created for the final synthesis of the hardware and technological design of ARU with the determination of its energy efficiency indicators.

3. The designed hardware and technological structure of ARU provides, due to the reduction of the multiplicity

of circulation of solutions from 7.77 to 7.1 units (by 8 %), an increase in cooling capacity by 12 %, and energy efficiency (thermal coefficient) by almost 5 %, which predetermined the possibility of lowering the temperature of the secondary condensation by 2.5 °C. At the same time, there is a change in specific costs, namely an increase in electricity by 1.48 kWh/t NH_3 and a decrease in natural gas by 0.41 nm^3/t NH_3. Taking into account the current cost indicators for natural gas and electricity, the application of the proposed technology provides a reduction in annual operating costs by USD 185,000, and therefore an increase in the economy of ammonia production in general.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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