

Multistage Electrodynamic Dehydrator with Heat Pumps

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Abstract. The aim of this work is the utilization of the secondary steam energy through its thermal transformation in electrodynamic dehydrators developed by the authors. To achieve this goal, the use of heat pumps is proposed. A hypothesis is formulated that the use of electromagnetic energy sources in the process of removing moisture from food solutions, followed by the transformation of secondary steam energy, will allow for the formation of reverse energy flows. A method for calculating energy efficiency in the presence of direct and reverse flows is presented. Multistage dehydrators, where electrodynamic systems are used at the final stage and heat pumps at the previous stages, are analyzed. It is shown that the formation of reverse flows significantly increases the overall energy efficiency. The use of an electrodynamic apparatus at the final stage solves the problems of obtaining a highly concentrated quality solution. The application of heat pumps at the remaining stages allows for the efficient use of secondary steam energy. The most significant result is the matching schemes of heat pumps with the dehydrator and the environment. The importance of the work lies in the substantiation and confirmation of the high energy efficiency of organizing reverse energy flows, and the proposed installation with combined systems — electrodynamic and heat pump. By calculation, the modes have been established in which the overall efficiency for two-stage apparatuses with heat pumps can be increased from 0.4 to 0.6, and for four-stage dehydrators from 0.4 to 0.8.

Keywords: electrodynamic systems, heat pumps, energy efficiency, reverse flows of energy.

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Deshidratator electrodinamic cu multe trepte cu pompe de caldura

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Rezumat. Scopul lucrării este de a utiliza energia secundară a aburului prin transformarea sa termică în deshidratatoare electrodinamice dezvoltate de autori. Pentru atingerea acestui scop, se propune utilizarea pompelor de căldură. S-a formulat o ipoteză că utilizarea surselor de energie electromagnetică în procesul de îndepărtare a umidității din soluțiile alimentare, urmată de transformarea energiei secundare a aburului, va permite formarea fluxurilor de energie inversă. Este prezentată o metodologie de calcul al eficienței energetice în prezența fluxurilor directe și inverse. Se analizează deshidratatoarele cu mai multe trepte, în care sistemele electrodinamice sunt utilizate în ultima treaptă, iar pompele de căldură sunt folosite în etapele anterioare. Se arată că, datorită formării fluxurilor inverse, eficiența energetică finală este semnificativ crescută. Utilizarea unui aparat electrodinamic în ultima treaptă rezolvă problema obținerii unei soluții foarte concentrate, de înaltă calitate. Utilizarea pompelor de căldură în etapele rămase permite utilizarea eficientă a energiei aburului secundar. Rezultatul cel mai important îl reprezintă schemele de coordonare a pompelor de căldură cu deshidratorul și mediul. Semnificația lucrării constă în faptul că a fost fundamentată și confirmată eficiența energetică ridicată a organizării fluxurilor de energie inversă; a fost propusă o instalație cu sisteme combinate — electrodinamică și pompă de căldură. Prin calcul s-au stabilit moduri în care la aparatele cu două trepte cu pompe de căldură randamentul final poate fi crescut de la 0,4 la 0,6, iar la deshidratatoarele cu patru trepte de la 0,4 la 0,8.

Cuvinte-cheie: sisteme electrodinamice, pompe de căldură, eficiență energetică, fluxuri inverse de energie.

Многоступенчатый электродинамический дегидратор с тепловыми насосами**Бурдо О.Г.¹, Терзиев С.Г.², Сиротюк И.В.¹, Славинская В.А.¹, Шит М.Л.³**¹Одесский национальный технологический университет, Одесса, Украина²ЧАО «ENNI FOODS», г. Одесса, Украина³Институт энергетики Технического Университета Молдовы, г. Кишинев, Республика Молдова

Аннотация. Целью работы является утилизация энергии вторичного пара путем его термотрансформации в разработанных авторами электродинамических дегидраторах. Для достижения поставленной цели предлагается использование тепловых насосов. Сформулирована гипотеза, что применение электромагнитных источников энергии в процессе удаления влаги из пищевых растворов, с последующей трансформацией энергии вторичного пара позволит сформировать реверсные потоки энергии. Приведена методика расчета энергетической эффективности при наличии прямых и реверсных потоков. Анализируются многоступенчатые дегидраторы, у которых на последней ступени используются электродинамические системы, а тепловые насосы — на предыдущих ступенях. Разработана программа расчета и оптимизации многоступенчатых дегидраторов с тепловыми насосами. Приведены результаты вычислительного эксперимента с двухступенчатым и четырехступенчатым дегидраторами. Показано, что за счет формирования реверсных потоков значительно повышается итоговый энергетический КПД. Обсуждаются вопросы оптимизации систем с реверсными потоками. Использование на последней ступени электродинамического аппарата решает проблемы получения высококонцентрированного качественного раствора. Применение на остальных ступенях тепловых насосов позволяет эффективно использовать энергию вторичного пара. Наиболее существенным результатом являются схемы согласования тепловых насосов с дегидратором и окружающей средой. Значимость работы заключается в том, что обосновано и дано подтверждение высокой энергетической эффективности организации реверсных потоков энергии, предложена установка с комбинированными системами — электродинамическими и теплонасосными. Установлены режимы эксплуатации таких установок и их оптимизации. Обоснованы режимы работы двухступенчатых и четырехступенчатых комбинированных электродинамических и теплонасосных систем. Определены пути повышения энергетической эффективности. Расчетным путем установлены режимы, при которых для двухступенчатых аппаратов с тепловыми насосами итоговый КПД можно повысить с 0,4 до 0,6, а для четырехступенчатых дегидраторов с 0,4 до 0,8.

Ключевые слова: электродинамические системы, тепловые насосы, энергоэффективность, реверсные потоки энергии.

INTRODUCTION

The processes of solution dehydration are extensively used in the chemical, food, pharmaceutical, and other industries. Dehydration is carried out in various ways: mechanical, thermal, and low-temperature. Mechanical methods have the lowest energy consumption because membrane technologies are not associated with phase transition processes. Converting the solvent into a solid phase (concentration by freezing) requires less energy than converting it into vapor, so evaporative technologies are the most energy-intensive dehydration systems. However, due to their simplicity in design and operation, evaporative apparatuses are the most widespread in production. At the same time, the principle of surface energy input in evaporative apparatuses has a significant drawback for some solutions. As the concentration of the solution increases, viscosity rises, the intensity of solution circulation decreases, the thickness of the boundary layer and its thermal resistance grow, and a taste of boiling and burning appears. In practice, this problem is solved by limiting the final concentration of the finished product. In recent years, research has

been actively conducted on the use of volumetric energy input principles and thermal transformation based on heat pumps. This work investigates the technical idea of combining electrodynamic systems and heat pumps for the utilization of secondary steam heat.

Problem Analysis and Formulation of the Scientific and Technical Hypothesis

In the work [1], the influence of various advanced dehydration methods using a heat pump dryer on the drying efficiency and quality of dried apples, bananas, grapes, marmalade, kiwi, and pineapples is considered.

Heat pump dryers are used as one of the useful and promising drying methods in the food industry due to their low energy consumption and costs, high coefficient of performance, high energy efficiency, high drying efficiency, low drying temperature and time, as well as reduced quality loss of the dried products.

In the study [2], black grapes of the *GP Kalecik karası* variety with seeds were dried in a closed-cycle heat pump dryer, designed for high-moisture content products, to study the behavior of grape pomace during drying. The influence of drying air temperature on the bioactive properties

and drying characteristics of winemaking by-products, as well as a system performance, is discussed.

In the study [3], a theoretical analysis and experimental investigation of a low-temperature sludge drying system using a heat pump is conducted. Based on verified theoretical models, a sensitivity analysis of evaporation temperature, condensation temperature, and air mass flow rate to the temperature and humidity of the air at the exit of the drying chamber, drying rate, and specific energy consumption (SEC) is performed.

In the work [4], a heat pump drying installation was studied in terms of system performance and energy efficiency when drying Kemer eggplants (*Solanum melongena L.*) at a constant air temperature and various operating conditions.

In the study [5], a simulation hydrodynamic model based on the experimental investigation of drying amaranth leaves in an optimized heat pump drying installation was developed. The distribution of the liquid area and the influence of various conditions on heat and mass transfer were investigated.

In the study [6], a hybrid drying system was developed, combining all the advantages of various drying methods. The aim of this study is to compare the experimental results of a heat pump drying installation and a heat pump drying installation with infrared radiation, determine the energy and exergy efficiency of the dryers, and analyze the drying kinetics of grated carrots to observe the efficiency of the drying installations.

In the work [7], a heat pump drying installation optimized from various configurations using computational fluid dynamics software was manufactured and tested. The experimental study was conducted in the optimized configuration for a temperature range of 50 to 60°C, a relative humidity range of 20 to 12%, and air speeds of 1.41 m/s, 2.39 m/s, and 3.24 m/s.

The resolution of the contradictions of traditional evaporative apparatuses is based on the scientific and technical hypothesis: "the use of electrodynamic systems with volumetric energy input at the final dehydration stage, followed by the utilization of secondary steam energy in a heat pump cycle for dehydration at the initial stages, will allow the production of additional hydrolate solution with significant energy savings."

Based on the formulated scientific and technical hypothesis, a schematic diagram of a

two-stage electrodynamic dehydrator with a heat pump has been developed.

At the final stage, an electromagnetic energy flow N_E is generated by electrical energy, which interacts with polar molecules of the solution, converting them into vapor (Fig. 1). As a result, the solution concentration (X_F) increases, and the finished product (M) is discharged from the unit.

The secondary steam (W_2) enters the evaporator (Ev) of the heat pump, condenses, and is discharged from the unit as a stream of hydrolate (G_H).

The condensation energy is transferred to the working fluid (G_C) of the heat pump and, with the help of the compressor ($Comp$), is transformed to a higher temperature level. This allows the condenser (Cd) of the heat pump to evaporate the raw material, the consumption of which (G_R) and the concentration (X_R).

Partially dehydrated solution with a concentration (X_1) in quantity (G_1) is fed into the last stage.

The energy effect of the installation lies in the ability to utilize the heat of the secondary steam, i.e., the organization of a "reverse" flow, which increases the energy efficiency.

In the case of "reverse" energy flows, the efficiency of the reverse elements is calculated.

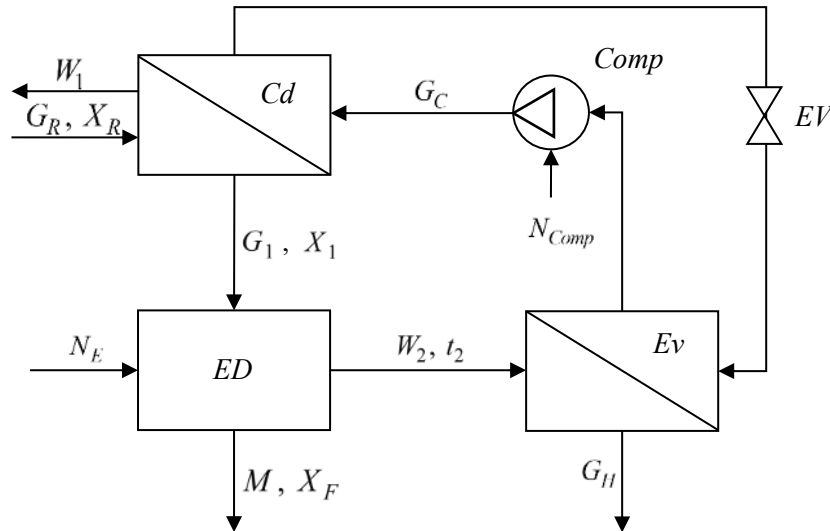
$$\eta_{pi} = \frac{Q_{pi}}{\mathcal{E}_T} \quad (1)$$

The overall thermal performance of the system is determined by:

$$\eta = \frac{\mathcal{E}_{np} + \sum_i Q_{Pi}}{\mathcal{E}_T} = \prod_{n=1}^n \eta_i + \frac{\sum_i Q_{Pi}}{\mathcal{E}_T} \quad (2)$$

Based on this hypothesis, calculations are proposed to operate with the basic characteristics of the energy source, such as fuel with a combustion heat of 40 MJ/kg.

That is, 1 kilogram of oil equivalent (kg OE) releases energy at 40 MJ/kg OE.



Cd — condenser of heat pump, *Ev* — evaporator of heat pump, *Comp* — compressor, *EV* — expansion valve, N_{Comp} — electric power of compressor, G_C — coolant flow, *ED* — electrodynamic dehydrator, N_E — electric power of ED, G_R — raw material flow, X_R — raw material concentration, G_1 — dehydrated solution flow, X_1 — dehydrated solution concentration, M — finished product flow, X_F — finished product concentration, W_1, W_2 — secondary vapor flow, t_2 — secondary vapor temperature, G_H — hydrolat flow

Fig. 1. Principal scheme of double-stage electrodynamic dehydrator with heat pump.

To conduct an analysis of the considered schemes, an indicator of fuel energy utilization efficiency is introduced:

$$d = \frac{Gn}{b} \tag{3}$$

where, b — 1 kg of fuel; G — amount of removed moisture, kg.

Based on this methodology, an analysis of a two-stage electrodynamic dehydrator with a reverse flow was conducted (Table 1). The energy of the secondary steam from the last stage is used, which is transformed to a higher temperature level by a heat pump. This allows evaporation to occur

in the first stage using the recovered heat. The heat pump's coefficient of thermal transformation for the considered temperature ranges is expected to be between 4 and 6.

Currently, a value of $do = 6 \text{ kg w/kg OE}$ has been achieved in tests of drying apparatuses with EMF. It has been visually observed that a steam-water mixture exits the chamber. The apparatuses operate in a barodiffusion mode, significantly reducing energy consumption. It is realistically achievable to reach values of $do = 50 \text{ kg w/kg OE}$ with precise alignment of the EMF generator power with the characteristics of the food raw materials.

Table 1.

Comparison of energy efficiency indicators of various dehydration technologies.

Energy technology	Consumption per 1 kg of removed moisture		Capacity		
	of energy, E, MJ	of fuel, do, 1 kg OE	of direct flows	of reverse flows	Total
Traditional drying	4—10	0,1—0,25	0,4—0,1	0	0,2
Drying in the EMF	3	0,15—0,25	0,5—0,8	0	0,4
Evaporation + traditional drying	3—6	—	0,3—0,4	0	0,3—0,4
Traditional evaporation	3	—	0,5	0	0,5
Two-stage dehydrator with heat pump	1,5	—	0,4	0,2	0,6

Based on the proposed hypothesis, calculations are suggested to operate with the basic characteristics of the energy source, for example, fuel with a combustion heat of 40 MJ/kg.

Using the proposed methodology, an assessment of the energy efficiency of traditional drying and evaporation technologies, as well as the methods proposed by ONUT (Odesa National University of Technology) for drying and evaporation in an electromagnetic field, has been conducted. The assessments indicate the energy and economic advantages of the proposed apparatuses. Naturally, the capital costs for the design and manufacturing of such apparatuses

will be higher than for traditional constructions, necessitating separate calculations.

Let's consider the dehydration kinetics in a two-stage setup with a heat pump using the following initial data. The solution type is aqueous, pressure is 30 kPa, initial concentration of the solution X_I is 0.1, final concentration of the product X_F is 0.85, amount of finished product M is 4 kg, electrical power of the 2nd stage N_E is 2 kW, product temperature at inlet t_I °C, evaporation temperature t_{Ev} °C, and the 2nd stage operates on a heat pump cycle (Figure 2).

The cycle time is assumed to be 7220 seconds.

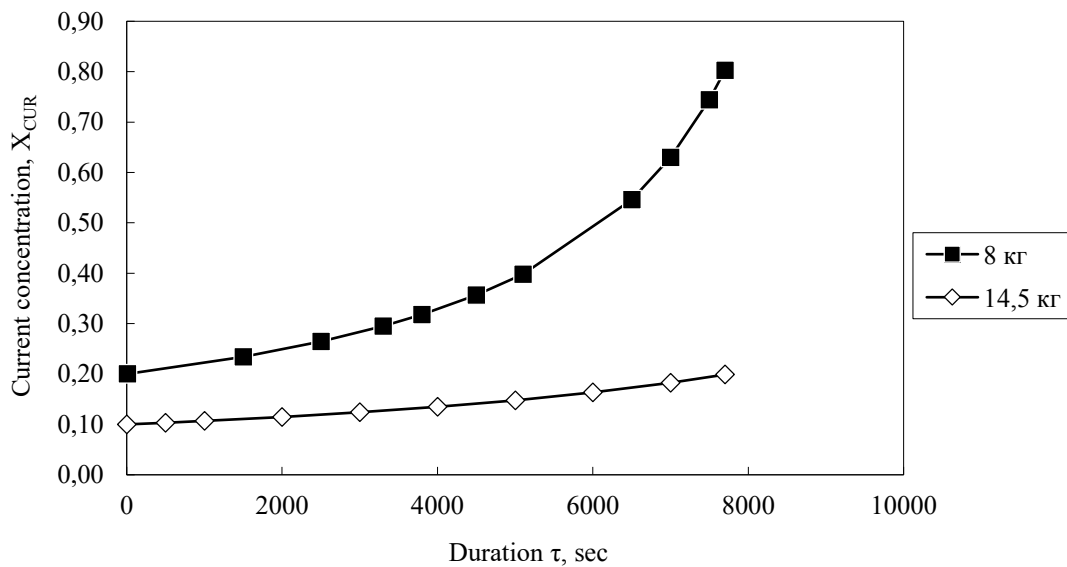


Fig. 2. Dehydration kinetics in the 2-stage plant.

It is evident that in the 1st stage, 14.5 kg of moisture has been removed, with the concentration increasing by 0.5%. In the 2nd stage, 8 kg of moisture has been removed, and the concentration has increased fourfold (from 0.2 to 0.8).

With an increase in the number of heat pump stages, the energy efficiency of the installation will improve. Let's conduct an analysis in a four-stage installation with heat pumps using the following initial data (Table 2).

Table 2.

Summary of initial data for the four-stage dehydrator with heat pumps.

№	Parameter	Dimension	Value
1	Pressure, P	kPa	30
2	Initial concentration of solution, X_I	—	0,1
3	Final concentration of product, X_F	—	0,85
4	Mass of finished product, M	kg	4
5	Electric power of 4 th stage, N_E	kW	2
6	Cycle duration, τ	sec	7220

The computational experiment was conducted for an aqueous solution.

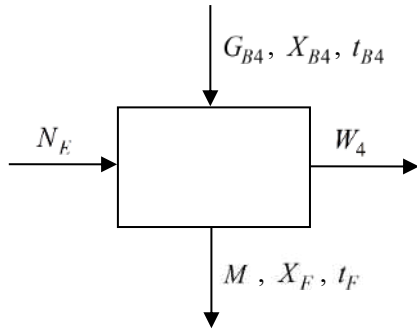
Calculation Methodology. Useful energy is considered the energy expended on the formation of the vapor phase, the amount of which is denoted as W . Here, $W_1 = W_2 = W_3 = W_4 = W$. Thus, optimization is performed based on parameter W . The amount of useful energy is determined by the relationship:

$$Q_V = W \cdot r \quad (4)$$

where r is the heat of phase transition, in Joules per kilogram (J/kg). The evaporation temperature is the same in all stages, t_{EV} , °C.

Calculation Methodology for the Fourth Stage.

Let's consider the material and energy balances of the reactor.



N_E — electric power of ED, G_{B4}, X_{B4}, t_{B4} — flow, concentration and temperature of dehydrated solution after 3rd stage, M, X_F, t_F — flow, concentration and temperature of finished product, W_4 — secondary vapor flow

Fig. 3. Reactor inlet and outlet streams.

Parameters: M, X_F, N_E are the initial data, the temperature is determined by the pressure in the reactor depending on the type of solution. The

amount of evaporated moisture W is calculated according to equation (4), which, together with G_{B4} , is the main result of the calculation of this stage and the input parameters for the third stage.

Methodology for calculating the third stage.

Let's consider the material and energy balances of the 3rd stage. The known parameters of the 3rd stage are $G_{K3} = G_{B4}$ and $X_{K3} = X_{B4}$. The parameters P, t, W, τ remain constant.

Full material balance:

$$G_{I3} = G_{K3} + W \quad (5)$$

Material balance for the target component:

$$G_{B3} \cdot X_{B3} = G_{K3} \cdot X_{K3} \quad (6)$$

Energy balance:

$$N_{Comp} \cdot \psi = W \cdot r \quad (7)$$

where ψ is the coefficient of thermal transformation of the heat pump, which can vary within the temperature ranges of the problem from 4 to 6, N_{Comp} is the power of the heat pump compressor.

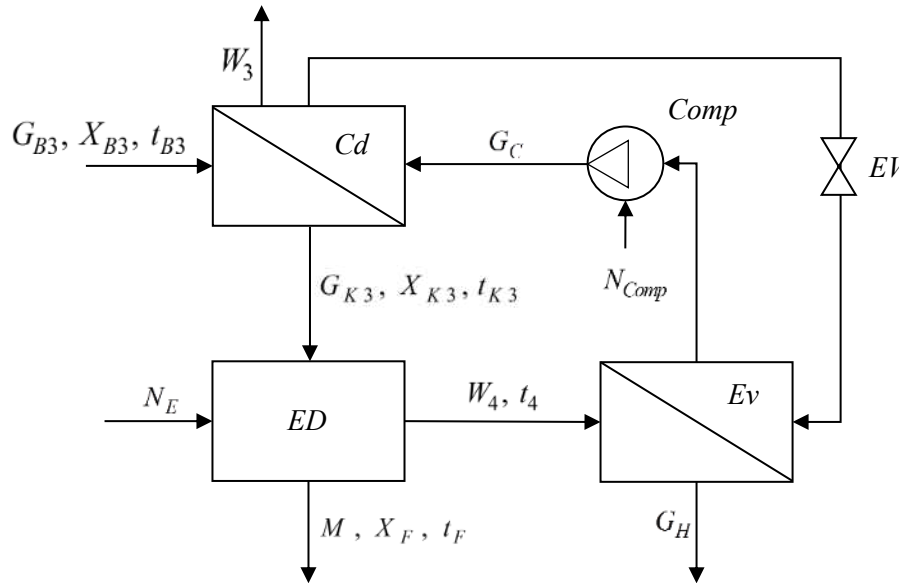
The parameters G_{B3} and X_{B3} are the main results of this stage and input parameters for the 2nd stage. The physical schemes and computational relationships for the 2nd and 1st stages are similar to the 3rd stage when corresponding indices are aligned. The peculiarity of calculating the 1st stage lies in determining the amount of initial solution G_R that corresponds to the initial solution concentration value X_R (Fig. 2) and the established cycle time.

The estimations were conducted using the following set of initial data (Table 3).

Table 3.

Summary of initial data for the calculation of a 4-stage electrodynamic heat pump dehydrator.

№	Parameter	Value	№	Parameter	Value
1	P , kPa	30	5	X_F	85
2	t , °C	20	6	N_e , kW	2
3	M , kg	4	7	W , kg	5
4	X_C	0,1	8	ψ	5



Cd — condenser of heat pump, *Ev* — evaporator of heat pump, *Comp* — compressor, *EV* — expansion valve, N_{Comp} — electric power of compressor, G_C — coolant flow, *ED* — electrodynamic dehydrator, N_E — electric power of ED, G_{B3}, X_{B3}, t_{B3} — flow, concentration and temperature of dehydrated solution after 2nd stage, G_{K3}, X_{K3}, t_{K3} — flow, concentration and temperature of dehydrated solution after 3rd stage, M, X_F, t_F — flow, concentration and temperature of finished product, W_3, W_4 — secondary vapor flow, t_4 — secondary vapor temperature, G_H — hydrolat flow

Fig. 4. Physical model of the third stage.

An acceptable cycle time of $\tau = 7200$ sec was established for the initial data (Table 1). The calculation results are presented in Table 4.

Table 4.

The results of the calculation for the four-stage microwave dehydrator with a heat pump.

Stage	Input		Output		Input		Output		Input		Output		Input		Output	
	<i>G</i>	<i>X</i>	<i>G</i>	<i>X</i>	<i>G</i>	<i>X</i>	<i>G</i>	<i>X</i>	<i>G</i>	<i>X</i>	<i>G</i>	<i>X</i>	<i>G</i>	<i>X</i>	<i>M</i>	<i>X</i>
First	32	0,1	20	0,16	—	—	—	—	—	—	—	—	—	—	—	—
Second	—	—	—	—	20	0,16	14	0,23	—	—	—	—	—	—	—	—
Third	—	—	—	—	—	—	—	—	14	0,23	9	0,36	—	—	—	—
Fourth	—	—	—	—	—	—	—	—	—	—	—	—	9	0,36	4	0,8

Table 5.

Initial data for calculation of four-stage dehydrator.

V_I, m^3	V_I, kg	X_I	X_F	$W, kg/sec$	
0,009	9	0,36	0,8	0,00069	4 th stage
0,014	14	0,23	0,36	0,00069	3 rd stage
0,02	20	0,161	0,23	0,00083	2 nd stage
0,032	32	0,1	0,161	0,0017	1 st stage

Based on these initial data, a computational experiment was conducted using a specialized program.

As a result, material balances were established: 32 kg of solution is required for the

1st stage, 20 kg for the 2nd stage, 14 kg for the 3rd stage, and 9 kg for the 4th stage. The kinetics of current concentrations (X_{CUR}) in the four stages are presented in Table 6.

Table 6.

Dehydration kinetics in 4 stages.

Duration τ , sec	X_{CUR} 4 th stage	X_{CUR} 3 rd stage	X_{CUR} 2 nd stage	X_{CUR} 1 st stage
10	0,36	0,23	0,16	0,10
1500	0,41	0,25	0,17	0,11
2500	0,45	0,26	0,18	0,12
3300	0,48	0,27	0,19	0,12
3800	0,51	0,28	0,19	0,13
4500	0,55	0,30	0,20	0,13
5100	0,59	0,31	0,20	0,14
6500	0,72	0,34	0,22	0,15
7000	0,78	0,35	0,23	0,16
7200	0,80	0,36	0,23	0,16

The kinetics is graphically represented in Fig. 5.

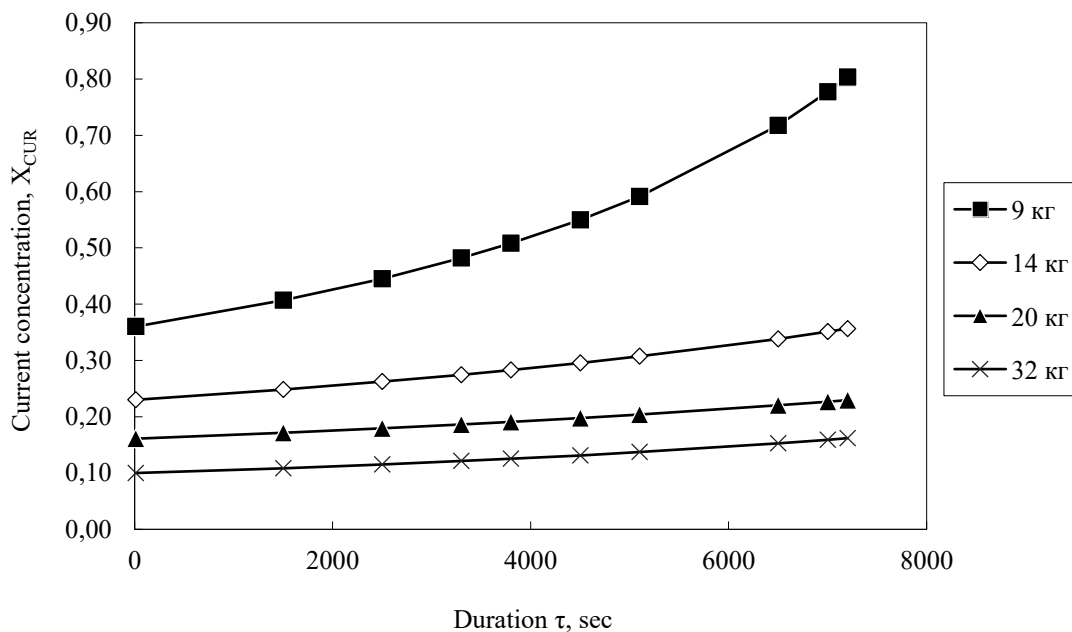
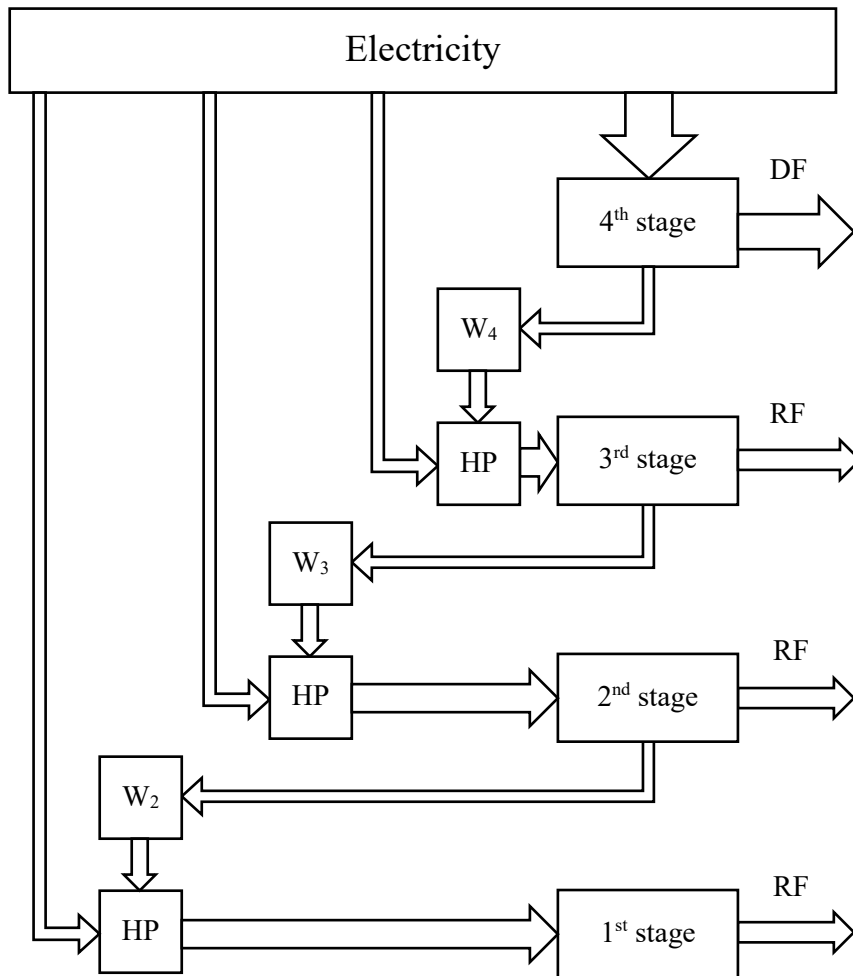


Fig. 5. Dehydration kinetics in the 4-stage plant.

The separate analysis of organizing direct and reverse flows is of practical interest, independent of primary fuel considerations. In this case, energies of the secondary steam flows are considered separately, along with the energy consumption of compressors in the heat pump stages 1, 2, and 3, and the energy consumption of the electrodynamic dehydrator in stage 4 (Fig. 6).

The scheme in Fig. 6 can also be implemented with multiple evaporators and gas coolers and a single compressor.

Further cooling of the working fluid streams after the gas coolers is achieved by using two-section gas coolers, where the second section is designed as heat exchangers for 'water-refrigerant' and/or 'air-refrigerant'.



HP — heat pump, SF — direct flow, RF — reverse flow, $W_1 - W_4$ — secondary vapor flow

Fig. 6. Conversion of energy flows in the 4-stage plant.

Depending on the outside air temperature, the refrigerant is cooled either by water or by air.

The developed program allows calculating any combinations of electromagnetic and heat pump systems.

However, questions of economic efficiency require accounting for specific scientific and technical contradictions.

On the one hand, the degree of increasing the potential of the vapor flow is not so significant and is not a problem for heat pumps.

On the other hand, the temperature level of the secondary steam requires serious analysis when assessing energy efficiency.

The reduction in temperature levels is ensured by an intermediate circuit linking the dehydrator and the evaporator of the heat pump EV (Fig. 7).

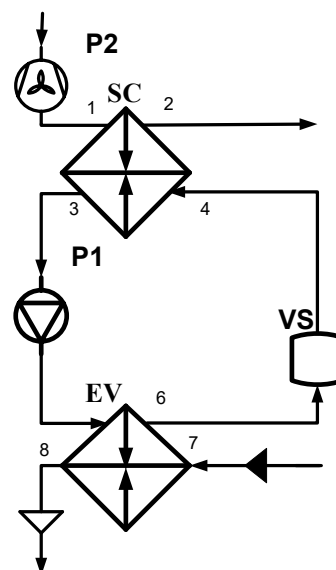


Fig.7. Intermediate circuit diagram.

Vacuum pump P2 supplies gas at a temperature of 50–60°C to the heat exchanger SC of the intermediate circuit, using water as the heat carrier. VS expansion vessel. P1, pump. Water at a temperature of 25–30°C enters the evaporator. The heat power transferred by it is regulated, to a limited extent, by changing the performance of pump P1. In a three-pump scheme, the heat power transferred by the circuit can be adjusted by changing the surface area of the heat exchangers and adjusting the performance of the pumps. To align temperature levels, it is also possible to use an "air-steam" heat exchanger to connect the evaporator and dehydrator without using an intermediate circuit. In heat pump schemes, it is advisable to use carbon dioxide as a refrigerant.

In the article, calculations for two-stage and four-stage cycles are based on the most tough temperature regimes. Softening the regimes is possible by reducing the pressure in the dehydrator.

CONCLUSIONS

The combined use of electromechanical systems and heat pumps represents a new technical solution in the advancement of dehydration equipment. The effectiveness of this approach arises from understanding the scientific-technical contradiction that occurs from the interaction of electromagnetic fields and heat transformers. Formation of the reverse energy flows can significantly enhance the overall energy efficiency of the equipment. The paper presents a methodology for calculating energy efficiency considering the formation of such reverse flows. The computational experiments have shown that for two-stage units with heat pumps, the overall efficiency can be increased from 0.4 to 0.6, and for four-stage dehydrators from 0.4 to 0.8. These results provide a basis for designing pilot-scale multistage dehydrators incorporating electrodynamic and heat pump systems.

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