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AUTOMATED SYNTHESIS OF RECYCLING WATER SUPPLY SYSTEMS AT CHEMICAL ENTERPRISES

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Abstract: This article describes the technique of automated synthesis of recycling water supply system of a chemical enterprise with the use of expert systems theory and comprises sequential solving of the following problems: variant generation for structures of technological schemes of water treatment stages and selection of the best variant based on criteria set; calculation or choice of hardware design for a particular technological scheme.

Notations

$C_{\text{in}}, C_{\text{out}}$ и C^{lim} – total concentration of contaminants in water at the beginning and at the end of production cycle for a target product, and their maximum allowed values;

F_w – integral criterion for the *w*-th variant of RWS system;

G – water discharge;

K – set of variants for structural schemes of RWS systems;

k_{opt} – optimal variant of technological scheme of an auxiliary part of RWS system;

m_{ik} – expenditure rate for materials needed for water purification process at the *i*-th stage of the *k*-th variant of RWS system;

m'_{il} – expenditure norm of *l*-th material needed for water purification processes at the *i*-th stage;

N_k – number of stages for the *k*-th variant of RWS system;

Nt – number of stages in the scheme;

N_l – number of expenditure materials types;

n_i – number of main units of equipment at the *i*-th stage;

Pb_{ki} – static probability of fire (explosion) at the *i*-th stage of the *k*-th variant of RWS system;

Q_1, Q_2 – criteria for selection problems for technological scheme structure and equipment for RWS system respectively;

R – set of hardware design variants for RWS system auxiliary part;

r_{opt} – optimal hardware design variant for RWS system;

$S_{ik}(G)$ – consolidated capital expenditures (cost of basic and auxiliary equipment) for implementation of processes at the *i*-th stage of the *k*-th variant of RWS system;

$S'_{ik}(G, m_{ik})$ – consolidated operating expenses for implementation of processes at the *i*-th stage of the *k*-th variant of RWS system, including the cost of expendable materials (complexones, electricity, etc.);

st_l – unit cost of the *l*-th type of expendable material;

Te_{ki} – technological effectiveness of water preparation at the *i*-th stage including: type of process and equipment with the corresponding expendable materials;

$T_{\text{in}}, T_{\text{out}}$ и T^{lim} – set of temperature levels at the beginning and at the end and maximum feasible value of the minimum temperature of water to produce the target product;

V_i – main size of equipment unit at the *i*-th stage;

Pt_{ki} – probability of non-failure work of equipment on the i-th stage of the k-th variant of RWS system; $W = K \times R$ – set of synthesis variants for RWS system; $w_{opt} = \{k_{opt}; r_{opt}\}$ – an optimal variant;	α_i, β_i – coefficients reflecting dependence of equipment cost at the i-th stage on material type and basic size; ρ_i – weight coefficients; Ψ, Ω – functional operators; $\rho_i \omega_{1i}(k)$ – weighted loss for the i-th criterion.

Introduction

Nowadays many sectors of economy use water for manufacturing of target products. After water goes through different processes at the enterprises or is used in household purposes, it loses its initial quality and adversely affects the state of natural water reservoirs which receive this wastewater. One of the most water-intensive sectors of the economy and, simultaneously, one of the most intense "generators" of polluted waste water is chemical industry. In order to eliminate water pollutants dump into water reservoirs in a relatively short period of time, it is necessary to develop and gradually implement self-contained systems of water recycling. Such systems allow: to significantly reduce industrial consumption of fresh water, to use fresh water only for drinking purposes and to fill losses in recycling systems, to significantly reduce or even eliminate losses of valuable raw materials and supplies occurred with sewage dumping. Eeffective and reliable operation of such systems is only possible when the choice of appropriate equipment is made taking into account all production requirements and environmental conditions.

Analysis of literature [1, 5–9] shows that these papers are mostly focused on the issues related to hardware design for existing technological schemes, and to a lesser extent on selection of the most suitable technological scheme for concrete conditions and criteria specified by consumers.

Therefore the purpose of this paper is to develop the procedure of automated synthesis of water preparation stages that determine the effectiveness of recycling water supply (**RWS**) system of a chemical enterprise.

The RWS system consists of two parts. The first includes stages of target products manufacturing processes, technological processes that use water for heating or cooling of equipment (reactionary mass in it). The other part contains stages which provide restoration of consumer characteristics of water and its supply to the main technological scheme.

Stages of water preparation are: cleaning, cooling (heating), adding (if necessary) and water injection. Fig. 1 shows possible variants of water preparation stages that implement various technological processes; Fig. 2 depicts possible variants of water preparation schemes for RWS system.

1. Statement of the problem

In general, the problem of automated synthesis of water treatment stages for a self-contained FWS system includes: structure generation for a technological scheme, choice of type, quantity and basic geometric dimensions of equipment for each stage of the chosen scheme.

Input parameters are: efficiency of technological scheme for target products manufacturing, pressure in the scheme, initial and final temperature of the target product and recycling water, heat-exchange surface, characteristics of main equipment, target products and recycling water (viscosity, density, thermal conductivity coefficient, specific heat, pH, total hardness, alkalinity, content of calcium, iron, sulfates, total dissolved solids), scheme of the main part of RWS system and pipelines diameters.

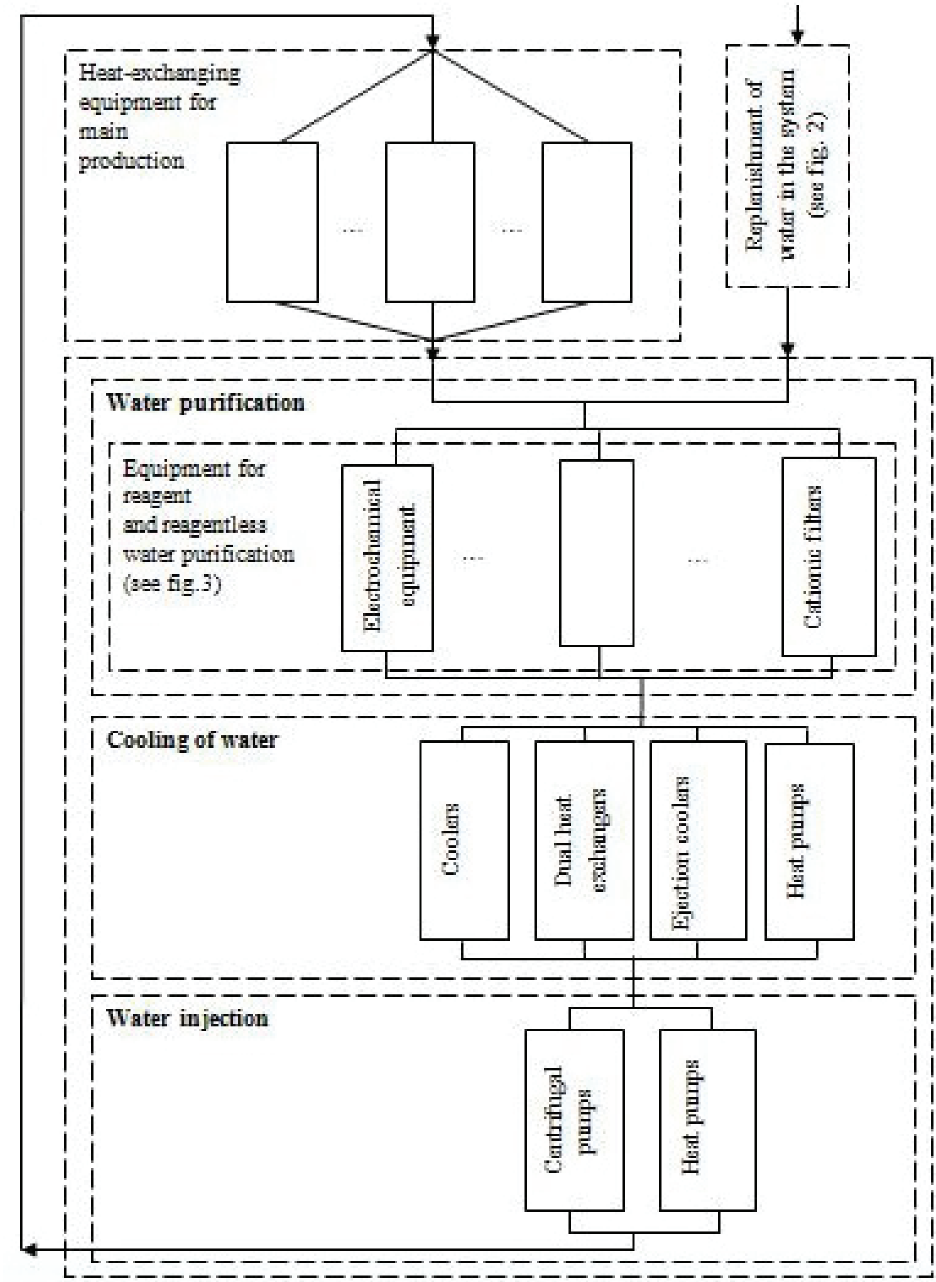

Fig. 1. Possible variants of water recycling scheme

In the formalized form, the problem is to find the minimum value of an objective function

$$I_{\text{opt}} = \min_{w \in W} F_w, \tag{1}$$

subject to constraints

$$T_{\text{out}} \le T^{\text{lim}}, \quad C_{\text{out}} \le C^{\text{lim}} \tag{2}$$

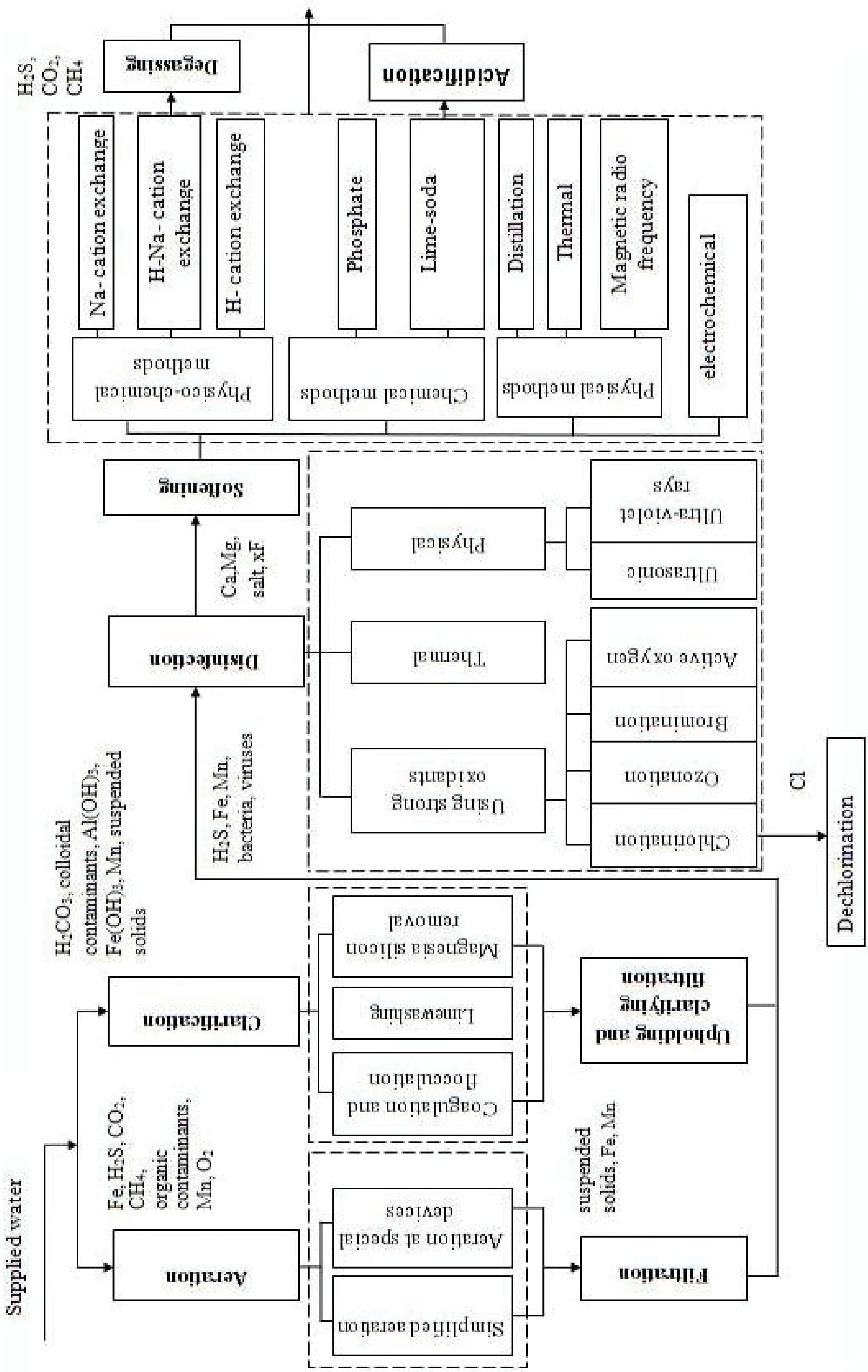

Fig. 2. Possible variants of water preparation in RWS system

and operators which represent mathematical models of decision support for variants generating of:

– structural chart of an auxiliary part of RWS system:

$$\Psi : G \times T_{\text{in}} \times T_{\text{out}} \times T^{\text{lim}} \times C_{\text{in}} \times C_{\text{out}} \times C^{\text{lim}} \to K \ ; \tag{3}$$

– hardware design for the structure chat of an auxiliary parts of RWS system:

$$\Omega : G \times T_{\text{in}} \times T_{\text{out}} \times T^{\text{lim}} \times C_{\text{in}} \times C_{\text{out}} \times C^{\text{lim}} \times k_{\text{opt}} \to R \ . \tag{4}$$

Problem (1) – (4) belongs to a class of combinatorial problems. If stated as above, the solution to this problem cannot be obtained due to high dimensionality of system variables set, complexity of mathematical models of technological processes at each stage, etc. For these reasons the procedure of RWS system synthesis consists of a sequential consideration of two sub-problems of smaller dimension which in addition have independent values for design process:

– variants generation for technological schemes structures of an auxiliary part of a RWS system and their optimal choice;

– calculation of hardware design for the chosen technological scheme.

If there is no solution for the second stage of synthesis, decision maker (**DM**) chooses a different solution form the set of solutions obtained at the first stage. This choice is based on the rules discussed below.

1.1. Problem of selection of technological scheme structure

Problem of selection of technological scheme of an auxiliary parts of RWS system from a set of possible variants on the basis of mathematical optimality criteria is, as a rule, rarely solved due to complexity of imposed system conditions and a large set of evaluation criteria as well. The most advanced method for solving of this problem type is the use of expert systems [1]. In order to choose an optimal structure of a process from a set of variants it is necessary to clearly define the evaluation criteria, which are divided into three groups: cost, reliability and safety. In this case, it is recommended to use an integrated assessment based on allocation of weights between these summing groups subjected to specific conditions.

In this paper we propose the following problem statement for technological scheme structure generation: find a sequence of process steps of the system such that under conditions:

$$T_{\text{out}} \le T^{\text{lim}} \ , \ C_{\text{out}} \le C^{\text{lim}} \ , \tag{5}$$

for the operator represented by a mathematical model of variants generation for structural schemes of an auxiliary part of RWS system (3), the following equation holds:

$$k_{\text{opt}} = \arg\min_{k \in K} Q_1(k) . \tag{6}$$

As we propose to use multi-criteria selection of the optimal technological scheme structure, it is necessary to choose normalization and ranking methods for the set of criteria and a multi-criteria selection method. In this paper the optimality criterion Q_1 represents the sum of weighted relative losses of the following criteria: reduced costs for implementation of an auxiliary part of RWS system, reliability of the system, technological effectiveness and the safety of process [2].

Integral criterion Q_1 is

$$Q_1(k) = \sum_{i=1}^{4} (\rho_i \omega_{1i}(k)) \ , \tag{7}$$

Here ρ_1, ρ_2, ρ_3, ρ_4 are the weights

$$\rho = \{\rho_i\} = \left\{\rho_i : \rho_i > 0, i = 1,...,4, \sum_{i=1}^{4} \rho_i = 1\right\}, \tag{8}$$

where $\rho_i \omega_{1i}(k)$ – weighted loss of the i-th criterion; $\omega_{1i}(k) = \omega_{1i}(F_{1i}(k))$ $(i = 1,...,4, k \in K)$ – monotonic functions which convert each objective function $F_{1i}(k)$ to dimensionless form; $F_{11}(k)$ – economic criteria which includes costs of implementation of the system; $F_{12}(k)$ – criterion of reliability of system functioning; $F_{13}(k)$, $F_{14}(k)$ – criteria of technological effectiveness and criterion of safety respectively. Here we find minimum value for function $F_{11}(k)$, and maximum values for functions $F_{12}(k)$, $F_{13}(k)$, $F_{14}(k)$.

Functions $\omega_{1i}(k)$ $(k \in K)$ are written as:

$$\omega_{11}(k) = \frac{F_{11}(k) - F_{11}^0}{F_{11}^{\max} - F_{11}^0}; \quad \omega_{12}(k) = \frac{F_{12}(k) - F_{12}^0}{F_{12}^0 - F_{12}^{\min}}, \tag{9}$$

$$\omega_{13}(k) = \frac{F_{13}(k) - F_{13}^0}{F_{13}^0 - F_{13}^{\min}}; \quad \omega_{14}(k) = \frac{F_{14}(k) - F_{14}^0}{F_{14}^0 - F_{14}^{\min}}. \tag{10}$$

Here $F_{11}^{\max}$ – maximum value of minimized function $F_{11}(k)(k \in K)$ on a feasible set K; $F_{12}^{\min}$, $F_{13}^{\min}$, $F_{14}^{\min}$ – minimum values of maximized functions $F_{12}(k)$, $F_{13}(k)$, $F_{14}(k)$ $(k \in K)$ on a feasible set K; F_{11}^0, F_{12}^0, F_{13}^0, F_{14}^0 – optimal values of objective functions $F_{11}(k)$, $F_{12}(k)$, $F_{13}(k)$, $F_{14}(k)$ $(k \in K)$ respectively on a feasible set K. Values of $\omega_{1i}(k)$ $(i = 1,....,4,\ k \in K)$ range from 0 to 1.

We need to find a compromise variant $(k \in K)$ that will not be optimal for objective functions $F_{11}(k)$, $F_{12}(k)$, $F_{13}(k)$, $F_{14}(k)$, but it will satisfy the integral criterion $Q_1(k)$.

In order to find a single solution of a complex problem one has to set the weights $\rho_i (i = \overline{1,4})$, which satisfy (8) and reflect relative importance of objective functions $F_{11}(k)$, $F_{12}(k)$, $F_{13}(k)$, $F_{14}(k)$. In this case the most effective methods are ranking method and allocation of weights [3] (the latter is used in this paper).

Economic criterion. During the process of filling in a database of water preparation methods at each stage we take into account estimated consolidated cost of their implementation. This criterion does not provide exact cost value, as at this stage we have data only about water preparation stages based on which we can give approximate cost estimation of schemes functioning for an auxiliary part of a RWS system using expert estimations [4]. Components of criterion $F_{11}(k)$ are

$$F_{11} = \sum_{i=1}^{N_k} S_{ik}(G) + \sum_{i=1}^{N_k} S'_{ik}(G,\ m_{ik}),\ \ k \in K. \tag{11}$$

It should be noted that different expendable materials can be used in implementation of process steps, for instance, we can use oxyethylidenbiphosphone acid, nitrilotrimetilfosphonic acid and others to implement the complexone technology.

Criterion of equipment reliability. Reliability is a property of equipment to perform its functions maintaining its initial characteristics within acceptable limits, corresponding to the terms and conditions of its use, maintenance and repair within time span. Reliability is a complex property, thus, it can comprise no-failure operation, maintainability and conceivability separately or in combination depending on equipment functions and operational conditions for the equipment unit and for its parts

$$F_{12} = \max_{K} \prod_{i=1}^{N_k} Pt_{ik} , \quad k \in K . \tag{12}$$

Data on reliability indicators for individual types of equipment is listed in Table. Criteria of reliability and safety can be described similarly.

Table

Fragment of a database for water preparation process

Stage	Method	Equipment	Equipment reliability (0–1)	Technological effectiveness, rank (0–10)	Probability of fire/explosion (0–1)
Water treatment	Electro-chemical	APU-150	0.78	6.5	$3.5 \cdot 10^{-4}$
		…	…	…	…
	Acoustic	Water King 1	0.68	5.2	$2.6 \cdot 10^{-4}$
		Acoustic-T2	0.73	5.3	$3.1 \cdot 10^{-4}$
		Ekoacoustic	0.7	5.3	$3.0 \cdot 10^{-4}$
		USP-300	0.63	4.8	$2.7 \cdot 10^{-4}$
		…	…	…	…
	Magnetic	AktiMAG TS156	0.86	8.5	$3.5 \cdot 10^{-4}$
		...	...	...	...
	Complexone technology	Complexone-6	0.82	4.5	$3.5 \cdot 10^{-4}$
		ADK-08(07)	0.6	7.8	$2.3 \cdot 10^{-4}$
		IZH-25	0.83	4.9	$2.7 \cdot 10^{-4}$
		Impulse-2	0.78	6.8	$2.5 \cdot 10^{-4}$
		…	…	…	...
	Cation filters	D-V4450	0.86	5.8	$1.7 \cdot 10^{-4}$
		…	…	…	...
Water cooling	Coolers	Rosinka-5	0.80	8.5	$2.5 \cdot 10^{-4}$
		EKM	0.85	7.9	$2.3 \cdot 10^{-4}$
		GMVB-10	0.79	8.7	$2.4 \cdot 10^{-4}$
		VODEH-700	0.81	7.4	$3.1 \cdot 10^{-4}$
		GM-2	0.84	7.9	$2.2 \cdot 10^{-4}$
		…	…	…	…
	Dual heat exchangers		0.84	8.3	$2.7 \cdot 10^{-4}$
	Ejection Coolers	OVE-25-03-13	0.79	7.9	$2.6 \cdot 10^{-4}$
		ROSA	0.83	8.1	$2.1 \cdot 10^{-4}$
		…	…	…	…
	Thermal pumps		0.87	7.4	$1.5 \cdot 10^{-4}$
		…	…	…	…
Water injection	Pumps	Centrifugal pumps	0.82	6.0	$4.8 \cdot 10^{-4}$
		Turbine pumps	0.81	6.0	$4.5 \cdot 10^{-4}$

Using data from a database created during purification, water cooling (heating) and other processes design and defining the aim, for example, quality of water in the system, we can find a combination of technological stages to achieving this aim with the use of decision-making mechanism. Fragment of such database is shown in Table.1. The database contains rules, empirical knowledge and general data that is available to experts.

For a formalized description of data sets required to solve the above problems it is necessary to create a structured database. Data structure for this research area is displayed as a set of informational and logical models (**ILM**) and rule-based models (**RBM**) of decision support systems. Data normalization requirements for such models should be fulfilled and models themselves should be represented in canonical form.

In general view, an ILM for selecting of technological schemes of water purification stages and of appropriate hardware design represents a sum of data sets and links between them written in the form of production rules.

A coherent system is formed by combining several process steps with different efficiency (e.g. water purification process). First, we choose feasible variants of system structure using data about parameters of water at each technological stage and linked stages. Then we choose an optimal scheme for the auxiliary part of RWS system based on estimations of consolidated reduced costs, reliability, technological effectiveness and safety criteria.

Feasible set of technological schemes for RWS systems is formed using a heuristic algorithm. At first we formulate relationships between technological stages that allow to receive required water parameters, input and output of the main equipment used at certain stages, links between current and proceeding stages and other similar relationships in the form of rules.

Since dimension space of combination set does not exceed 1000, and taking into account high performance of modern personal computers, the solution can be obtained by exhaustive search through all possible combinations of schemes.

1.2. Choice of equipment

The next step at synthesis of water preparation stages for RWS systems is calculation and choice of standard equipment sizes for a selected technological scheme.

Most types of equipment have standardized sizes (e.g. cooling towers, pumps, etc.). Ejection coolers, dual heat exchangers and heat pumps can be manufactured according to individual orders.

This problem can be stated as follows: for each stage of an auxiliary parts of RWS system we have to find type of equipment, its geometric dimensions and quantity of each type that provide normal functioning regime of the whole system

$$r_{\text{opt}} = \arg\min_{r \in R} Q_2(r), \tag{13}$$

subject to constraints

$$T_{\text{out}} \le T^{\text{lim}}, \; C_{\text{out}} \le C^{\text{lim}}, \tag{14}$$

for the operator represented by a mathematical model of decision-making support for hardware design variants generation for an auxiliary part of RWS system (4).

Components of the criterion are

$$Q_2 = \sum_{i=1}^{Nt} n_i \alpha_i V_i^{\beta_i} + \sum_{i=1}^{Nt} \sum_{l=1}^{Kl} m'_{il} st_l \, . \qquad (15)$$

Mathematical model of decision making for hardware design selection for specific equipment types includes formulae for calculation of equipment volumes and parameters based on the notions shown in [5–9, etc.]. All methods of calculation for certain equipment types of RWS system for software design problem are presented as a base of calculation modules.

Since the number of standard sizes for each equipment type is not large (for example, cooling towers “Rosinka” have only five sizes) it is appropriate to use full exhaustive search for calculation of its required quantity. By doing so we achieved the global minimum of reduced cost criterion for the given problem.

2. Example of problem solution

To solve problems (5) – (12) and (13) – (15) we have developed an information system which includes a database of equipment used in RWS systems and software that allows user to select an optimum scheme of RWS system and equipment with necessary characteristics.

Automated synthesis procedure for a RWS system of a chemical enterprise was implemented at modernization of RWS system of the public corporation “Pigment” (Tambov). Based on the proposed approach we selected the scheme which includes the following equipment: electrochemical water purification apparatus “APA-150”; cooler Rosinka, centrifugal pump 150-125-315 with characteristics: supply – 200 cu.m/h, pressure – 32 m, with engine capacity of 30 kVt/1500, with initial water characteristics: pH – 7.8, chlorides 269 mg/l, sulphate – 332 mg/l, hardness – 9.2 mEq/L, iron – 3.2 mg/l, suspended solids – 16 mg/l, transparency of – 20 cm.

Conclusion

The proposed procedure of automated synthesis of technological scheme for recycling water supply system for a chemical enterprises using the theory of expert systems allows to choose the most suitable water purification system for specific conditions and criteria set by consumers under conditions of large-scale dimension of variants.

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Технология автоматизированного синтеза системы оборотного водоснабжения химического предприятия

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Ключевые слова и фразы: водоподготовка; система оборотного водоснабжения.

Аннотация: Рассматривается процедура автоматизированного синтеза системы оборотного водоснабжения химического предприятия с использованием теории построения экспертных систем, включающая последовательное решение задач: формирование вариантов структур технологической схемы стадий водоподготовки и выбора оптимального варианта с позиций множества критериев; расчет или выбор аппаратурного оформления для определенной технологической схемы.

Technologie der automatisierten Synthese des Systems der Umlaufwasserversorgung des chemischen Betriebes

Zusammenfassung: Es wird das Verfahren der automatisierten Synthese des Systems der Umlaufwasserversorgung des chemischen Betriebes mit der Benutzung der Theorie des Aufbaues der Expertsysteme betrachtet. Es besteht aus den aufeinanderfolgenden Lösungen der Aufgaben: die Formierung der Varianten der Strukturen des technologischen Schemas der Stadien der Wasseraufbereitung und der Wahl der optimalen Variante von der Position der Kriterienmenge; die Berechnung und die Wahl der Apparaturgestaltung für das bestimmten technologischen Schema.

Technologie de la synthèse automatisée du système de distribution d'eau circulant de l'entreprise chimique

Résumé: Est examinée la procédure de la synthèse automatisée du système de distribution d'eau circulant de l'entreprise chimique avec l'emploi de la théorie de la construction des systèmes d'expert comprenant une solution successive des problèmes suivants: formation des variants des structures du schéma technologique des stades de la préparation de l'eau et du choix d'un variant optimal du point de vue de multiples critères; calcul ou choix de la forme mathématique pour un schéma concret technologique.

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