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NATO Science Fellowships Program

R E P O R T
on

DEVELOPMENT OF NEW COAGULANTS FOR TERTIARY WASTEWATER TREATMENT (FILTRATION ASPECTS IN ENVIRONMENTAL APPLICATION)

Prepared for

Ministry of National Economy of Greece
Direction of International Economic Organizations
Athens, Greece

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March, 1995

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FINAL REPORT

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This research was made possible through NATO Science Fellowship Program and supported by individual grant through Ministry of National Economy of Greece, Direction of International Economic Organizations. The authors are thankful to Technical University of Crete which submitted the Laboratory for carrying out the research.

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INTRODUCTION

The laboratory of Production Engineering and Management Department, Technical University of Crete has conducted the research concerning the development of new coagulants for tertiary wastewater treatment. Investigation of coagulation of colloidal particles using pre-hydrolyzed aluminium is a part of the program. In the present research the emphasis is given to the interaction of the hydrolysis products with the natural organic substances present in water (i.e., humic and fulvic acids), as well as the coagulation of biological colloids in effluents from biological treatment plants. The project aims at the treatment of effluents intended for irrigation.

For coagulated particle removal from treated water different types of separation processes are used, filtration/microfiltration being one of them. The aim of this research supported within the framework of NATO Science Fellowships Program is to investigate filtration application for wastewater treatment. The field of the research was determined by the conception “Acting local, thinking global”, so the problem of filtration was more broadly elaborated than it is required for the specific tasks of tertiary wastewater treatment.

The aims of the project are to elaborate recommendations for filtration of treated wastewater on the basis of deep bed filtration achievements and analysis with generalization of some problems in solid-liquid filtration.

1. THE DEVELOPMENT OF FILTRATION AS FLEXIBLE TECHNOLOGY

1.1. Wastewater treatment schemes

There are many methods and technologies for wastewater treatment. Regularly, wastewaters contain hazardous materials. Filtration is in the centre of attention here but it does not mean the filtration exclusiveness in comparison with other processes [1].

Hazardous wastewaters which contain or generate a solid phase after treatment can be classified into three groups:

1. Wastewaters containing main hazardous components in the liquid phase, while the solid phase is inactive or relatively innocuous.
2. Wastewaters containing main hazardous components in the solid phase when liquid is inactive or relatively innocuous.
3. Wastewaters containing hazardous components both in liquid and solid phases.

We consider it to be unimportant whether there is the solid phase in the liquid before treatment or whether it is produced during the waste treatment.

The following problems can arise when treating the waste:

(i) methods of treatment of liquid and solid phases of slurry are often contrary;

(ii) in certain cases during liquid treatment the solid phase presents a serious problem which can be caused by adsorption, catalysis, chemical reactions with reagents used for liquid treatment or due to fouling of equipment, etc.;

(iii) chemical treatment of solids (for example neutralization, precipitation, oxidation, etc.) demands a lot of chemical reagents, because in spite of possible small solid phase volume in the slurry, the solid phase particles can contain major part of hazardous materials. If in the liquid the contamination concentration is as a rule up to some percents then in the solid phase the hazardous contamination can reach up to 100% per all solid phases;

(iv) despite comparatively small solid volume in the total volume of the waste liquid, processes of solid separation and treatment are complicated and their cost reaches up to 40 - 50% of the total cost of hazardous waste liquid treatment as estimated by experts.

The first group of wastewater with the main contaminations in the liquid phase can be separated by filtration on filters which necessarily accomplish cake washing and dewatering (if applicable). After that the cake is disposed and the liquid passes to subsequent treatment.

Some versions of treatment schemes are present in Fig.1. This scheme can include the direct slurry filtration or slurry filtration after pre-treatment, as well as filtration of the treated liquid phase after primary filtration if the solid is created in the liquid as a result of further treatment. Sometimes, if coarse particles with good filterability are created at the primary stage of treatment, they can be used as filter aids for filtration in the next stage (scheme 4, Fig.1).

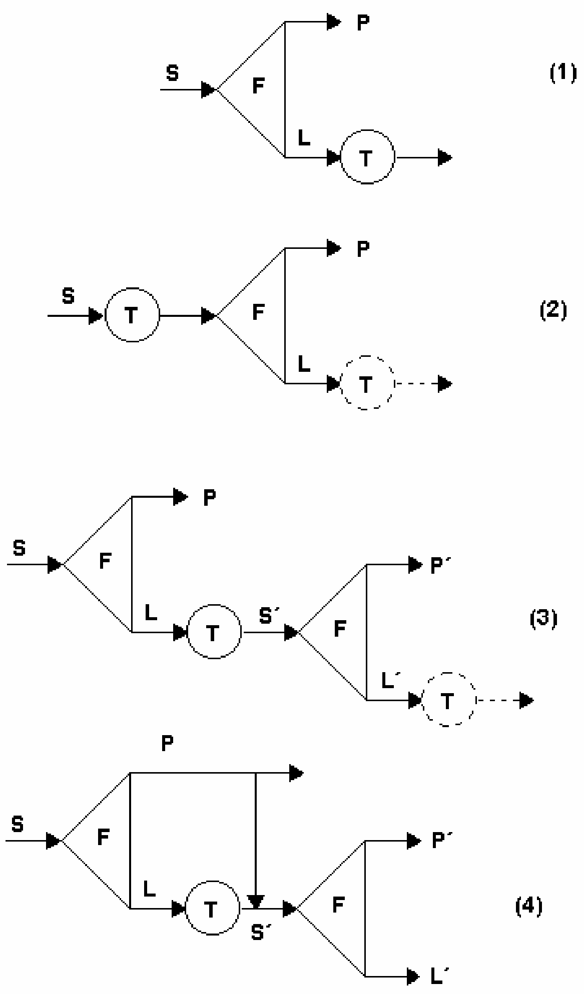


Fig.1. Schemes of wastewaters separation of the first group. S - wastewater/slurry; F - filtration; T - treatment; P - solid phase; L - liquid.

The second group of wastewaters can be separated by filtration immediately. To reduce hazards of solids, the cake undergoes treatment with chemical reagents, solvents or by isolation, destruction, etc. (Fig. 2). Here slurry filtration directly (scheme 1) or preliminary thickening by filtration (scheme 2) with the following treatment of concentrated slurry can be possible. The hazardous contamination in the solid phase occupies only a part of it, solvent extraction of contaminants can be done with the filtration followed. Combination of filtration with extraction, thermal processing (drying, etc.) or with suitable chemical operations is possible (scheme 2).

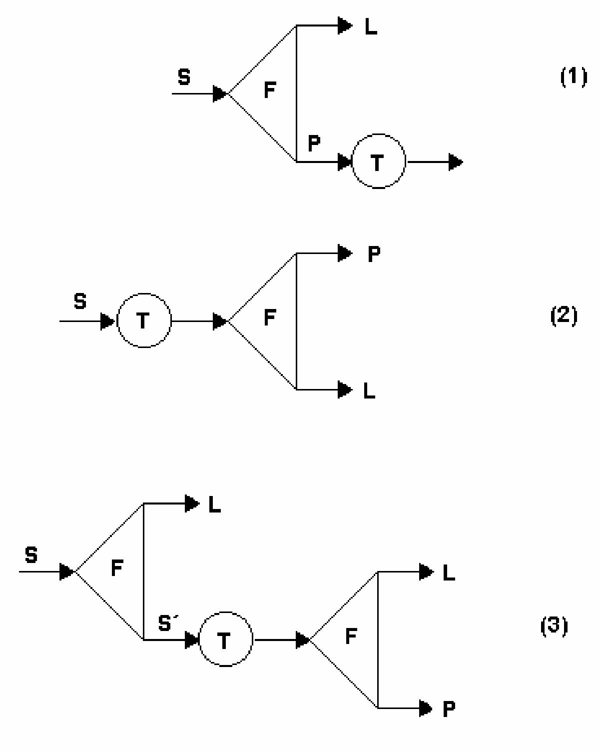


Fig.2. Schemes of wastewater separation, the second group.

The slurry (concentrated) can be received after filtration of some types of filters, for example filter-thickeners, deep bed filters, etc. Depending on technological conditions the slurry can be treated by one of the known methods or returned to the head of technological scheme.

As a rule the concentration of solids in the liquid decrease stage by stage of treatment and using the deep bed filtration becomes more probable.

The third group of wastewaters supposes a great variety of possible sequences of treatment operations and filtration. Treatment of these slurries presents different combinations of technological schemes for groups 1 and 2.

1.2. Filtration from the Point of View of Flexible Technology

As a rule, the wastewater delivered to treatment has unstable composition, so the flexibility must be given to the technological system for supporting steady state working conditions. In general the definition of flexibility can be given as following [2]:

Flexible chemico-technological system is a system of machines, apparatus and control devices, connected by material, energy and information flows. The system is intended for realization of certain tasks and is able to adopt itself to the change of both external and internal (inner-system) conditions, keeping its main characteristic functions on account of excess connections, i.e. technological, design, structural and control ones.

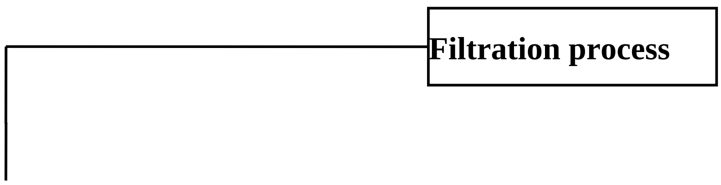
The analysis shows that today a new tendency in filters designing has been formed side by side with the development of traditional types of filtering equipment [3]. Here filters are considered as units of a flexible technology.

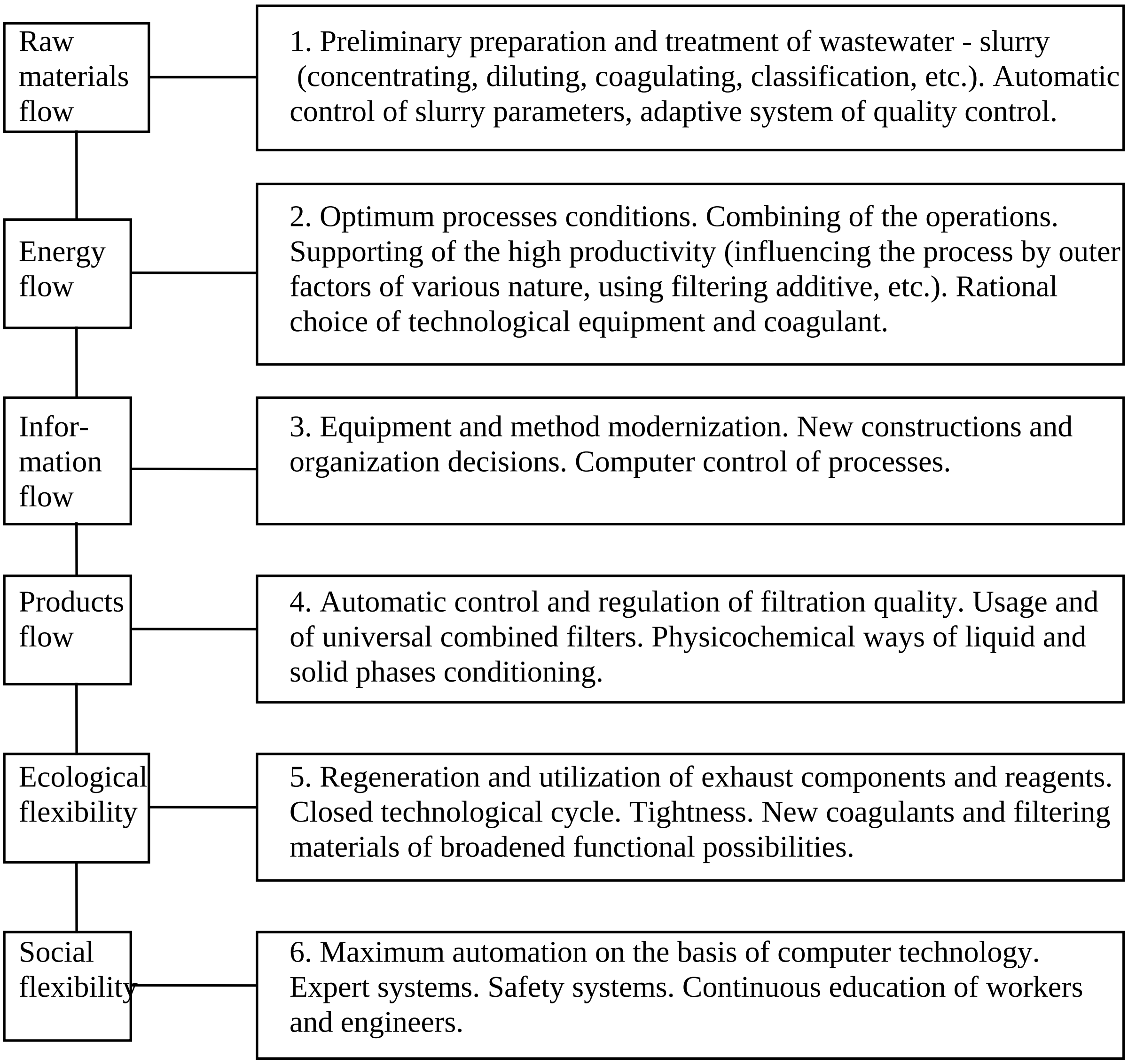
It is possible to apply the definition of flexibility to more particular technological systems, for example, to filtration because filtration in general presupposes preliminary slurry treatment and other operations. These operations are interconnected; the success of the operation that follows depends on all previous ones.

Filtration as a flexible process may be presented as follows, see the scheme on the next page (Here coagulation + filtration stages will be taken into account).

Filtration progress demands preliminary analysis of the production which is to use it.

1. Determination of the production program. Characterization of the disperse system to be filtered and its volume. Qualitative and quantitative criteria of the process.
2. Technique of the filtration process or thickening (continuous, batch, equipment connection scheme, etc.). Organization of transport streams. Additional means. Type of filtering equipment.
3. Organization of information flows: registering the type of signals and the way they come to the operator's console, to the system of automatic information treatment; mentioning the form of information exchange with controlled objects.
4. Possibility of continuous process when some part of the equipment fails. Optimum charge of equipment. Possibility to improve technologies.





When speaking about flexible technologies it is necessary to dwell on poly-functional technological filtering modules.

Technological modules need sectioned equipment, involving combinations of various hydro-mechanical separation processes, additional equipment for physicochemical treatment and transfer of treated slurry. The filtration process may be combined with coagulation, thickening, floatation, cyclonage, centrifugation, etc. The module may contain sectors for treating the slurry with reagents, for heating (cooling), thinning and distillation of the thinner.

In spite of the design complexity of the modules they give an additional opportunity to utilize heat, recycle gas and liquid phases when specific consumption of energy and materials is reduced.

1.3. Conclusions

Certainly the above schemes do not limit the scope of filtration-separation systems as there are various constructions of filters. Besides to operate a separation system with a filter efficiently one must strictly control a wide range of process conditions.

When developing a separation system with filters it is necessary to provide maximum combinations of the main processes and auxiliary operations. That will reduce filter shutdown time and increase the system average capacity per cycle.

Strict control of all operations in time and space is a necessary condition for the efficient performance of a modern filter, especially when there are several filters operating system. In this case to provide optimum sequence of operation of several filters it is necessary to use time-table theory.

Providing a filter with a modern control system considerably increases the cost of filter system which can be compensated only by optimization of filtration process in terms of the highest capacity and minimum operation cost.

As a rule, increase of process equipment automation degree requires redesigning of the main processes to increase their stability to external disturbing factors.

Thus when coming to highly automated filters design - technological problems acquire new aspects demanding deeper investigation into the theory of filtration and deep bed filtration in particular.

General approach should cover the stages of suspension pre-treatment, e.g. coagulation, settling or centrifuging as well as the processes of filter washing, replacement, etc.

Unique approach to the above mentioned processes makes it possible not only to estimate precisely separate stages of suspensions separation and dewatering, but to forecast possible ways of the processes that follow them, e.g. coagulation, settling   filtration   dewatering   washing   squeezing-out   drying.

In particular in the range of general approach to flocculated suspension filtration and to other stages of separation and post wastewater treatment first of all as far as the subject covered by the article is concerned it is necessary:

1. To select and investigate suspension pre-treatment by physico-chemical methods or by pre-thickening, for instance by settling or cycloning which give the most easily forecast and controlled results;

2. To develop methods of properties stabilization for suspension being filtered, e.g. to maintain preset concentration, temperature, viscosity, particle average size, etc., which is achieved by active stage (1) control and regulation;
3. To provide steady characteristics of filtering medium resistance and removal efficiency during filtration by controlling: pressure, particles concentration, flock size and other process parameters;
4. To select washing/regeneration, dewatering, cake squeezing-out operating conditions taking the properties of the cake formed as a basis (porosity thickness distribution, permeability characteristics, cake compressibility), etc.;
5. To improve calculation methods of modelling slurry separation which forms compressible flocs or cake;
6. To develop methods of process optimization based on general mathematical model of flock formation and its properties in separation processes;
7. To develop optimum conditions of the bed thickness, filter media particle size, their total surface area and the time needed for their backwashing;
8. To analyse possibilities of applying test filtration method to determine cake properties and to extrapolate the results to industrial filtration. (The term "test filtration" as used herein refers directly to filter unit where test filtration is done just before industrial filter start-up rather than cake properties determination in laboratory conditions. The results of filtration are analysed by computer and solution about correcting industrial filter operating conditions is made accordingly).

A more complete filtration theory is necessary for a group of deep bed filters for wastewater purification, since more careful control of process parameters is needed. The high cost of this system demands the guarantee of maximum cycle productivity, the established process parameters being kept strictly.

The attention of experts must be fixed on the theory of coagulation/flocculation, filtration and optimization.

2. DEVELOPMENT OF FILTERS CLASSIFICATION METHOD FOR OPTIMIZING FILTERS SELECTION

In many cases when an expert needs to select a filter he is faced with the problem of a great variety of equipment types. So, often the expert must use one of the two ways of the filtering equipment choosing: 1) choose a filter on the basis of the long terms specific filters usage traditions in specific technological schemes or 2) select a filter on the basis of bench-scale tests and the method of "Trials and Errors".

Filtration techniques and technology development make it advisable to extend classification principles for optimizing filters selection.

There are a number of established approaches to the classification of the filtering equipment. Most often filtration equipment is classified according to the methods of creating the driving force of the filtration process.

The major shortage of this classification is different types of filtering equipment belonging to the same group although they have different function principles. For example, the group of equipment where the filtration driving force is vacuum getting in vacuum drum and belt filters (continuous filtration) with continuous movement of filter medium, leaf and cartridge filters (batch filtration) with fixed filter elements, etc. The group of filters working under hydrostatic pressure includes deep bed filters (fixed or movable grained bed) and belt filters for the coolant which acts continuously or semi-continuously. The group of filters with pressure driving force looks more eclectic.

This classification system needs a large amount of actual information. As a rule the system does not allow to conduct either a detailed analysis of possible filters constructions or synthesis of new constructions. Moreover the calculation methods of filters from the same group can differ cardinally. It makes difficult to use the classification system and its computer application.

The aim of the below described principles of classification is to find out some trends in filters design and filtering equipment usage. The basis for filtering equipment classification here is space and time position of filtering elements (FEs) or filtering medium during the filtration process as well as during FEs regeneration [4]. In this paper the classification method will be improved and modified.

Note that for numerous filtration processes the regeneration cannot be considered as an independent process, for instance, when the regeneration of filter medium occurs at the same time as filtration takes place. Here we consider as regeneration not only methods of filter medium output increasing but also methods of cake removal from filtering medium surface or protect the surface against cake formation, since in numerous processes we try to change environmental conditions around FEs during filtration.

According to the proposed classification scheme all filtering equipment may be divided into 2 main groups: 1) filters with fixed FEs during filtration and 2) filters with FEs which change their spatial position during filtration (filters with movable FEs).

The abbreviated names of filters sub-groups are expressed by conditional indices shown in Fig.3. Point of departure for classification is shown in Fig.4.

a b c d e i j

|___|• |___| (|___| |___|) — |___|/ |___|• |___|

Fig.3. Conditional indices of filters sub-groups used. Here
(a) - 1 - continuous filter; 2 - batch filter.
(b) - 1 - fixed filter medium (FEs); 2 - movable medium (FEs).
(c) - PM - periodical movement; CM - continuous movement; RM - FEs reciprocating motion.
(d) - C - FEs movement by closed trajectory; O - FEs movement by open trajectory.
(e) - 1 - continuous filter medium; 2 - interrupted (discrete) filter medium.
(i) - CN - Continuous regeneration of FEs; P - periodical regeneration of FEs.
(j) - FR - all FEs (medium) regeneration; PR - regeneration of the part of FEs (medium).

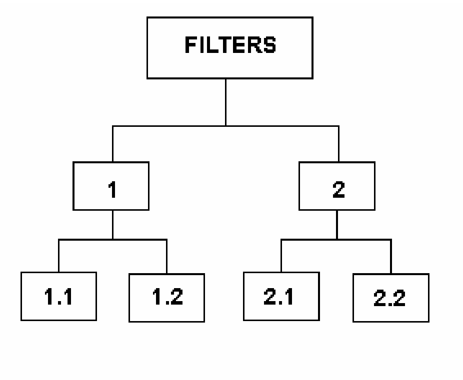


Fig. 4. Point of departure for classification. 1 - Continuous filters; 2 - Batch filters;
1.1 - Fixed FEs; 1.2 - Movable FEs; 2.1 - Fixed FEs; 2.2 - Movable FEs.

As a rule, in most cases the FE (filter medium) regeneration is taking place during filtration or after it for either continuous or batch filters.

In both cases FE regeneration may be accomplished by means of hydro-mechanical, mechanical and physical ways. Hydro-mechanical regeneration is carried out by changing the direction or velocity of the fluid and pressure in various parts of the filter. Jet flow, turbulence and hydro-shock are used. Mechanical regeneration is the removal of contaminants from the FE surface with the help of mechanical action such as shock, vibration, oscillating movements, shaking, cut-off, shear, etc. Physical regeneration methods suppose usage of various physical fields and their combinations to affect polluted FEs. These are sonic, infra and ultrasonic, electric, magnetic fields, centrifugal forces, etc.

During regeneration FEs may be both in fixed position and in motion. Here we shall consider cases when filter medium or FE regeneration takes place during filtration. However the described below classification method permits to extend it to the field of regeneration operations which take place when filtration is completed.

2.1. Continuous Filters with Fixed FEs (Filtering Medium)

These filters can have continuous filter medium (1.1-1) or interrupted (discrete) filter medium in the view of filter elements or single sections (1.1-2), Fig.5.
The group of filters with continuous regeneration of the total surface of filtration or of some part of it, as well as filters with periodic regeneration of all filtering surface or its part during filtration are shown in Fig.5.

Let's enumerate the most widespread filters constructions belonging to sub-groups of lower levels of classification.

1.1-1/CN.FR. These are filters with continuous filter medium and continuous regeneration of the total filter medium during filtration. They may be the following:

- - filters with tangential movement of filtrated liquid relative to the surface of FEs (cross-flow filters);
- - dynamic filters where discs with paddles are placed between fixed annular filtering elements located on the axial driving shaft. Rotating discs create slurry flow along filtering surface;
- - cyclone filters;
- - screw filter-presses;
- - filters with Talor vortex;
- - tank filter-thickeners and Nutch filters with continuous stirring and other less spread varieties of filters.

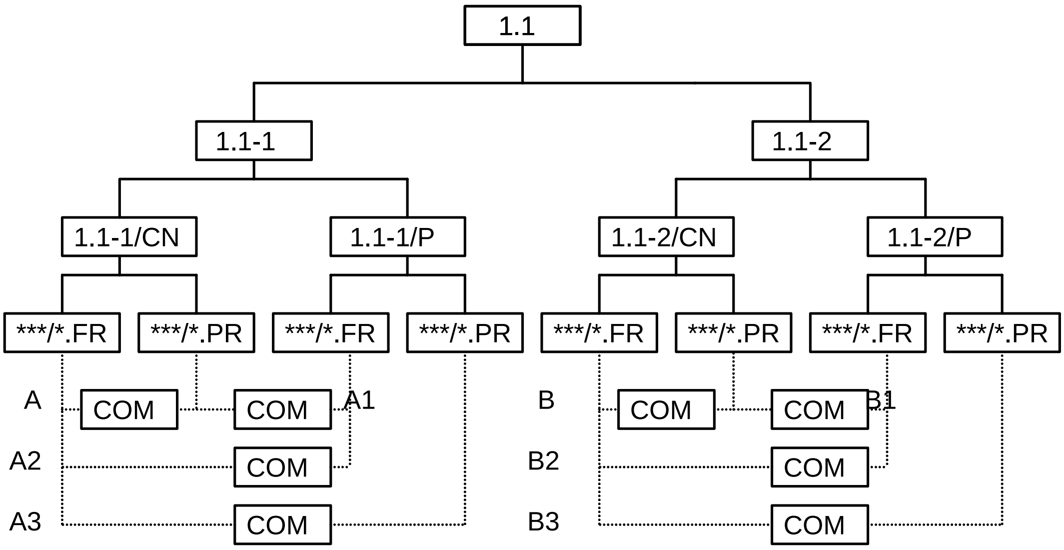


Fig.5. The classification scheme of continuous filters within fixed FEs (1.1). Here (1.1-1) and (1.1-2) are filters with continuous filter medium and discrete FEs, accordingly. ***/CN and ***/P - filters with continuous and periodical FEs regeneration during filtration, accordingly; ***/*.FR and ***/*.PR - filters with regeneration of total filtration surface (of all FEs) and regeneration of some part of total filtration surface (part of FEs of their total number), accordingly. COM - combined (joint) regeneration action on FEs (filter medium) of FR and PR during filtration.

To intensify FEs regeneration physical regeneration methods can be used here. Filters of the group are of great interest due to their comparatively simple design and a broadening field of application in micro- and ultrafiltration, where analogous designs are used.

1.1-1/CN.PR. Filters with continuous filter medium and continuous regeneration of a part of medium during filtration. The characteristic of the filters is that they impose regeneration of some part of filtering surface on filtration process, i.e. the total filtering surface or all filtering elements are under filtration conditions, regeneration zone continuously moving over their surface. Only part of the filtering surface is regenerated at any given moment. Filters of the type are the following:

- filters provided with movable devices positioned above filtering surface for suction, blowing or outwash of pollutants, or filters with movable devices placed at the inner side of filtering surface and operating in accordance with the principle of blowing or outwash;

- filters with scrapers, brushes for removing solid pollutants, and other devices used for the same purpose, continuously moving over filtering surface.

Filters of this type have recently begun to be used wider because they happen to realize continuous filtration close to 1.1-1/CN.FR models. At present, however, their application range is limited by movable mechanical devices operating under conditions of abrasion wear, which makes the filter design more complicated and demands thorough control of the devices during their operation. Besides, it is problematic to apply them for filtration of slurries giving cake with great adhesion to filtering medium.

1.1-1/P.FR. Filters with continuous filter medium and periodical regeneration of filtering surface during filtration.

During filtration periodic regeneration of the total filtering surface or some part of it is accomplished here, as a rule, after equal and quite short periods of time. This assures high filtration rate when regeneration time is much less than filtration period.

Filters of this type include a small group of filters, in which regeneration of filtering surface (cake removal) is done by periodical imposition of vibration. As a result the accumulated cake slips from the filtering element without stopping filtration. Regeneration is also possible by means of quick changes of form and configuration of filtering surface, which results in cake cracking and its discharge from filter element due to inertial forces. At this moment filtration is continued.

Filters in which filtering surface regeneration is done by impulse influence on its filtrate back flow (for example, filtration through filter element in direction opposite to gravity force) can be considered in this group.

These filters are practically of semi-continuous functioning but the duration and frequency of additional periodic effect during regeneration of the total filtration surface being much less than filtration time, they may be conventionally referred to the group of continuous filters.

All above-mentioned regeneration methods may be used to intensify the process of regeneration. It is possible to impose periodic influence force as an additional constituent on the total filtering surface according to the scheme: 1.1-1/(CN + P).FR = A2. For example, during cross-flow filtration the periodical impulse of filtrate back flow affects filter medium, Fig.5, A2.

Scheme 1.1-1/CN.(FR + PR) = A, Fig.5, A, can be realized in cross-flow filters when a movable device is used for continuous regeneration of a part of filter medium. Also, the scheme A1 = 1.1-1/CN.PR + P.FR is possible where the same impulse force is used for periodical regeneration of the total filtering surface when another device simultaneously performs continuous regeneration of the part of filtering surface.

1.1-1/P.PR. These filters are more often represented by the variety of 1.1-1/CN.PR sub-group filters with a regeneration device being set in motion periodically. For example the device is used when maximal differential pressure of filter medium is to be reached. But usage of this filters type is limited.

The next combination of possible filtration methods is: 1.1-1/CN.FR + P.PR = A3. This takes place in tubular crossflow filters with filtration from inside outside. For removing contamination from inside FE surface the tube cleaning bodies (spherical or other shape bodies) are passed periodically through tubular filtering element with slurry stream.

The group of filters 1.1-2/CN.FR is most often represented by filter-thickeners where the filter elements are continuously washed by filtering slurry flow which brings to minimum solids deposition on filtering surface.

The negative characteristic of filters 1.1-2/CN.PR is the regeneration, by turns, of a part of FEs or single FEs when other FEs work in filtration conditions. Then the filtration conditions for the whole of the filter are not stopped. Usually these are filters having a funnel for suction of the cake. The funnel is periodically brought to filter elements, some part of the purified liquid being lost together with the cake because of the reverse flow of filtrate during suction.

1.1-2/P.FR - filters with filter elements which are periodically simultaneously regenerated by back flow impulses of filtrate.

To the 1.1-2/P.PR group some modifications of 1.1-2/CN.FR filters can be related when a device for FE regeneration is set in motion after critical filtration parameters are reached.

Here there also can be combinations of different periodical and continuous regeneration operations during filtration: 1.1-2/(CN+P).FR =B2; 1.1-2/CN.FR + P.PR = B3; 1.1-2/CN.PR + P.FR = B1, etc.

The majority of filters types (1.1) are represented by filter-thickeners for slurry concentration.

2.2. Continuous Filters with Movable Filter Elements (1.2)

The scheme of the classification is shown in Fig. 6. We may distinguish the following sub-groups (1.2) of filters:

1) filters with periodical movement of filter medium or FEs 1.2(PM);

2) filters with continuous movement of filter medium or FEs 1.2(CM) and

3) filters with reciprocating motion of filter medium of FEs 1.2(RM) for example, when a piston with reciprocating motion plays the role of filter element.

The filter medium or FEs can move by closed **(*.C) or open **(*.O) trajectory (See Fig.6 and Fig.3, level (d)).

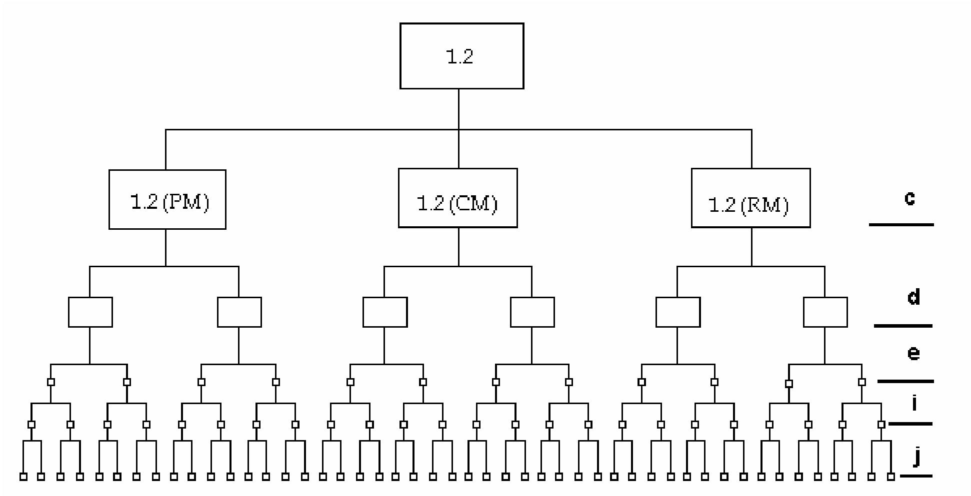


Fig.6. Scheme of classification of continuous filters with movable FEs (1.2): 1.2(PM), 1.2(CM) and 1.2(RM) - filters with periodical, continuous or reciprocating movement of FEs or filter medium, accordingly (Level c). Level (d): **(*.C) and **(*.O) - filters with FEs movement by closed trajectory and open trajectory, accordingly. Level (e): **(*.*)-1 - filters with discrete filter medium or FEs; **(*.*)-2 - filters with continuous filter medium. Level (i): **(*.*)-*/CN - filters with continuous regeneration; **(*.*)-*/P - with periodical regeneration. Level (j): **(*.*)-*/*.FR - all FEs (medium) regeneration; **(*.*)-*/*.PM - regeneration of a part of FEs (medium).

The next sub-groups, Level (e):

1). Filters with continuous filter medium **(*.*)-1, i.e. filter medium represented by closed surface or layer on different parts of which different operations are made simultaneously (filtration, dewatering, washing, drying, discharging, etc.).

2). Filters with discrete filter medium or FEs when on single FE or discrete parts of filter medium only one fixed operation is realized simultaneously **(*.*)-2.

Both sub-groups of filters can be divided into Level (i) and then Level (j) by analogy with 1.1 group of filters. Note, the Levels (c) and (d) have filters with movable filter medium or FEs only.

Examples of different sub-groups of filters, Level (e), are given below. 1.2(CM.C)-1. These are drum and disk vacuum or pressure filters; belt filters; belt filter-presses; filters with movable grainy filter medium (layer) when after passing through filtration zone the grainy medium is put to regeneration and returned to filtration zone; plate vacuum filters; centrifugal filters when filtration takes place through rotating filter element.

1.2(CM.O)-1. These are filters with a roll filter belt which is unwound from the roll to the filtration zone; belt filters with a precoat filter layer which works as filtration medium.

1.2(PM.C)-1 - filters with grainy filter media which are removed from filtration zone periodically and after regeneration come back to the filtration zone.

1.2(PM.O)-1 - filters with roll filter medium (belt) which is periodically moved to the filtration zone to take the place of exhaust belt part, for example, the filter with roll filter belt for coolant filtration.

1.2(CM.C)-2. These are tilting-pan vacuum filters; rotary cartridge filters and rotary-disk filters.

1.2(CM.O)-2. These are conveyor type filters with disposable FEs, for example filters elements of cartridge or candle types installed on the conveyor system before filtration, are moved in the filtration zone and after filtration are removed from the conveyor.

In some cases the movement of filter medium can be periodical like in cases with: 1.2(PM.C)-2 - rotary cartridge filters etc. 1.2(PM.O) - conveyor type filters.

In most cases filters of (1.2) type are intended for dewatering moderate or highly concentrated slurries.

The reciprocating motion of filter medium can be considered as utmost case of medium movement by closed trajectory.

The regeneration of filter medium or FEs in the most continuous filter types (1.2) is realized out of the filtration zone. But the version with additional regeneration of a filter medium or FEs in the filtration zone is not without sense if the filtration task is slurry thickening.

In the discussed group of filters note should be taken of rotary and conveyor filters the design development of which can give a new perspective to filtration system of moderate volume treatment of concentrated slurry.

Like in the filter group considered above (1.1), different features of filter constructions can be combined here, for instance in rotary-conveyor filters type. The design development of this type of filters is in the preliminary stage now.

2.3. Batch Filters (2.1) and (2.2)

Batch filters are the oldest type of filtering equipment having the greatest variety of constructions. Batch filters can be divided into filters with disposable FEs and filters with multiuse FEs.

Into the group of filters with disposable FEs we include filters where FEs (filter medium) do not regenerate and are subjected to replacement after filtration cycle. This group of filters is well investigated since they are intended for work in hard conditions.

The sub-group 2.1 has the same scheme as sub-group 1.1, Fig.5.

2.1-1 - filters with fixed continuous disposable filter medium. The single plate, disk or belt filter media or filters with single FE are implied here as continuous medium. If the quantity of filter elements or media is more than one, these filters change to group 2.1-2 with discrete filter medium. As a rule filters with disposable filter medium are used for a liquid clarification of for finishing filtration. These filters are intended for liquid filtration with small solid phase concentration usually when clogging filtration takes place. Continuous regeneration for the filters is used rarely.

2.1-1. In most cases this group of filters is the constructive development of the previous group but with repeated regeneration of FEs in the filter. Example: 2.1-1/CN - nutch or pressure filters with stirrer; 2.1-1/P - automatic filter-press FPAKM.

2.1-2/CN or 2.1-2/P are the constructive development of version (2.1-1). Filtering equipment is: multi-element candle, cartridge, tube, bag, disk filters; some types of filter-presses and lift filters. Position of filter elements during regeneration is not changed.

The regeneration of FEs in batch is conducted many times, so expenditures on regeneration become comparable with filtration expenditures. So, it is possible here to divide this type of filters into some sub-groups according to technical means characteristics which are used for regeneration processes: 1) manual regeneration; 2) mechanized regeneration; 3) automated regeneration; 4) robot or manipulator regeneration.

All technical means for filters regeneration and servicing can be used in the same types of filtering equipment. For example, small filter-presses served by manual means, moderate sized filter-presses supplied with mechanized regeneration means, large scale filter-presses supplied with automated and/or robot technical means for filter servicing.

The qualitative changes of filter servicing technical means take place when we pass from one group to another. The filter servicing by robot integrates all named above in points 1 - 3 technical means on a principally new level.

The robot system can be mostly used for filter servicing with many identical filter elements. New original filter constructions can be designed when robot system servicing is used.

Batch filters with continuous movable filter media 2.2(*.*)-1 may have disposable filter media with movement by open trajectory (The filter medium movement is carried out after filtration has been finished). The filters of 2.2 group include: automated filter-presses; horizontal belt filter-presses with hydraulic press; tank (disk) filters with endless filtering belt; filter-presses with paper filtering belt for coolant; "Nutrex" filter, etc.

Discrete movable filter medium 2.2(*.*)-2 is used in disk filters with centrifugal cake discharging ("Funda" type); disk filters with brushes for removing ("Indrex Brush-Cleaned Pressure Filter" type); some types of filter-presses.

2.4. Conclusions

The classification characteristic features have received a deeper gradation of filters constructions. The symmetric scheme of filters arranged in grades, Fig.7, gives the possibility of designing new filters versions by synthesis of different sub-groups features. This scheme is convenient to use in expert systems and for elaboration of new constructions of filters.

Different types of filters which have similar sets of indications can be compared with each other with the help of the method, for instance, batch filters with fixed filter elements and batch filters with movable FEs, etc. This can ensure optimal filters construction selection.

The problem of the scheme application to similar classification of filtration processes calculation methods needs further investigation. There are many obstacles here: hydrodynamic conditions influence on filtration, influence of properties of suspension and filter medium, particle concentration in liquid, etc. Nevertheless we hope, that the classification development can regulate the calculation methods on the "block" approach basis in the future:

Filtration = Filtration + Environmental + Regeneration

(as technological processes)	**(deep bed, cake, blocking, combined, etc.)**	**conditions near the filter medium surface**	**of filter medium permeability**

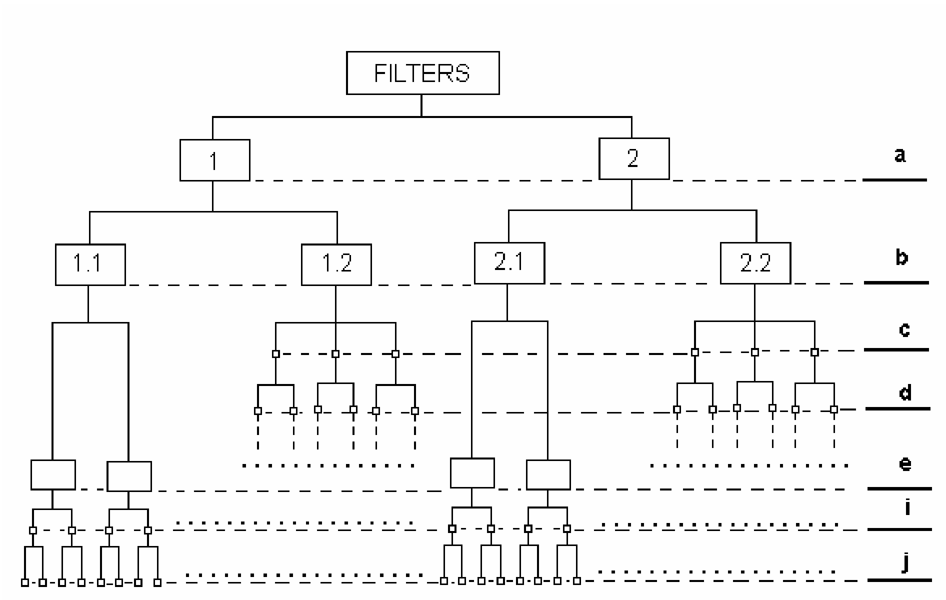


Fig.7. The general scheme of the classification. Levels (a), (b), (c), (d), (e), (i) and (j) see Fig.3. Levels (c) and (d) have filters with movable filter medium or FEs only (sub-groups 1.2 and 2.2).

The scheme discussed here is the first approach of the classification method development on the basis of space and time position of filter elements.

3. DEEP BED FILTRATION

3.1. Deep bed filtration in the classification scheme

According with general classification system, Fig.3, the following scheme for deep bed filters (DBF) can be developed: a). Continuous DBF and b) Batch DBF.

a) Continuous deep bed filters, Fig.8

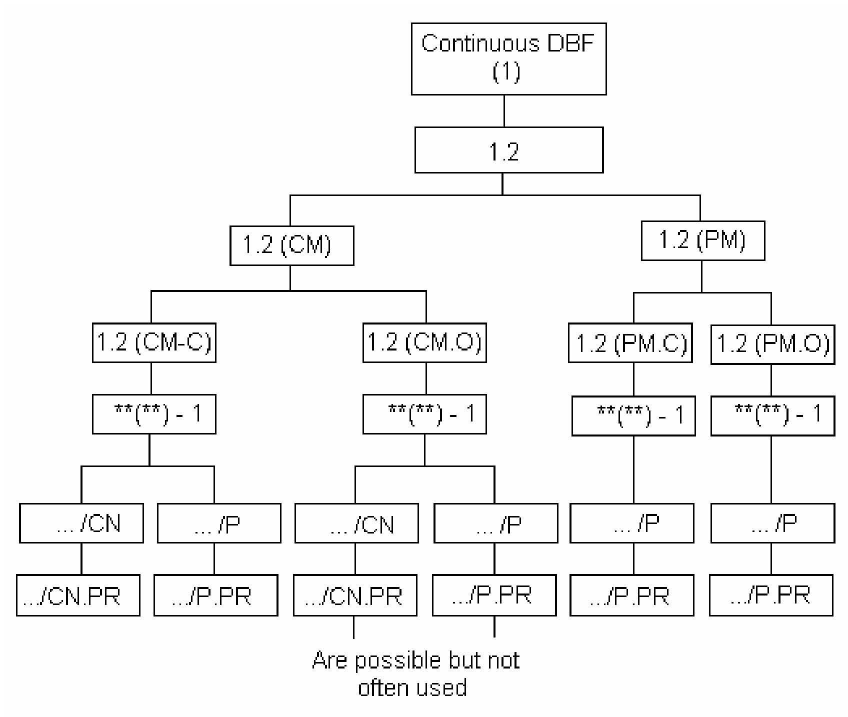


Fig.8. Continuous deep bed filters scheme.

The group of continuous DBFs includes filters with continuous filtration and movable medium (grained medium) - group 1.2 (DBF with movable packed-bed grained medium; DBF with fluidized bed). In both cases the medium moves continuously by closed trajectory (more often for DBF with packed-bed when grained filter medium after regeneration comes back to filtration zone) or open trajectory (more often for DBF with fluidized bed) - 1.2(CM.O). The filter medium for both types of filters can be considered as continuous: *.*(*.*)-1 which depending on the filter construction can be regenerated continuously (when a part of the medium is continuously removed from filtration zone to the regeneration zone) or periodically. For filters with periodical movement of filter medium 1.2(PM) the regeneration can be only periodical 1.2(PM.*)-1/P. For all DBF types during filtration only a part of filter medium can be regenerated.

The scheme of continuous DBFs is more often used for treating moderate volumes of liquid since filter constructions are complicated.

Using the classification method we can develop a group of DBFs which are possible in principle but not well prompted (It is continuous DBFs with reciprocating movement 1.2(RM)), Fig. 9.

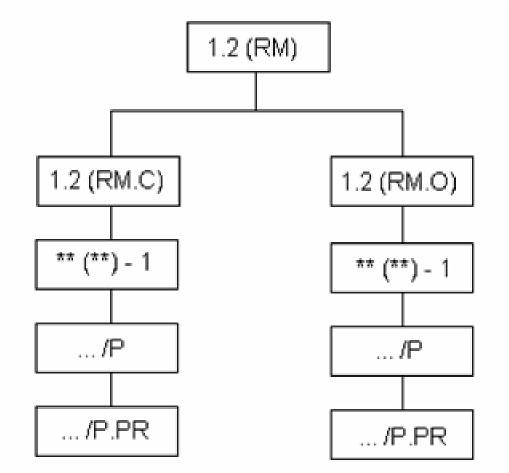


Fig. 9. The scheme of continuous filters with reciprocating movement of filter medium.

This group of filters consists of fluidized pulsed bed filters (pulsed columns) and filters with vibrated bed. These types of DBFs have a problem with retention of pollutants and are not used widely.

b). Continuous DBFs with fixed filter medium (2.1), Fig.10, is a more widely used group of deep bed filters. It is explained by simplified construction and good reliability.

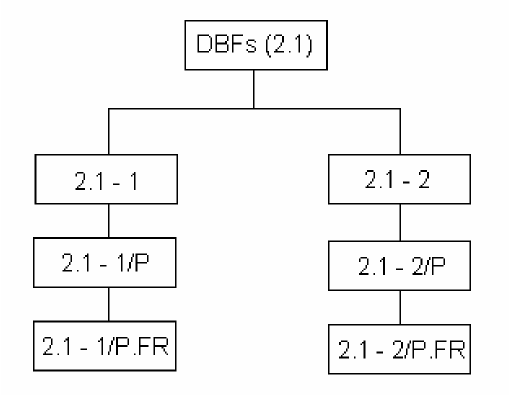


Fig.10. Scheme of DBFs with fixed filter medium.

We have included filters with stratified bed (dual and multiple-media filters) in the 2.1-2 - DBFs with discrete filter medium. The reason is that filter bed properties are changed unevenly from one layer to another. Examples of bed types 2.1-1 and 2.1-2 are shown in Fig.11.

Filer beds, type 2.1-1 Filer beds, type 2.1-2

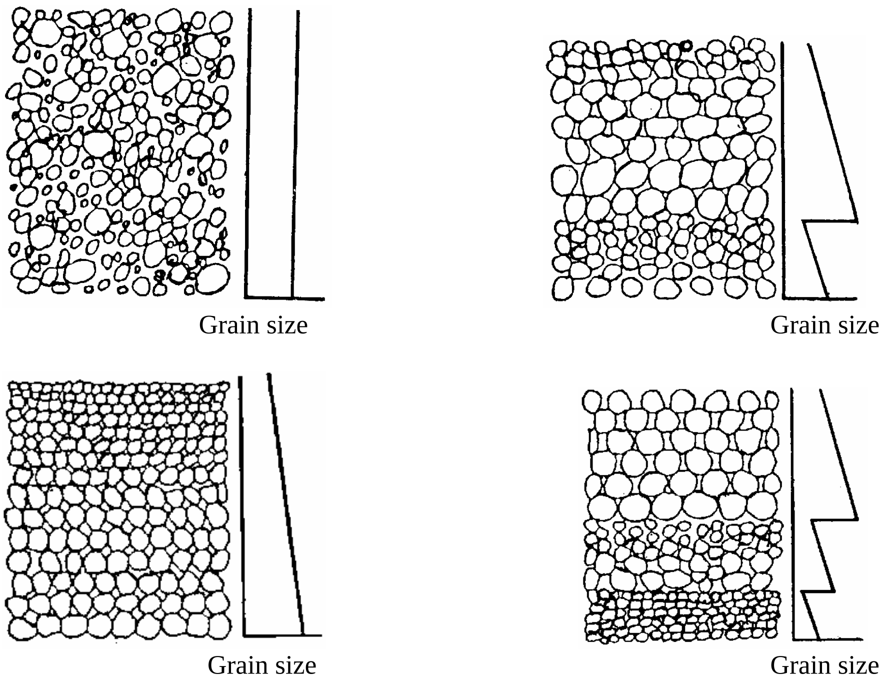


Fig.11. Scheme of filter media bed configuration (Examples borrowed from (fig.4 [5]). For easier serving of deep bed filters in our case for tertiary filtration of wastewater the most preferable is a single media filter containing sand as a medium.

3.2. Tertiary wastewater treatment by contact filtration

On the basis of the general principles of filtration analysis discussed above the analysis of different solid phase removal schemes for tertiary wastewaters with the concentration of solids about 10 mg/l was made. The tertiary wastewater volume treated per day is some cub. m.

The low concentration of solids and small particle size (about microns) make it necessary to use pre-treatment of liquid by a coagulant or flocculant. Some variants of tertiary wastewater treatment are possible here. Below presented schemes are based on solid phase flows.

1. Flocculation (reactor-flocculator) Sedimentation / Thickening Cake filtration (cartridge filter, filter-press, etc.).

2. Flocculation (reactor-flocculator) Thickening (cross-flow filtration, etc.) Cake filtration (cartridge filter, filter-press, etc.).

3. Flocculation (reactor-flocculator) Sedimentation (thickening) Deep bed filtration (sand filter).

4. Flocculation (reactor-flocculator) Deep bed filtration.

5. Deep-bed filtration (contact filtration) with a flocculant adding.

Negative factors of

n.1 are: batch process of separation; highly compressible flocks generation which are formed in compressible filter cakes - low output;

n.2 - the same problems as in n.1; big energy expenditures because of slurry circulation through cross-flow filter;

n.3 - batch process of separation which is bad for sand filter operation; deep bed filter top layers clogging by highly compressible flocks when thickening slurry passes through the filter - low output;

n.4 - uneven flocks distribution within filter layer depth (clogging top layers); high head loss.

In comparison with the schemes mentioned below contact filtration has the following disadvantages: compact scheme; continuous process control; flocks formation within the deep bed and good conditions for adsorption of the flocks in the filter; more even flock size distribution within the filter bed. Hence, the deep bed contact filtration is more preferable.

3.3 Recommendation of filtration conditions selection.

As a sewage tertiary treatment process deep bed filtration in conjunction with coagulation may produce filtrates of exceptional clarity, with the suspended matter scarcely detectable by turbidimetric instruments [6]. Usually the process of filtration with introduction of a coagulant before a deep bed filter is named contact filtration.

The coagulation in contact with outside solid surface differs from coagulation in water volume as it: 1) proceeds faster; 2) needs smaller dosage of coagulants; 3) is less sensitive to water temperature; 4) gives good results even for low turbid water.

A uniform filter does not become uniformly clogged with deposit, the upper layers carrying the burden and the lower layers contributing little.

Coagulation

The results obtained by Jar-test experiments cannot be directly applied to filtration, because head loss criteria may limit coagulant dosage to well below the optimal destabilization point [7].

Turbidity measurements after Jar-tests and glass fibre filtration have given the best indication for the optimal polymer dosage [8].

In order to increase flock storage (i.e., specific deposit) in the direct filtration process, a design option should be adjusted the flocculation velocity gradient toward higher values, realizing that filter head loss profiles must also be considered [18].

Dense flocks under effect of a drag force penetrate into deeper layers of the filter thanks to ripening. In the investigation of the motion when the solid is sphere relative to the porous one in fluid at rest [9], it is found that in all cases, the drag force exerted on the porous sphere increases as the permeability decreases for any separation distance.

In the work presented in [7] the fragile hydroxide-flocks are produced under velocity gradients of about 20 1/sec with a detention time of 2 min for the metal-salt mixing, and another 2 min for the mixing of the polymers under similar turbulent conditions. The resulting suspension consists of dense flocks no larger than 100-150 microns. No further slow flocculation is applied except for the low turbulent motion in the water above the filter media. Lower velocity gradients and longer mixing time cause the production of macro-flocks leading to the adverse formation of a sludge-blanket on top of the filtration media.

Removal efficiency

The minimum of particles removal efficiency occurs at about 1 micron where the particles are too large for diffusion, too small for gravity and small for interception [6]. But for flocculated suspension the condition can be different.

Contact filtration (deep bed filtration of lake water after particle destabilization by injection optimal polymer (Cal-Floc) dosage into raw-water feed line with no other treatment) has been studied in laboratory-scale experiments [8]. The following conclusions can be done:

- ripening occurs for all particle sizes initially and continues for small particles in the range of 1 - 6 microns for several hours, but it is apparently slowed or reversed for large particles in the range of 6 - 13 microns. This result occurs for all media sizes, flow rates, particle concentration studied (1.2 - 3.7 mg/L). The decreasing removal efficiency of these larger particles in the suspension needs to be studied in experiments of greater duration.

- poor removal of particles 6 - 13 microns is identified through particle size distribution measurements. This poor removal may be caused by surface chemical effects or by flock break-off.

In laboratory-scale filtration experiments conducted with settled water from a lime-softening plant, breakthrough is discovered to be greatly influenced by particle detachment. Particle detachment occurs most dramatically in an intermediate size range for the suspension studied. The explanation is that they come into the filter as much smaller particles, form flocks on the surface of the media, and are detached as flocks with the size of 3-7 microns [10]. The removal might have appeared low because flocks of smaller particles measured at lower filter depths are counted as intermediate-sized particles that are not removed [11].

The lab.-scale filtration experiments [12] have shown that: ripening, that is, increased removal efficiency with time, occurs in all experiments but is significantly different for differently-sized particles. The largest particles are effectively removed initially and improved in removal efficiency slightly. Intermediate-sized (6.3 -10 microns) particles were not effectively remove initially but improve in removal efficiency rapidly and dramatically. The smallest (1.6-2.5 microns) particles measured are not effectively removed for a few hours, but then show a significant increase in removal efficiency.

Rates of filtration

Normally filtration rate is from 5 to 15 m/h with a trend towards higher rates [6]. According to recommendation [13] – 8 - 12 m/h.

Increased velocity pushes particles deeper into the filter bed prior to capture. This better use of the bed depth leads to reduced head loss and, therefore, allows treatment of larger quantities of water before filter bed cleaning is necessary [8].

Doubling the filter velocity up to 13 m/h reduces the removal efficiency of all particles sizes somewhat but results in more uniform capture throughout the depth of the filter (suspension solids 3.7-9.6 mg/l). A deeper penetration of particles into the bed before capture leads to more even distribution and less overall increase in head loss [12].

In order to obtain an efficient design, it is normally suggested that designs permit unit filter run volumes between 200 and 400 cub.m/m^2. This corresponds to run lengths in between 16 and 33 hr at a filtration rate of 0.20 cub.m/(m^2/min) (about 12 m/h) [5].

Media size

Media size varies from about 0.4 to 2.5 mm (usually about 0.5 -1.0 mm [5]) and is graded in various layers (dual media or multi-media) or is size-graded continuously, as in up-flow filters [6].

As has been shown [8], increased media size (from 0.8 to 1.85 mm) allows using the entire bed for removal and reducing head loss, although greater depth is required for equivalent removal.

Filtration velocity also affects removal efficiency, bed depth use, and head loss - but to a lesser extent than media size. When filter media are small (0.8 mm), collection of particles occurs predominantly in the top of the filter bed; in the lower bed section, filter coefficients = $-\ln(C/C_0)/L$ are small and ripening is not significant. The presence of previously retained particles is essential for the ripening process and for the effective use of the full filter bed.

The thicknesses of the layers

The filter layers depth is normally about 0.6 to 1 m [6]. Operating systems generally fall into the ranges shown in Table [5].

Media Size and Depth Ranges for Operating Systems by [5]

Media	Depth, m
0.4-0.6 mm sand	0.25-0.30
1.0-1.2 mm sand	0.60-0.90
0.8-1.0 mm anthracite	0.50-0.60
1.4-1.6 mm sand or anthracite	0.75-0.90
1.6-1.8 mm sand or anthracite	0.90-1.10
2.0-2.4 mm sand or anthracite	1.25-1.50

Head-loss

Head loss for gravity filters is usually up to 2.5 m water gauge (2-4 m [5]) and pressure filters up to 7.5 m [6].

For full flock penetration into the bed with the no of cake filtration at the media surface, the head loss measurements showed linear increase with time (the data for aluminium sulphate and ferric chloride) [14].

Head loss development is more rapid for fine suspensions, but over the entire depth of the bed this effect is counteracted to a certain extent by more coarse suspensions leading the deposit distribution being more concentrated towards the top of the filter [15].

Using the head-loss curves from the top layer of the filter as a basis for prediction of head-loss throughout the filter may give inaccurate results. The (dh/dL) - sigma curves will very from layer to layer, and there is not necessarily a consistent progression from one layer to another, e.g. layer 1 may give a more rapid or a less rapid increase than layer 2, depending upon the operating conditions [15].

Filter runs between washes:

Filter runs between washes: normal are about 24 h; up to 100 h (where the water to be filtered does not contain a high organic load) but in sewage tertiary treatment filtration a daily washing is desirable to prevent anaerobic decomposition of the deposits retained in the filter pores [6].

Regeneration

When the energy required reaches the maximum available, the filter media have to be cleaned: reverse flow backwashing, assisted by air scouring or auxiliary wash jets [6].

The maximum hydrodynamic force occurs in the range of 0.6-0.7 porosity for expanded beds of sand normally used in filtration. This coincides with 40-50% bed expansion which is typical for backwash of 0.4-0.6 mm sand at a rate of 0.6 cub.m/(m^2min) [5].

Filter collector modification

Particle trajectory in unit cells of sinusoidal shape is computed for various initial values of the entrance position of the particle [16]. Calculated results for various cell orientations show that vertical pores are the least effective collectors. Horizontal unit cells may have filtration efficiency 2-3 times higher than vertical ones for the same flow rate. Thus, although horizontal and oblique flows of a suspension in a packed bed occur at lower rates than in the axial direction, the increased deposition rate in horizontal or oblique pores contributes significantly to the overall filtration rate. Numerical results agree with the experimental observation that deposition in oblique flow channels contributes substantially to the overall rate of deposition.

In further research it is found that substitution of even a few relatively large unit cells (weak collectors) into a network of otherwise uniformly sized unit cells increases the flow rate of lateral streams and leads to higher filter coefficients thanks tp high impact factors in transverse pores. Despite its computational involvement, the model developed here is capable of yielding valuable filter coefficient estimates which elucidate the critical role of pores that are not aligned with the average direction of flow. More specifically, it is shown in this work that use of non-uniform pore size may lead to substantially increased values of the initial filter coefficient thanks to the contribution of oblique pores to the overall deposition rate [17].

On the basis of the research published [16, 17] can be suggested for filter oblique position of packed bed which needs experimental investigation.

CONCLUSIONS

The problem of filtration application was discussed in the project report.

The aims of the project are to elaborate recommendations for filtration of treated wastewater on the basis of deep bed filtration achievements and analysis with generalization of some problems in solid-liquid filtration. Filtration is in the centre of attention here but it does not mean the filtration exclusiveness in comparison with other processes.

The wastewater treatment schemes are discussed. The following problems can arise when treating the waste:

(i) methods of treatment of liquid and solid phases of slurry are often contrary;

(ii) in certain cases during liquid treatment the solid phase presents a serious problem which can be caused by adsorption, catalysis, chemical reactions with reagents used for liquid treatment or due to fouling of equipment, etc.;

(iii) chemical treatment of solids (for example neutralization, precipitation, oxidation, etc.) demands a lot of chemical reagents, because in spite of possible small solid phase volume in the slurry, the solid phase particles can contain major part of hazardous materials. If in the liquid the contamination concentration is as a rule up to some percents then in the solid phase the hazardous contamination can reach up to 100% per all solid phases;

(iv) despite comparatively small solid volume in the total volume of the waste liquid, processes of solid separation and treatment are complicated and their cost reaches up to 40 - 50% of the total cost of hazardous waste liquid treatment as estimated by experts.

It is possible to apply the definition of flexibility to filtration because filtration in general presupposes preliminary slurry treatment and other operations. These operations are interconnected; the success of the operation that follows depends on all previous ones.

Filtration as a flexible process may be presented as follows:

1. Preliminary preparation and treatment of wastewater - slurry (concentrating, diluting, coagulating, classification, etc.). Automatic control of slurry parameters, adaptive system of quality control.
2. Optimum processes conditions. Combining of the operations. Supporting of the high productivity (influencing the process by outer factors of various nature, using filtering additive, etc.). Rational choice of technological equipment and coagulant. Filtration progress demands preliminary analysis of the production which is to use it.
3. Equipment and method modernization. New constructions and organization decisions. Computer control of processes.
4. Automatic control and regulation of filtration quality. Usage of universal and combined filters. Physicochemical ways of liquid and solid phases conditioning.
5. Regeneration and utilization of exhaust components and reagents. Closed technological cycle. Tightness. New coagulants and filtering materials of broadened functional possibilities.
6. Maximum automation on the basis of computer technology. Expert systems. Safety systems. Continuous education of workers and engineers.

Filtration demands preliminary analysis of the production which is to use it:

1). Determination of the production program; Characterization of the disperse system to be filtered and its volume; Qualitative and quantitative criteria of the process.

2). Technique of the filtration process or thickening (continuous, batch, equipment connection scheme, etc.); Organization of transport streams; Additional means; Type of filtering equipment.

3). Organization of information flows: registering the type of signals and the way they come to the operator's console, to the system of automatic information treatment; mentioning the form of information exchange with controlled objects.

4). Possibility of continuous process when some part of the equipment fails.

5). Optimum charge of equipment; Possibility to improve technologies.

In this paper the classification method will be improved and modified. The basis for filtering equipment classification here is space and time position of filtering elements (FEs) or filtering medium during the filtration process as well as during FEs regeneration.

According to the proposed classification scheme all filtering equipment may be divided into 2 main groups: 1) filters with fixed FEs during filtration and 2) filters with FEs which change their spatial position during filtration (filters with movable FEs).

The classification characteristic features have received a deeper gradation of filters constructions. The symmetric scheme of filters arranged in grades gives the possibility of designing new filters versions by synthesis of different sub-groups features. This scheme is convenient to use in expert systems and for elaboration of new constructions of filters.

Different types of filters which have similar sets of indications can be compared with each other with the help of the method, for instance, batch filters with fixed filter elements and batch filters with movable FEs, etc. So, we can ensure optimal filters construction selection.

The problem of the scheme application to similar classification of filtration processes calculation methods needs further investigation.

On the basis of the general principles of filtration analysis the analysis of different solid phase removal schemes for tertiary wastewaters with the concentration of solids about 10 mg/l was made. The tertiary wastewater volume treated per day is some cub. m.

The low concentration of solids and small particle size (about microns) make it necessary to use pre-treatment of liquid by coagulant or flocculant.

In comparison with the other schemes the contact filtration has the following disadvantages: compact scheme; continuous process control; flocks formation within the deep bed and good conditions for adsorption of the flocks in the filter; more even flock size distribution within the filter bed. So, the deep bed contact filtration is more preferable.

Recommendations of filtration conditions selection were made.

The following research is necessary in the future: To improve calculation methods of modelling slurry separation which forms compressible flocks or cake. To develop methods of process optimization based on general mathematical model of flock formation and its properties in separation processes.

REFERENCES

1. A. Yelshin. The Development of Filtering Equipment for Hazardous Materials.//Fluid/Particle Separation Journal. - 1992. - Vol. 5, No.3. - p. 126 - 129.

2. El'sin A.I. "Entwicklungstendenzen des filtrationsprozesses als flexible technologie und die bewertung der porosen medien aus der sicht der entropie", Mechanische Flussingkeitsabtrennung. Vortragstexten. 23. Deskussionstagung mit Internationaler Bet iligung (11-12 October 1988). Magdeburg, DDR, pp. 85-91, (1988).

3. A. Yelshin. "Filtration and filtering equipment development tendencies". Revue. Ser. XM-1. Chemical & Petrochemical Engineering. Moscow, TsINTICHIMNEFTEMASH (1992). 44 pp. (Russian).

4. A. Yelshin. New classification of filtering equipment // Filtration and Separation on Processes and the Environment. Proceedings of American Filtr. and Sep. Society National Meeting. 8-12 May, 1994. Chicago, IL, USA. - 1994. - Vol.8. - 5 pp.

5. Tertiary Filtration of Wastewaters. By the Task Committee on Design of Wastewater Filtration Facilities // J. of Environmental Engineering, Vol.112, No.6 (1986). pp. 1008 -1025.

6. K.J. Ives. Deep Bed Filtration. Solid-Liquid Separation. L. Svarovsky, Editor, 3rd ed. (1990) Butterworth & Co. Cambridge, UK p.358.

7. Boller M.A. Chemical Optimization of Tertiary Contact Filters// J. of Environmental Engineering. Vol. 110, No. 1 (1984), pp. 263-276.

8. S.C. Clark, D.F. Lawler, R.S. Cushing. "Contact Filtration: Particle Size and Ripening". Journal AWWA, December (1992), pp. 61-71.

9. Michalopoulou A.C., Burganos V.N., Payatakes A.C. Creeping Axisymmetric Flow Around a Solid Particle Near a Permeable Obstacle// AIChE Journal. Vol. 38, No. 8, (1992), pp. 1213-1228.

10. Moran M.C., Moran D.C., Cushing R.S., Lawler D.F. Particle Behavior in Deep-Bed Filtration: Part 2 -Particle Detachment// J.AWWA, Vol. 85, No. 12 (1993) pp. 82-93.

11. D.C. Moran, M.C. Moran, R.S. Cushing, D.F. Lawler. Particle Behavior in Deep-Bed Filtration: Part 1 - Ripening and Breakthrough.// J. AWWA, Vol. 85, No. 12 (1993) pp. 69-81.

12. J.L. Derby, D.F. Lawler, T.P. Wilshusen. Depth Filtration of Wastewater: Particle size and ripening// J. Water Pollut. Control Fed. (1991), Vol. 63, p. 228.

13. Babenkov E.D. Water purification by coagulants. Moscow, Nauka (1977). 356 pp.

14. J. Haarhoff, J.L. Cleasby. "Comparing Aluminium and Iron Coagulants for In-line Filtration of Cold Water". Journal AWWA, April (1988), p. 168-175.

15. R.I. Mackie, R. Bai. The Role of Particle Size Distribution in the Performance and Modelling of Filtration// Wat. Sci. Tech. Vol. 27, No. 10, pp. 19-34.

16. C.A. Paraskeva, V.N. Burganos, A.C. Payatakes. Three-Dimensional Trajectory Analysis of Particle Deposition in Constricted Tubes// Chem. Eng. Comm. (1991), Vol. 108, pp. 23-48.

17. V.N. Burganos, C.A. Paraskeva, A.C. Payatakes. Three-Dimensional Trajectory Analysis and Network Simulation of Deep Bed Filtration// J. Colloid and Interface Sci., (1992) Vol. 148, No. 1, pp. 167-181.

18. M.R. Collins, G.L. Amy, C.W. Bryant. Evaluation of Factors Affecting Performance of Direct Filtration//J. Environmental Engineering. Vol. 113, No. 2, (1987) pp. 330-344.