RW 1272.

Batch water purification: An option for small scale users

By Mr A Botha, B Eng (Hons) (Chem) Pretoria University; Division of Water Technology, CSIR.

Providing adequate drinking water of acceptable quality to small communities is a complex problem. A water purification system is described in terms of chemical engineering principles. The flocculation system and specifically the equivalent plug flow reactor is then evaluated to determine the stability of the system. This analysis indicated that this system is complex and may only be controllable in large purification plants. An analysis of a batch reactor indicated that this type of flocculation system results in a more stable and appropriate system for small scale water purification plants.

The control, operation and optimisation of water purification processes is complex and requires skilled operators. Small communities seldom have access to, or are able to afford, such skilled personnel. This leads to problems regarding the quality of water supplied by small water purification systems.

The objective of this discussion is to describe water purification in terms of chemical engineering principles and to derive a simple solution to enhance the ability of small communities to ensure adequate drinking water of an acceptable quality.

Chemical reactors

In order to optimise chemical reactions, special vessels or reactors, with specific flow patterns and designs are used.

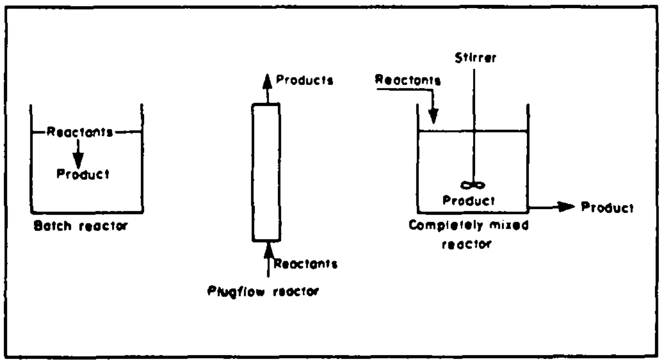

Figure 1: *Basic reactor types.*

The three basic types of reactors used in chemical reactions, shown in **Figure 1**, may be described as follows:

● Batch reactor

Usually this type of reactor is a tank fitted with a stirrer and heating element. This tank is filled with reactants, a reaction takes place and the product is removed when the reaction is complete. A batch reactor is one in which chemical and thermal changes occur with respect to time.

● Plug flow reactor

This type of reactor usually takes the form of a tube into which reactants are pumped from one end and the product removed from the other. Plug flow is a simplified picture of the motion of a fluid, where all the fluid elements move with a uniform velocity along parallel streamlines, with no back-mixing. All chemical and thermal changes may therefore be related to a length unit, parallel to the fluid flow direction.

● Perfectly mixed flow reactor

Usually this reactor is a tank fitted with a stirrer into which reactants are pumped continuously and the product drawn off continuously. This reactor type is the opposite extreme from the plug flow reactor and it is assumed that the concentration and temperature is uniform throughout the reactor. This implies that any fluid element entering the reactor must be completely mixed within an infinitely short period of time and all chemical and thermal changes take place immediately upon entering the reactor.

Water purification

The primary aim of water purification is the removal of

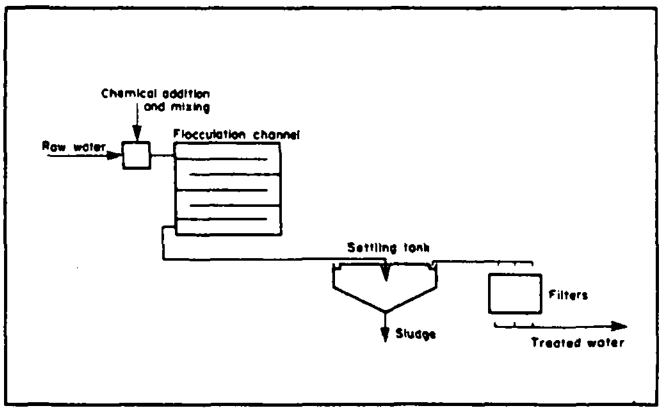

Figure 2: *Schematic outlay of a water purification plant.*

colloidal particles from the raw feed water. This is a relatively complex process, since the concentration of colloidal particles in surface waters vary considerably. Changes in flow rates or the disturbance of sediments affect the concentration of the colloidal particles and quality variations can be expected.

The basic purification of drinking water may be summarised as follows: raw water is treated with chemicals, flocculation takes place and the resultant flocs are removed by settling or flotation and/or filtration. A very basic configuration of a water treatment plant is illustrated in **Figure 2**.

In relation to a typical water purification plant, a typical chemical treatment plant is illustrated in **Figure 3**.

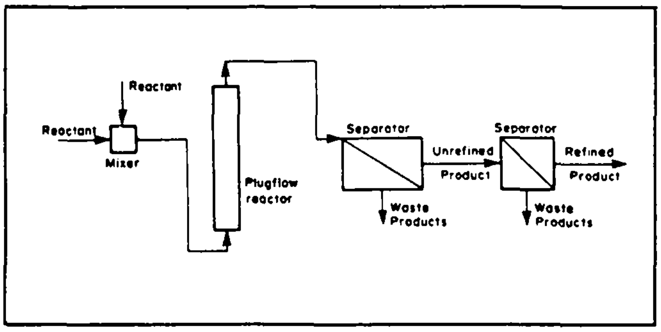

Figure 3: *Chemical equivalent of a water treatment plant.*

From Figures 2 and 3, it is clear that the settler, filter and separation processes are physical processes, where theoretically, no chemical reaction takes place. It is assumed that the only reactions that take place do so in the flocculation unit or the equivalent plugflow reactor. We will therefore concentrate on the flocculation unit and the equivalent chemical reactor.

Coagulation

One of the most important problems in water purification is the removal of colloidal matter which forms part of the impurities. Coagulation is a two-step process involving particle destabilisation, by means of coagulant addition, followed by particle transport to promote collisions between the destabilised particles to enhance aggregate formation. From a kinetic point of view, the sequence of aggregate formation proceeds as follows: the destabilised particles combine to form minute primary particles, which in turn coalesce into micro particles and finally the product — macro particles or particle aggregates.

Generally coagulation systems consist of the following units:-

- A rapid mix unit, to ensure homogeneous diffusion of reactants.
- A slow agitation unit to enhance floc formation.

In this paper, it will be assumed that the rapid mix unit is ideal and that all reactants enter the flocculation unit as a completely homogeneous mixture and floc formation takes place only in the flocculation unit. It is furthermore assumed that the formation of flocs may be described as a first order reaction with respect to the concentration of particles, the velocity gradient and the floc volume fraction.

Equivalent chemical system

In order to investigate the stability of the coagulation system, an equivalent chemical system will be used. The assumptions made in the previous section regarding the reaction order of floc formation will be applied to the equivalent chemical reactor.

In general, coagulation systems are built to achieve plug flow, with less emphasis on perfectly mixed systems. We will therefore use a plug flow reactor to describe a conventional flocculation system.

Equation 1 is the continuity equation of A over a plugflow reactor.

$$\frac{d(C_A/C_{AO})}{d(V/F_{AO})} = -R_A \quad \ldots\ldots\ldots\ldots 1$$

with R_{AO} ≡ molar feed rate of reactant A kmol/s (feed rate of colloidal particles/s)

R_A ≡ rate of reaction of component A per unit volume kmol/m³s (rate at which colloidal particles form flocs per unit volume)

V ≡ ractor volume m³

C_A ≡ concentration of component A (concentration of colloidal particles)

C_{AO} ≡ Concentration of component A in the feed stream (Concentration of colloidal particles in the feed stream)

The hypothetical definition of the symbols in the equivalent coagulation system is given in brackets.

In order to solve Equation 1, a rate equation is needed. The rate of reaction can often be described as expressed in Equation 2.

$$R_A = k_c C_A^a - C_B^b \quad \ldots\ldots\ldots\ldots 2$$

with k_C ≡ rate coefficient or rate constant

R_A ≡ rate of reaction i.e. conversion of reactant A

$C_A . C_B$ ≡ Molar concentration of component, footnotes A and B indicate which component (kmol/m³)

a, b ≡ powers indicating reaction order

This rate equation may be used to describe the following reaction:

A + B → P

Weber (1972) proposed Equation 3 as descriptive of the rate equation in the flocculation process.

$$\frac{dN_O}{dt} = -4\frac{a}{\pi} G \Omega N_O \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 3$$

with N_O ≡ total concentration of particle in suspension at time t

a collision efficiency factor, giving an indication of what fraction of the total number of collisions leads to aggregate formation

G ≡ velocity gradient s^{-1}

Ω ≡ volume of colloidal particles per unit volume of suspension.

This indicates that the reaction rate is first order with respect to the concentration of particles, the velocity gradient and the floc volume fraction i.e.

A → P

Stability analysis

By integrating equation 1 the following result is obtained:

$$\frac{V}{F_{AO}/C_{AO}} = -\int_{C_{AO}}^{C_A} \frac{dC_A}{R_A} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 4$$

Table 1: The effect of various factors on the flocculation process.

Factor	Effect
Flow rate	Design parameters may be exceeded with high flows. Flocs may not form or floc breakup may occur.
Colloid concentration	Flocculation may not take place due to lack of or excessive number of colloidal particles.
Velocity gradient	Flocs may not form or floc break may occur as energy requirements are not obtained or exceeded.
Chemical demand	Chemical dosages must be adjusted to changing raw water quality and flow.

This simplification is based on the fact that the reactor volume is constant while the molecular flow rate stays constant. In a dynamic system, changes in the flow rate will affect the residence time and therefore affect the completion of the reaction. Equation 4 will therefore not hold if F_{AO} is not constant.

The flow through a purification works is not a constant design feature, but rather a variable linked to consumer demand. This gives rise to large fluctuations in flow rates affecting the flocculation system severely. The reaction in this system is already dependent on three interrelated variables (N_o, G, Ω) as well as on chemical treatment before entering the system. The effect of various factors on the flocculation process is summarised in **Table 1**.

In large plants, with well trained operators and large flow rates, changing conditions tend to be handled with greater ease. As large reservoirs are used, it is possible to operate these plants very close to their design flow rates. Fluctuations in water quality are usually dampened by the large volume of water treated. For example: If the colloid concentration of $1 m^3$/unit time of water is to double, the effect on various plant sizes can be summarised in **Table 2**, using equation 5.

$$Z = \frac{e(Q-1)+2e}{Q}$$

$$= \frac{e(Q+1)}{Q} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 5$$

with Z ≡ average colloidal particle concentration kg/m^3

≡ normal colloidal particle concentration kg/m^3

≡ influent flow rate.

Table 2: Effect of colloidal concentration doubling in $1 m^3$ of water per unit time.

Plant size	Average colloidal particle concentration
$1 m^3$/hour ($24 m^3$/day)	2e
$10 m^3$/hour ($240 m^3$/day)	1,1e
$100 m^3$/hour (2.4 megalitre/day)	1,01e
$400 m^3$/hour (9,6 megalitre/day)	1,0025e

From Table 2 it is obvious that changes in water quality affect small purification systems very severely. Combating these quality fluctuations is very difficult in a continuous system, as chemical analysis to determine chemical dosages cannot be performed immediately. This introduces a time lag into the system. By the time the quality fluctuation has been identified and the chemical demand adapted, the fluctuation may be well into the system and the change in chemical dosage too late. This reduces the possibility of optimising chemical additions.

In short, an alternative solution to plug flow flocculation is needed for small users.

Batch reactor/flocculation system

As described earlier, the only chemical and thermal change in a batch reactor is with respect to time. The continuity equation for the entire reactor volume is given in equation 6.

$$\frac{d\,C_A}{d\,t} = -R_A \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 6$$

Which may be integrated to give equation 7:

$$t = -\int_{C_{AO}}^{C_A} \frac{d\,C_A}{R_A} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 7$$

with $t \equiv$ residence time.

Equation 3 may again be used to describe the reaction rate. In this instance we find that the number of variables is reduced. Following from the constant volume and controlled mechanical energy input, G is constant. Quality fluctuations still play a role. The effect thereof is more readily defined as follows: Chemical analysis (process control type) may be performed on each batch of water to be purified and chemical additions can be determined and optimised before the purification cycle is started. Irregular demand schedules may be met by frequent treatment cycles during peak demand and less frequent treatment cycles in low demand periods. The design capacity of a single reactor cannot be exceeded and a plant may be expanded, using modules.

Conclusions

- From this analysis it is possible to conclude that a batch flocculation system is a stable system with only water quality and chemical additions being the variables. These variables can however be determined so that additions can be optimised as part of the treatment cycle, with no time lag effect.
- Large treatment plants are more readily controlled as the variables have less effect on the total system and plug flow flocculation systems are adequate to ensure efficient flocculation.
- Small scale purification plants will benefit by the introduction of batch flocculation systems with improved process control capabilities.
- Better optimisation of chemical additives may be achieved by the introduction of batch flocculation systems to small scale treatment systems.

Closure

The philosophy proposed here should not be left unexploited. The Division of Water Technology, CSIR undertook extensive research to promote this idea. Reactor sizes, chemical addition (based on previous experience, Chlor-floc reagents were chosen), mixing time and energy and treatment cycle times were evaluated. These laboratory results were applied to a pilot scale plant, which subsequently led to the design of a full scale system. The resulting treatment system, also known as 'Watermaker' (registered trademark) is currently being commercially exploited.

References

BENEFIELD LD, JUDKINS JF Jr and WEAND BL. Process chemistry for water and wastewater treatment. Prentice Hall, Inc USA, 1982.

FROMENT GF and BISCHOFF KB. Chemical Reactor Analysis and Design. John Wiley and Sons, Inc, USA, 1979.

PERRY RH and GREEN DW. Perry's Chemical Engineers handbook. Sixth Edition McGraw-Hill, Inc. USA, 1984.

POLASEK P. 'The Significance of the Root Mean Square Velocity Gradient and its Calculation in Devices for Water Treatment'. Water SA, Vol 5, No4, October 1979.

WEBER, WJ Jnr, Physiochemical Processes for water quality control. John Wiley and Sons, USA, 1972.

Division of Water Technology (012) 841-2276