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Redefining the purpose, goals and methods of disinfection in contemporary water supply systems

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Abstract: This paper presents a new concept of disinfection traditionally applied in water treatment systems. The new definition of this process results from the change in its functionality, aims and methods, which guarantee high quality of water supply.

The literature review and technical practice demonstrate a demand for disinfection to act as a functional element of the integrated water distribution system and an active intermediate link between the technology of water treatment and the water distribution network.

The presented concept of a disinfection process enables evaluation of water treatment, increases its effectiveness in integrated water treatment systems. Such defined disinfection addresses water conservation and its biological stability within the water supply network.

The presented here new concept of disinfection assigns its new role and function in the integrated water distribution system. The controlling and diagnostic function of the disinfection defined in the paper provides a transparent and comprehensive method, with considerable application in experimental design, as well as practical solutions for integrated water distribution systems.

The origins of disinfection

Every technological process has its own tradition and history as well as characteristic factors and reasons that determine its origin and development. This in particular relates to disinfection – decontamination of water as a process of destruction and/or removal of pathogenic microbes and endospores with physical and chemical methods. Disinfection is henceforth the primary aim of water treatment while the biological (i.e. virological, bacteriological and parasitological) quality of drinking water is the main criterion of its usability.

Water treatment technology including disinfection originated in the 19th century in response to widely spreading "water-borne epidemics", i.e. the infectious diseases spreading via water courses and affecting the digestive system. The development of microbiology and epidemiology, especially the discoveries of Louis Pasteur and Robert Koch solved the problem of the "water-borne epidemics" through the development of prevention methods. Technological advancement of the water treatment methods, in particular the collection of sewage by means of the closed ducts system and its treatment with disinfection radically improved public health and eliminated water-borne diseases. This led to a change in urban wastewater management systems, marked by a permanent introduction of water treatment and sewage treatment plants (Fig. 1). In those complex water supplying systems (WSS) the water treatment plant technology provides the infrastructure that guarantees high quality of drinking water.

Chlorine played a major role in the development of disinfection methodology, which helped to eradicate waterborne diseases and significantly improved public health.

The important factors of chlorine application were as follows:

- Hypochlorous acid (HOCl) was a strong and durable germicidal agent, mainly reducing number of vegetative forms of harmful bacteria that affected the digestive system,
- foolproof structure of the vacuum chlorinator designed at that time,
- relatively low costs of chlorine.

The effectiveness of chlorine disinfection is a function of its dose and the contact time, as well as temperature, pH, physicochemical and microbiological content of the treated water.

The effective dose of chlorine Dos(Cl_2) for the removal of the most potentially harmful microorganisms (not all) associated with disease affecting the digestive system is presented by the following function (1):

$$Dos(Cl_2) = Dem(Cl_2\ 0.5h) + (0.1–0.3)\ mgCl_2/L \qquad (1)$$

Where: Dem(Cl_2 0.5h) is the total chlorine demand (mainly as HOCl) in all the chemical reactions of digestion in the first

thirty minutes after the introduction of chlorine to the water treatment system; the numerical variable (0.1–0.3) mgCl_2/L describes the residual free chlorine essential in the disinfection process.

Total chlorine demand indicates the physicochemical composition of water, and its value depends on:

- the degree to which the pathogens are protected by the contaminants against the disinfection by chlorine,
- the amount of disinfection by-products (DBPs).

The above function (Eq. 1) defines a method for estimating a dose of chlorine Dos(Cl_2) required in the disinfection and the measure of its effectiveness with regards to the removal of bacteria. The effectiveness of the water treatment is indicated by residual free chlorine of at least 0.1 mg/L after thirty minutes of the application.

An important achievement of disinfection technology is the development of drinking water quality control described by a number of bacteriological parameter limits for endospores of pathogens, including the presence of *Escherichia coli* as an indicator of contaminated water.

The new role of disinfection in the provision of safe drinking water

Drinking water safety (Huck and Coffey, 2003, Sozański and Huck 2007) is a term which:

- covers a whole set of problems related to public health risks resulting from life-long water consumption,
- stimulates readiness of the integrated water supply system for active prevention of disruptions leading to malfunction or inefficiency.

Drinking water safety control in the integrated water supply system (WSS) can be achieved through an assessment of the effects and characteristics of the disinfection process described as:

- the final and effective barrier for pathogens including microorganisms resistant to conventional methods of disinfection,
- the factor responsible for monitoring and diagnostics of the water treatment technology prior to disinfection,
- the agent affecting water conservation in the distribution system.

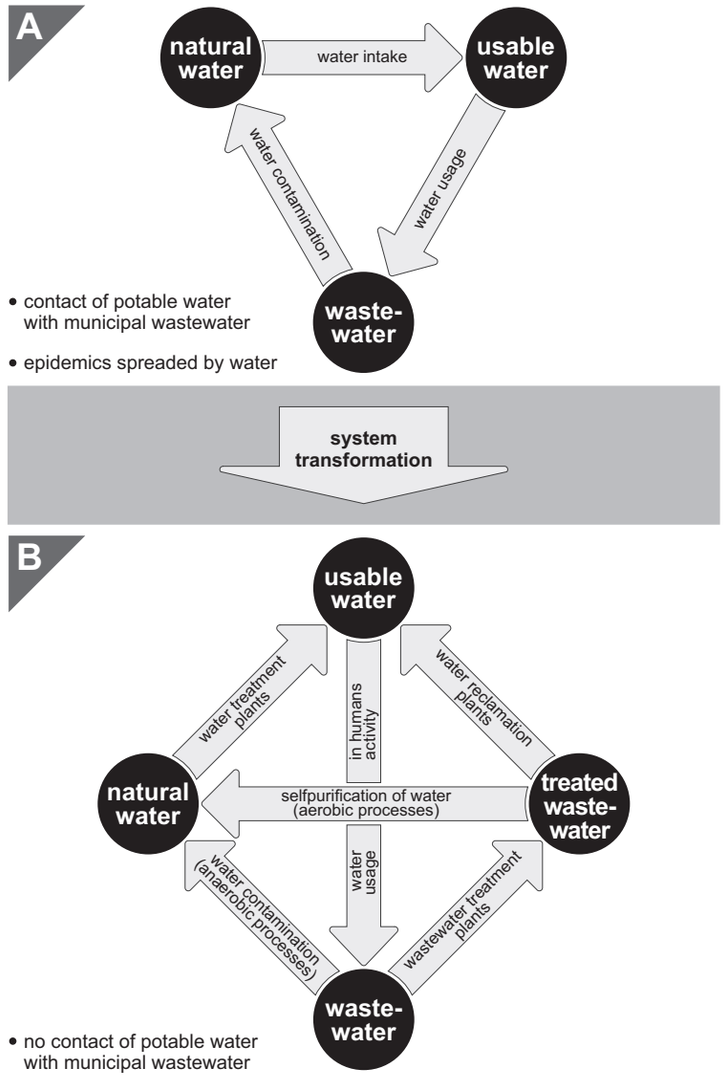


Fig. 1. Conceptual model of the water supply systems (A) prior to the development of water treatment technology and (B) in modern water supply systems

These three integrated and complementary aims of disinfection dictate its formative functionality as a link between water treatment and water distribution, responsible for monitoring and the diagnostics in the integrated WSS. In this framework, disinfection achieves the stable high quality of drinking water. Given current technology, it is still difficult to accomplish these three aims especially in the systems that incorporate treatment of the surface water (Pharand et al. 2015, Hamouda et al. 2016). These issues need to be addressed by pilot studies that could investigate a detailed design of water treatment technology, integrated with the aims of disinfection (Bellamy et al. 1998). The World Health Organization (WHO) recommends that a technological solution that fully integrates WSS and disinfection should be prioritized, as the microbiological contamination of water is considered the greatest health risk with rapid and widespread consequences (WHO 2000). In contrast, the chemical contamination of water (e.g. the cumulative toxic contamination with heavy metals) causes undesirable health problems in a much longer term and is therefore assigned a lower priority by WHO.

The effective disinfection eliminating microorganisms present in water cannot be achieved by disinfection as a stand-alone process as presented in the model of "terminal barrier", which assumes that disinfection acts as the final epidemiological and sanitary element independent from the other stages of water treatment. The limitations of this concept were identified in many cause-effect and experimental studies which suggest that:

- there is a great variety of microorganisms (viruses, bacteria, protozoa) in the surface water with a significant resistance to the disinfectants used in water treatment, e.g. intestinal viruses, bacteria spores and protozoan cysts (Banihashemi et al. 2015, Fortmann-Roe et al. 2015),
- it is currently impossible to effectively remove pathogens with an application of physical and chemical methods without forming undesirable disinfection by-products (Costet et al. 2011, Chuang and Tung 2014, Hua et al. 2015),
- the water distribution system is a large, specialized and not well inspected physico-chemical and biological hydraulic reactor with ideal conditions for the recontamination of water (Lipponen et al. 2004, Hoefel et al. 2005, Zhang et al. 2009, Scott et al. 2015).

The results of the studies demonstrate a demand for disinfection to act as a functional element of the integrated water distribution system and an active intermediate link between the technology of the water treatment and water distribution network. The new concept of the disinfection process assumes its controlling and diagnostic functions. This concept can be applied to aid evaluation of the water treatment process leading to increase its effectiveness and concerns water conservation and its biological stability in the water supply network. This model of disinfection with its monitoring functionality (Fig. 2) allows for the evaluation of expected disinfection effects, as well as adjustments during the operation of the water distribution system (decisions related to the operation of the water treatment plant and the maintenance of water network are based on the interpretation of the monitoring results).

The monitoring structure consists of four integrated monitoring loops with different range.

Individual monitoring loops include:

Loop 1:
– evaluation of disinfection (removal of microorganisms, formation of by-products),
– selection of the type and dose of disinfectant.

Loop 2:
– assessment of water treatment processes (removal of suspended solids and pathogens, decreasing turbidity and colour as well as TOC, DBP and their precursors) and disinfectant demand,
– intensification of treatment effects, especially regarding the above indicators.

Loop 3:
– sanitary and physicochemical evaluation of water in the network including taste, odor, oxygen content, heterotrophic bacteria, content of the remaining disinfectant, DBP, organic compounds,
– improvement of the method and parameters of water disinfection, water quality protection and methods of cleaning the network.

Loop 4:
– assessment and comparison of sanitary and physicochemical quality of water entering the network and retained in it depending on the retention time,
– intensification of biological methods of water treatment to increase biological stability of water, as well as network cleaning (as in the third monitoring loop).

More specific applications of disinfection monitoring include:

- the effects of rapid filtration with coagulation and/or membrane filtration in the removal of pathogens resistant to classic disinfection methods (Huck et al. 2002, Hartshorn et al. 2014, Bodzek et al., 2019),
- the effects of chemical oxidation and/or UV radiation in pathogen inactivation (using classic methods), including the evaluation of the disinfectant dose and the concentration of by-products formed in relation to the physicochemical composition of the disinfected water (Jachimowski and Nitkiewicz, 2019),
- the evaluation of the type, the concentration and the retention time of the residual disinfectant remaining in the water network, which is responsible for preserving the biological water quality,
- the evaluation of the actual biological stability of water defined by the loss of the potential for the microorganisms to revive in relation to the methods and frequency of water network cleaning.

The role of disinfection as a controlling and diagnostic process requires an intensive water treatment technology in the integrated "multiple barrier" treatment systems (Fig. 3). In these systems the final 3rd barrier of pathogen inactivation and water conservation is integrated with the previous two barriers: the 1st barrier responsible for the removal of fine particles and some microbial pathogens (Upton et al. 2017) and the 2nd barrier – the removal of the dissolved organic compounds (Kaleta et al. 2017). In the 3rd barrier the disinfection aims at preserving the biological quality of the water in the water distribution network with the method of residual disinfectant.

The concept of the multiple barrier water treatment technology aims at effective treatment even in the unstable conditions including a sudden increase in the physicochemical or biological contamination of raw water (Pharand et al. 2015, Hamouda et al. 2016).

This is only possible if the processes of the two main technological barriers are stable and highly effective (Fig. 3) identified by:

- the 1st barrier that removes particle pollutants (e.g. colloids) and microorganisms which are particularly resistant to the traditional methods of the disinfection,
- the 2nd barrier that decreases the content of the soluble organic compounds in the water responsible for the production of the toxic disinfection by-products and the development of biological processes in the water distribution network.

Turbidity is used as the effectiveness indicator of the 1st barrier due to the adsorption properties of the small particles that act as the carriers for micro-pollutants and microbial pathogens protecting them from disinfectants (LeChevallier et al. 1981, Lusardi and Consonery 1999). The 1st barrier guarantees the effective removal of the pathogens, including those resistant to the traditional methods of the disinfection, if the turbidity is reduced below 0.1 NTU (Hoff 1978, Qualls et al. 1983, Phillippi et al. 2005).

The evaluation of the 2nd barrier is more complex and requires determination of the changes in the values of the biodegradable organic matter (BOM) indicators (Kooij et al. 1982) including:

- the assimilable (by the micro-organisms) organic carbon (AOC),
- the biodegradable dissolved organic carbon (BDOC).

The effective results of the 2nd barrier are described by the BOM parameter limits of AOC ≤ 10µgC/L and BDOC ≤ 0.15 mgC/L. These limits are applied together with the residual disinfectant method (i.e. chlorine limit of 0.1–0.3 mgCl_2/L) which ensures the biological water stability in the network. In practice, it is difficult to achieve the technological effectiveness of the 2nd barrier by decreasing the concentration of the BOM parameters to the above limits.

In summary, the effective disinfection of the 3rd barrier is defined by a disinfectant – the chemical oxidant dose Dos(Ch.O.) in a method presented by equation (2).

$$\text{Dos(Ch.O.)} = \text{Dem(Ch.O.(Ret))} + \text{Dos(WC)} \qquad (2)$$

The oxidant dose Dos(Ch.O.) should be greater than the oxidant demand – Dem(Ch.O.(Ret)) in the pipeline during its retention time (Ret), the difference being the amount of the disinfectant remaining in the water and preserving its biological stability – Dos(WC).

The application of the residual disinfectant method in the biological water conservation is an alternative substitute of the real biological water stability, which is the principal goal in modern integrated water distribution systems.

Equation (2) may be used for monitoring the achievement of this goal during the operation of integrated water supply systems. In this multistage system with parallel processes

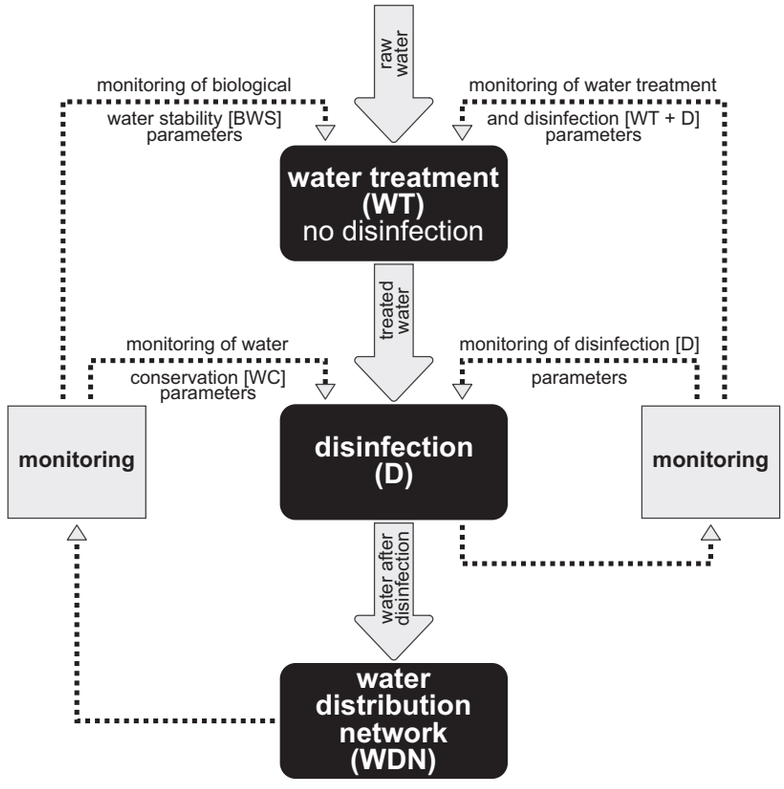


Fig. 2. Model of water treatment (WT) and the water distribution network (WDN) integrated with disinfection as an indirect link with comprehensive monitoring functionality

continuing over time, the following reduction targets have to be treated equally:

- Dem(Ch.O.(Ret)) by a decrease of the water retention time in the water network through its modernization (e.g. simplifying the structure of the network and minimizing the diameter of the pipes) and a more frequent cleaning of the network (e.g. the removal of biofilm from the pipes to reduce its metabolic activity);
- Dos(WC) as a result of an increased effectiveness of the 2nd and 3rd barriers (Fig.3) in relation to the microbiological or physicochemical pollutants e.g. AOC, BDOC, MAP (Hamouda et al. 2016).

The biological stability in the water network can be achieved through an application of the appropriate analytical method of its evaluation (e.g. AOC, BDOC) and by recognizing the causes and effects of interactions between the moment when water leaves the treatment plant and when the water becomes available in the distribution network (Banihashemi et al. 2015, Elhadidy et al. 2016). The distribution network can be considered as a large and specialized hydraulic-chemical and biochemical reactor with a long retention time. In the network there are zones of mixing and stagnation, and zones with oxidation and anaerobic conditions, which may strongly affect water quality. The incoming water is biologically and chemically stable, however its stability achieved by the treatment processes is under a considerable risk if it is present in the network for a long time. The internal surface of pipes is mostly covered by deposits (sediments), which create optimal conditions for heterogenic bio-catalysis of many reactions. One of these processes is the biodegradation, leading to destabilization of the system, that must be rebalanced to achieve biological water stability adapted to conditions in the network.

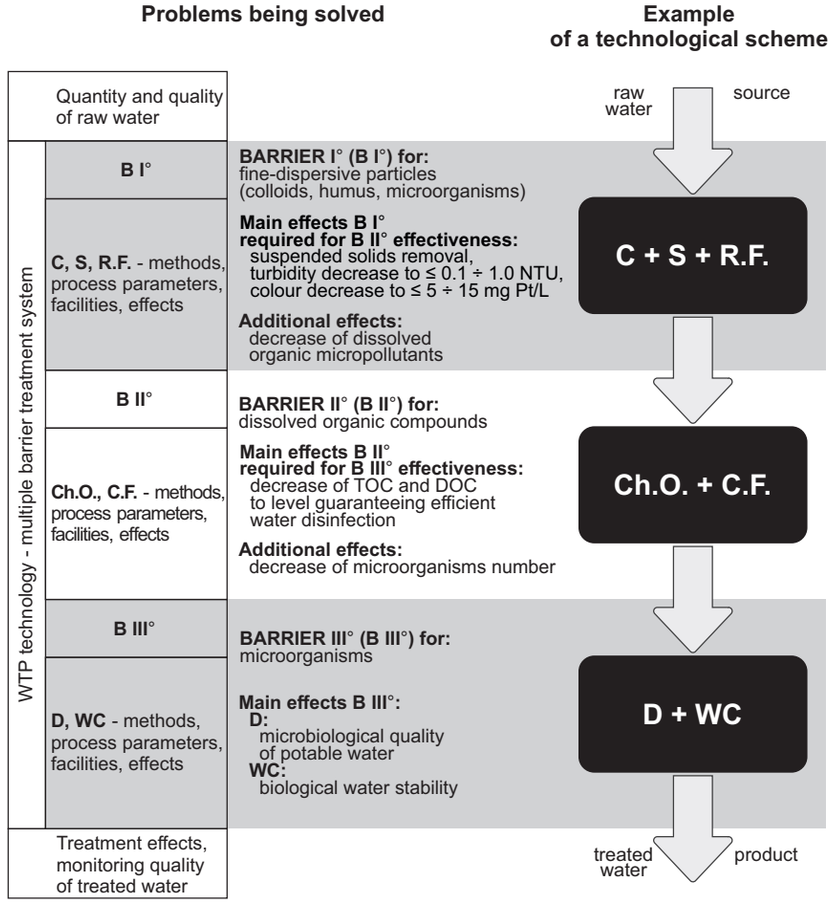
The vast water networks of the huge industrial and urban agglomerations need to be divided into zones with the application of the hydraulic networks model. Disinfection in those zones would follow the same rules.

The integrated solution of disinfection for water conservation and biological water stability need multistage pilot studies and technical experiments in considering the overall water supply system. The issues that need to be addressed include, in particular, the water treatment technology, its biological stability in the network and the hydraulic characteristic of the distribution system.

Design of the disinfection process – main aims of the research studies

The design of the disinfection process is a multistage mechanism dependent on:

- the state of knowledge,
- the results of the experimental studies,
- technological and economic interpretation of the results.



WTP - water treatment plant, **C** - coagulation, **S** - sedimentation, **R.F.** - rapid filtration, **Ch.O.** - chemical oxidation, **C.F.** - carbon filters, **D** - disinfection, **WC** - water conservation

Fig. 3. Multiple barrier concept of the water treatment system

There are three classes of disinfection methods according to the mechanism of pathogen removal:

- chemical oxidation through an introduction of a disinfectant, e.g. Cl_2, ClO_2, O_3, NH_2Cl and $NHCl_2$,
- photochemical UV radiation,
- separation techniques (e.g. coagulation with rapid filtration, membrane filtration).

In this classification the influence of thermodynamics is clear (distinct). The category of pathogen elimination through mechanical removal is the most effective group of disinfection methods in the above classification (Emelko 2001, Huck et al. 2001). The other methods of disinfection (i.e. chemical oxidation and UV radiation) can be limited by the potential conditions of the chemical processes, other chemical substances present in the water and the formation of the DBPs (Bellar et al. 1974, Rook 1974, Gunten and Pinkernell 2000, WHO 2000, Gumińska et al. 2010, Jachimowski and Nitkiewicz 2019). The best solution that guarantees water safety is based on integrated disinfection methods including all the three above categories (US EPA 1999, Dugan et al. 2001, Emelko 2001, Huck et al. 2001).

The key issues and aims of disinfection R&D are to determine:

- the required degree of pathogen inactivation during disinfection (described on the logarithmic scale) and by the processes preceding it (Hartshorn et al. 2014),
- the indicator microorganism for a chosen disinfection method, selected on the basis of the microbial resistance ranking and water quality,
- the effect of disinfection as a function of the concentration of the residual disinfectant (C) and the contact time (T) with a consideration of the structure and the hydraulic efficiency of the contact chamber, as well as the flow rate of the treated water (tracer method),
- the influence of the physicochemical and biological parameters of the water and their variability (e.g.: temperature, pH, turbidity, DOC) on the effects of disinfection (LeChevallier et al. 1981, Hartshorn et al. 2014).

Additionally, the experimental design of the chemical oxidation needs to address the following issues:

- the type of oxidant or oxidants, the dose, contact time and the points of application in the treatment train,
- the assessment of the type and concentration of the toxic DBPs depending on the type of disinfectant, the parameters of the processes involved and physico-chemical characteristics of the treated water (e.g.: temperature, pH, turbidity, DOC),
- the set of conditions for which the processes will not exceed the safe concentration limits of the DBPs.

The most important aspect of the design process of disinfection concerns the application of the UV radiation. This method of disinfection is considered to be very effective and complementary to chemical oxidation. Expected efficiency of UV pathogen inactivation (especially of the indicator organism) needs further investigation by pilot microbiological studies in the physical, chemical and biological conditions simulating the technical installation.

The scope of the research and its design relate to:

- the properties and the composition of admixtures and/or contaminants in the water prior to disinfection, in particular those affecting UV transmittance (turbidity, color, suspended solids, [Fe] and [Mn]),
- the radiation dose defined by the intensity and the time of radiation,
- characteristics of the disinfection process including the type of reactor and UV lamp, its distribution, and the water flow rate,
- the monitoring conditions described by the process parameters including the quality of treated water, the water flow rate, the radiation power and the results of the microbiological analysis before and after the disinfection,
- the disinfection by-products (type and concentration) as a function of the UV wavelength.

The assumed lack or minimal amount of by-products formed in UV-disinfection, should be the subject of a more complex research in the field of photochemistry (Włodyka-Bergier 2016). The photochemical transformations are the result of external electromagnetic radiation energy changing into chemical energy. Such transformations can occur when the disinfected water, depending on its physicochemical composition, is capable of absorbing the radiation. The interpretation of the photochemical reaction mechanism is possible due to the achievements of molecular spectroscopy and quantum chemistry.

In summary, the use of chlorine (Cl_2) in water treatment technology as the oxidizing disinfectant leads to both positive and negative effects. Its main attributes are versatility and effectiveness, which are decisive in its choice as the principal disinfectant. However, Cl_2 also leads to the production of harmful by-products of the oxidation which contain carcinogens and mutagens. This disadvantage limits Cl_2 application in the treatment of waste water and in the preliminary phase of the oxidation processes. The ambivalent nature of chlorine requires continuous water quality control at the intake and the distribution stages of the water supply system. It is however an undeniably important disinfectant of high quality treated surface water and underground water without organic content, e.g. humic acids.

Chlorine dioxide (ClO_2) and ozone (O_3) are very strong oxidizers applied in many water treatment systems as alternative or complementary disinfectants to chlorine, which leads to advantages and disadvantages. ClO_2 is a more effective disinfectant with a wider range of reactions, neutral in the presence of ammonia and not contributing to the production of highly toxic by-products of chlorine (e.g. trihalogenomethanes). ClO_2 is a more stable oxidizer than Cl_2 with a longer period as a residual disinfectant in the water distribution network. Nevertheless, its application as a disinfectant is limited to small doses (< 0.4 mg/L) due to the production of chlorites and chlorates, which are strong oxidizers considered as DBP formed during decomposition of the chlorine dioxide (Veschetti et al. 2005).

Ozone (O_3) is the chemical oxidant with the greatest potential in water treatment technology with additional application in other technological processes. This general functionality requires verification with experimental studies for specific local conditions of the water properties and characteristics. The chemical oxidation with O_3, in comparison with Cl_2 and ClO_2, produces a minimal amount of toxic

oxidation bi-products especially in the absence of bromides. On the other hand, O_3 is an unstable chemical compound that readily contributes to the production of biodegradable organic carbon (BDOC) and hence reduces the stability of high water quality. It is, therefore, necessary to introduce extra biological filtration in the final stage of water treatment with ozone.

The disinfecting properties of O_3 result from its molecular structure while H^+ radicals, which are produced during the chemical O_3 oxidation, have practically no influence on the effectiveness of the disinfection process. The O_3 disinfection, as in the case of Cl_2 and ClO_2, is most effective in direct contact with the endospores and viruses, but it decreases in contact with the microorganisms adsorbed by molecular colloids or in the biofilm structures of the corrosion residues (in the distribution network).

The most resistant to the disinfection processes, even with an application of ozone, are cyst, oocyst and protozoan spores.

The design of the disinfection process with chemical oxidation involves:

– two different approaches to the disinfection: (1) the complementary application of UV radiation with chemical oxidation regarded as the most effective method of disinfection, or (2) the applications of at least two different types of chemical oxidants with small doses repeated along the treatment network;
– the measure of efficiency of the disinfection described by an inactivation of at least 99% of the microorganisms, which is proportional to the concentration of the residual disinfectant and the contact time with the microorganisms in the treatment system (f = CT), and influenced by the conditions of water temperature, its reactivity and the hydraulic efficiency of the contact chamber;
– the effects of biodegradation in the water treatment and the biological stability of water (BSW), which are evaluated by the parameters of the biodegradable organic matter (BOM), e.g. AOC, BDOC and the microbiological available phosphorus (MAP). Their interpretation assumes that there are strong connections between: (1) the characteristics and biochemical properties of water, and (2) the activity of certain types of bacteria and comparative solutions of easily biodegradable compounds.

Valid evaluation of BSW depends not only on the appropriate methodology but also on an understanding of the interactions between the water characteristics and water quality between the water treatment plant and the water distribution network.

The general conclusions presented here highlight the complex problems of water treatment and water distribution in particular related to the effective method of residual disinfectant in the distribution network that would ensure the stable biological quality of water.

The conclusions

Disinfection is the principal and primary aim of the water treatment technology that ensures its high biological quality. It is a complex process with many requirements that are difficult to implement given the current state of knowledge. The new concept of disinfection presented here assigns its new role and function in the integrated water distribution system.

This approach to disinfection is presented here as a model, which:

- describes this process as the indirect link between the preceding processes of the water treatment and water distribution network with the features of a distinct hydro-biological reactor,
- extends its functionality to a process that ensures the removal of the most harmful, potentially pathogenic microorganisms and protects the treated water against its secondary contamination within the distribution network (water conservation).

The controlling and diagnostic function of the disinfection defined here provides a transparent and comprehensive method, with considerable application in experimental design, as well as practical solutions for integrated water distribution systems.

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