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Verification of Baffle Factor for Straight Pipe Flow

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Abstract

The baffle factor is a parameter widely used to describe flow system characteristics. This indicator is very important in designing disinfection devices. For example, it is used to convert the plug flow time to the actual fluid residence time in the flow system of interest. Its accurate determination is a complex problem requiring tracer experiments or computational fluid dynamics simulations. Therefore, in practice, it is often taken from tables provided in the literature. The literature sources, however, state that the baffle factor for a flow in a straight pipe is equal to unity, which implies the identity between the pipe flow model and the plug flow model. This assumption is doubtful. The aim of the present work is to verify the baffle factor values assumed for the pipe flow. The merit of this study is the analytical derivation of the expression describing the baffle factor value with respect to flow characteristics. To this purpose, the analytical solution of a one-dimensional advection-diffusion equation with a Heaviside initial condition was used. It was demonstrated that the aforementioned assumption is wrong, as the baffle factor for a straight pipe is significantly less than unity.

Key words: disinfection chamber, baffle factor, pipe flow

List of symbols

A – parameter characterizing the pipe;
BF – baffle factor;
c – dissolved substance or tracer concentration;
c_t – tracer concentration at time t;
c_0 – initial concentration of the tracer;
C_d – disinfectant concentration;
D_L – longitudinal dispersion coefficient;
ML – Morrill's index;
L – pipe length;
Q – flow discharge;
R – hydraulic radius;
t – time;

t_{10}	–	time after which 10% of the total tracer concentration c_0 reaches the outflow cross-section;
t_{90}	–	time after which 90% of the total tracer concentration c_0 reaches the outflow cross-section;
t_c	–	disinfectant contact time;
t_L	–	leading-edge arrival time;
t_{PF}	–	plug flow time;
t_T	–	trailing-edge arrival time;
T_{10}	–	auxiliary variable denoting the t_{10}/t_{PF} quantity;
T_{90}	–	auxiliary variable denoting the t_{10}/t_{PF} quantity;
T_t	–	auxiliary variable denoting the t/t_{PF} quantity;
V	–	reactor volume;
x	–	spatial variable;
α	–	arbitrarily chosen fraction $a \in [0; 1]$;
λ	–	Nikuradse's coefficient;
v	–	average flow velocity;
v^*	–	dynamic flow velocity.

1. Introduction

The efficiency of microorganism inactivation depends on the concentration C_d of the disinfectant and the time t_c during which microorganisms are exposed to that disinfectant. It is reasonable and theoretically justified to use the product of the two aforementioned quantities as a basic indicator of the effectiveness of the disinfection process. This quantity is usually denoted with the symbol Ct (Colorado Dept. 2014, U.S. EPA. 1989). The exact time of microorganism-disinfectant contact can be determined only in two cases. The first case is the batch reactor, in which the contact time is controlled by the device operator. The second case is the plug flow reactor, in which the contact time is equal to the product of the reactor volume V and the fluid flow discharge Q:

$$t_c = t_{PF} = \frac{V}{Q}. \tag{1}$$

It should be emphasized, however, that the plug flow is an idealized model that does not include the dispersion effect, which is always present in real flow phenomena, and affects them. As a result, the real time during which a mass remains in the system varies within a certain range between the leading-edge arrival time t_L and the trailing-edge arrival time t_T (Fig. 1) (Rehmann 2015). It is described by the well-known residence time distribution (RTD) curve.

The RTD curve can be determined by computational fluid dynamics (CFD) simulations or by experiments (using tracer methods). Such analyses can be performed at different levels of detail and accuracy and can include different factors influencing the course of the process considered (Paccione et al 2016). However, regardless of the

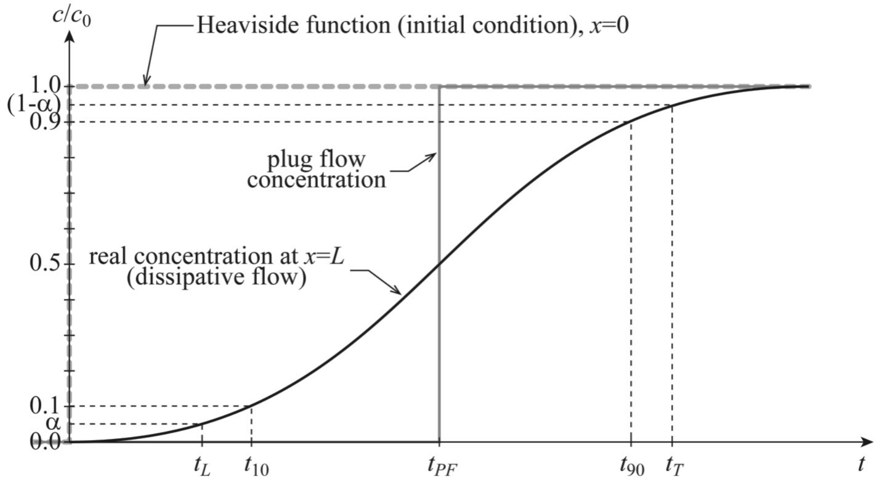

Fig. 1. Presentation of characteristic times of dissolved mass transfer (α – arbitrarily chosen fraction, $\alpha \ll 1$)

form and aim of the study, whether a scientific publication, technical report or device blueprint, the objective should always be kept in mind, and the outcomes should be presented in such a way as to make them verifiable by other researchers. An example of a publication in which, in the authors' opinion, data presentation is improper is the one by Wilson and Venayagamoorthy (2010). Its authors presented the outcomes of CFD simulations and compared them with measurements of hydraulic efficiency in selected disinfectant systems: pipe loop, pressurized tank system and baffled tank system. They obtained an outstanding agreement between the simulations and measurements. However, the publication provides no information necessary to reproduce the experiments described. This applies especially to the transport coefficients and the methodology of tracer concentration measurement that they used.

The abovementioned ways of determining the efficiency of disinfection do not diminish the usefulness of the Ct indicator. To make it useful in real case scenarios without the necessity of performing arduous computations or measurements, a methodology was proposed for conversion of the technical detention time (TDT) (which in practice coincides with the plug flow time) to a reliable contact time t_c. The conversion is done by means of the baffle factor (BF), also denoted as the short-circuiting factor (U.S. EPA. 1991):

$$BF = \frac{t_{10}}{t_{PF}}. \tag{2}$$

In Eq. (2), t_{10} denotes the time after which 10‰ of the total tracer concentration c_0 reaches the outflow cross-section during the step experiment. In such an experiment, the concentration value changes abruptly from 0 to c_0 (Fig. 1). In the reactor design process, the following relation can be used:

$$Ct = C_d \cdot t_c = C_d \cdot BF \cdot t_{PF}. \quad (3)$$

The BF value can be estimated individually for each object considered or can be taken from an appropriate table, such as Table 1. (Colorado Dept. 2014).

Table 1. Baffling factors

Baffling condition	Baffling factor	Baffling description
Unbaffled (mixed flow)	0.1	None, agitated basin, very low length to width ratio, high inlet and outlet velocities
Poor	0.3	Single or multiple unbaffled inlets and outlets, no intra-basin baffles
Average	0.5	Baffled inlet or outlet with some intra-basin baffles
Superior	0.7	Perforated inlet baffle, serpentine or perforated intra-basin baffles, outlet weir or perforated launders
Perfect (plug flow)	1.0	Very high length to width ratio (pipeline flow, perforated inlet, outlet, and intra-basin baffles)

Apart from disinfection device design, the BF concept can also be used as an indicator that characterizes flow conditions in the system considered. As can be noticed in Table 1, its value varies from 0 (which denotes the fully mixed flow) up to 1 (which denotes the perfect plug flow).

A quantity related to the baffle factor is the reciprocal of the Morrill dispersion index (Masschelein 1992):

$$MR = \frac{t_{90}}{t_{10}}, \quad (4)$$

in which t_{90} denotes the time after which 90% of the initial tracer concentration reaches the outflow cross-section.

Generally, the concept of the baffle factor (as well as the Morill index) as a quantity indicating the mixing intensity of the flowing liquid should be approved. It is a formally simple quantity, which can be estimated at different levels of detail, from very accurate to less accurate, using simplified methods, such as tables.

However, the assumption that BF for straight conduits is equal to one is doubtful. The aim of the present study is to verify this assumption on the basis of available information about this kind of flow.

2. Methods

Temporal and spatial variability of the conservative tracer concentration $c(x,t)$ in a simple circular conduit can be described by a one-dimensional mathematical model.

Such a model includes advection and longitudinal dispersion and is expressed by the following equation of one-dimensional advection-diffusion (Rutherford 1994):

$$\frac{\partial c}{\partial t} + v\frac{\partial c}{\partial x} = D_L \frac{\partial^2 c}{\partial x^2}, \tag{5}$$

where t denotes time, x is a spatial coordinate, and D_L is a longitudinal dispersion coefficient, which, in the case of a circular pipe, can be expressed by the classical Taylor's formula (Taylor 1954):

$$D_L = 10.06 \cdot R \cdot v^* = 3.56 \cdot R \cdot \sqrt{\lambda} \cdot v, \tag{6}$$

where R is the pipe radius, λ is Nikuradse's coefficient, and v is the average flow velocity.

In tracer experiments, by definition, a Heaviside step function should be taken as an initial condition (Fig. 1). Assuming that the point at which the tracer was introduced is $x_0 = 0$, Eq. (5) has an analytical solution (Chapra 1994):

$$c(x,t) = \frac{1}{2}c_0 \left[\operatorname{erfc}\left(\frac{x - v \cdot t}{2\sqrt{D_L \cdot t}}\right) + \exp\left(\frac{v \cdot x}{D_L}\right) \cdot \operatorname{erfc}\left(\frac{x + v \cdot t}{2\sqrt{D_L \cdot t}}\right)\right], \tag{7}$$

in which c_0 is the initial concentration.

In order to determine the characteristic times t_{10} and t_{90} from Eq. (7), simple rearrangements including Eq. (6) have to be done.

In order to simplify the notations, let us introduce the symbol T_t, which for $t = t_{10}$ takes the following value:

$$T_t(t = t_{10}) = T_{10} = BF = \frac{t_{10}}{t_{PF}}, \tag{8}$$

whereas for $t = t_{90}$:

$$T_t(t = t_{90}) = T_{90} = \frac{t_{90}}{t_{PF}}. \tag{9}$$

Noting that the ratio of the length of the conduit L to the average flow velocity v is equal to the plug flow time:

$$\frac{L}{v} = t_{PF} \tag{10}$$

and making simple rearrangements of Eq. (7), the following expression is obtained:

$$\begin{aligned} &\operatorname{erfc}\left(\sqrt{\frac{0.07A}{T_t}} - \sqrt{0.07A \cdot T_t}\right) + \\ &+ \exp(0.28A) \cdot \operatorname{erfc}\left(\sqrt{\frac{0.07A}{T_t}} + \sqrt{0.07A \cdot T_t}\right) = 2\frac{c_t}{c_0}, \end{aligned} \tag{11}$$

where c_t is a tracer concentration at time t, and A denotes the parameter characterizing the pipe

$$A = \frac{L}{R\sqrt{\lambda}}. \tag{12}$$

If $t = t_{10}$, then

$$\frac{c_t}{c_0} = 0.1, \tag{13}$$

and if $t = t_{90}$, then

$$\frac{c_t}{c_0} = 0.9. \tag{14}$$

The solution of the tracer advection-diffusion equation with an initial condition in the form of a Heaviside function (Fig. 1) rearranged to the form of Eq. (11) makes it possible to determine the baffle factor (Eqs. (8) and (13)) or the Morrill index on the basis of Eqs. (4), (8), (9) and (14):

$$MR = \frac{T_{90}}{T_{10}} = \frac{T_{90}}{BF}. \tag{15}$$

A relationship in the form of Eq. (11) is inconvenient for qualitative analysis, and therefore its simplified version can be used:

$$\operatorname{erfc}\left(\sqrt{\frac{0.07A}{T_t}} - \sqrt{0.07A \cdot T_t}\right) = 2\frac{c_t}{c_0}, \tag{16}$$

as it can be shown that the product of the exponential and the erfc functions in Eq. (11) is insignificantly small (Masschelein 1992).

3. Results and Discussion

3.1. Straight Conduit

The baffle factor for a circular pipe as a function of the system characteristics $BF(A)$ can be determined from Eq. (11) or Eq. (16) only by numerical methods for solution of non-linear algebraic equations.

The outcomes of the computations are displayed in Fig. 2, where two plots of the function $BF(A)$ are shown. One is determined using the full expression (Eq. (11)), whereas the other is determined from the simplified expression (Eq. (16)). As expected, the differences between those two expressions produce outcomes insignificantly different from a practical viewpoint.

Analysis of the functions displayed in Fig. 2 confirms the previously expressed doubt about the assumption, made in technical recommendations (f.e. Table 1), that the flow in a straight pipe is a plug flow, which implies $BF = 1$. The plot (Fig. 2) clearly shows that in such a pipe $BF < 1$, even if the pipe is very long (by the standards of disinfection devices). Analysing the maximal value $A = 500$ presented in Fig. 2

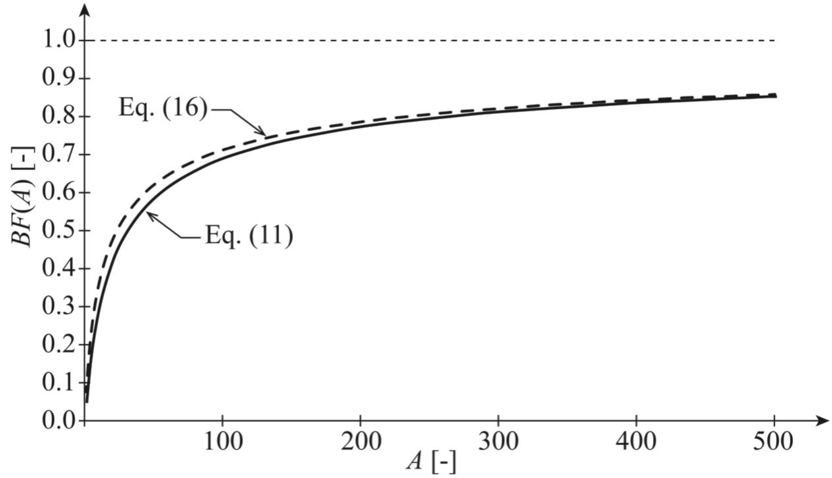

Fig. 2. Baffle factor versus the geometrical parameter A given by Eq. (12) estimated for straight pipe flow

(when BF hardly reaches 0.85), we find (Eq. 12) that it can be obtained for $R = 0.05$ m (which is a relatively low value, compared to typical dimensions of UV lamps) and $\lambda = 0.02$ (smooth walls), for a pipe length $L = 3.5$ m. It is much greater than the length of a typical UV lamp (which amounts to about 1.0 m).

To complement the analysis, the reciprocal of the Morrill dispersion index was also determined (Eq. (4)). The function was calculated using Eqs. (8) and (9), where T_{90} was the solution of Eq. (11) with a condition given by Eq. (13). Finally:

$$\frac{1}{MR} = \frac{t_{10}}{t_{90}} = \frac{BF}{T_{90}}. \tag{17}$$

The variability of this function (Eq. (17)) with respect to the parameter A is displayed in Fig. 3. As can be noticed, this indicator, analogous to BF, is significantly smaller than unity. Moreover, it increases more slowly than BF, which is a consequence of its formal definition ($t_{90} > t_{PF}$).

3.2. Alternating Direction Conduit

It is interesting that when a conduit of a constant cross-sectional shape changes direction (also multiple times, as in a pipe loop conduit type), the baffle factor value for such a system increases. Empirical and numerical experiments presented by Wilson and Venayagamoorthy (2010) indicate that, for example, for

$$Q = 0.000505\ \mathrm{m^3/s}, \quad BF = 0.93, \quad \frac{t_{10}}{t_{90}} = 0.82;$$

$$Q = 0.001093\ \mathrm{m^3/s}, \quad BF = 0.91, \quad \frac{t_{10}}{t_{90}} = 0.79.$$

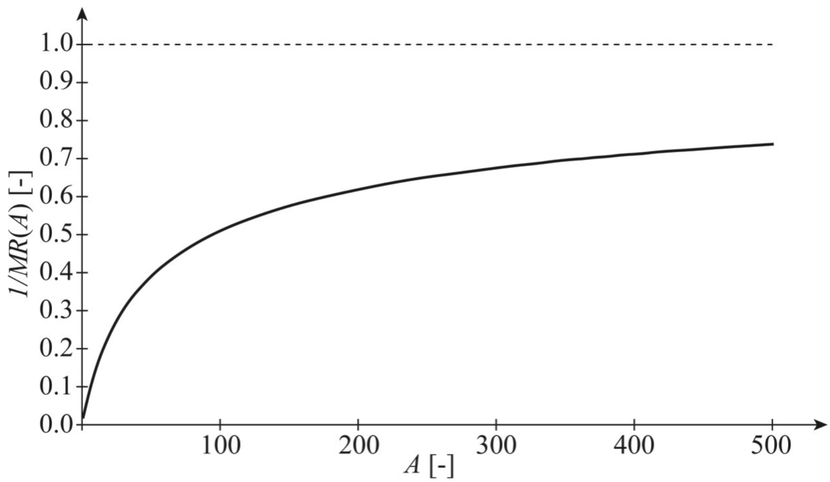

Fig. 3. Reciprocal of the Morrill index against the parameter A for straight pipe flow

This means that the curvature of conduits makes flow conditions closer to the plug flow when compared to the straight conduit. This fact can be explained by the influence of the pipe curvature on the dispersion of the dissolved substance in the flowing medium (Fukukoka and Sayre 1973, Rutherford 1994). It turns out that the change in the flow direction increases transversal dispersion and, at the same time, decreases flow profile variability, which weakens longitudinal dispersion. As a result, the flow becomes more similar to the plug flow.

The same relationship was observed in baffled tank system experiments (Wilson and Venayagamoorthy 2010). With the increasing number of baffles (according to the schematic diagram in Fig. 4.), the *BF* value rises as well, from 0.3 for one baffle up to 0.88 for 10 baffles.

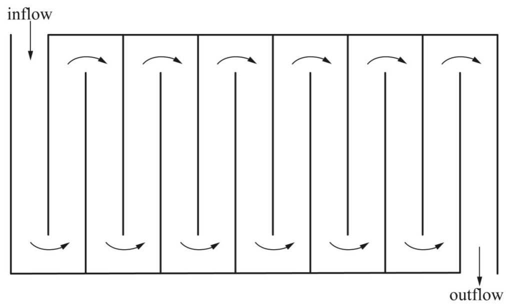

Fig. 4. Schematic diagram of a baffled tank

In view of the above observations, this is not surprising, as with the increasing number of baffles, the baffled tank becomes more similar to a pipe loop. It confirms the well-known principle that alternations in flow direction intensify mixing.

4. Summary

The baffle factor is a convenient technical parameter describing the flow characteristics of a flow system. Specifically, it can be used to convert the plug flow time to the actual time of fluid residence in a disinfection tank (Eq. (3)).

Baffle factor values can be determined empirically or numerically for certain objects of interest. However, this approach is time-consuming and often problematic. Therefore, in practice (at least when approximate values are sufficient), it can be estimated from the literature (Table 1).

What should be highlighted is the fact that, according to the literature, the value of BF for flow in straight pipes is equal to one, which coincides with the plug flow. It is obvious, however, that dispersion in such conduits influences the flow process, making the BF value smaller than one.

The actual value of BF was determined using a one-dimensional advection--diffusion equation (Eq. (5)). The solution has the form given by Eq. (11). This relationship, or alternatively its simplified version (Eq. (16)), makes it possible to determine the BF value for pipes.

The present study also emphasizes that the BF value for straight pipes is smaller than it is for pipes with alternating flow direction.

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