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Influence of the hydrodynamic efforts on the efficiency of the regeneration of the granular filtering material in a water treatment plant

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ABSTRACT

This article aims to study the hydrodynamic conditions of the parameters that influence the removal of dirt particles and aggregates by the drainage of wash water into filter materials for better regeneration efficiency. The water treatment plant with a nominal capacity of 600 $m^3 \cdot h^{-1}$ is located in the city of Parakou in Benin. It appears that one of the causes of the poor performance of the methods used for water treatment is the insufficient value of the shear stresses of the movement created by the flow of washing water in the filter bed. The use of hydro-elevators and hydrocyclones for the removal of particles from the surface of the grains of the filtering material under hydraulic load makes it possible to reduce the quantity of remaining pollution respectively by 1.5 to 2.5 times compared with the combined washing of water and air. To this end, the performance of grain washing in the hydrocyclone is explained by the presence of centrifugal field, self-separation and the friction of the particles between themselves and on the wall of the apparatus. The regeneration of the filter material under the action of ultrasonic waves reduces the remainder of particles compared to washing with water and air about 6 times.

Key words: granular filter, regeneration, wash water, water treatment plant, yield

HIGHLIGHTS

- Study of the hydrodynamic conditions for dirt particles and aggregates removal.
- Regeneration efficiency of the granular filtering material.
- Calculation of the value of the shear stresses of the movement created by the flow of washing water in the filter bed.
- Regeneration of the filter material under the action of ultrasonic waves.

1. INTRODUCTION

Granular filtration is a treatment process that appears to be relatively simple but in reality is quite complex and has been the subject of much research in order to model and better understand the principles for describing the performance of filter media (Cescon & Jiang 2020; De Sanctis *et al.* 2020). Granular filters operating with a type of flow must be washed with the appropriate methods, the best known of which are the use of a water jet on the surface, washing in air before washing with water and finally simultaneous injection of air and water, both against the current. The use of a surface water jet consists of a periodic reversal of the flow, the filtration is stopped and the permeate compartment is put under pressure and the produced water passes back through the filter but in the opposite direction to the filtration to take off the cake formed during the filtration phase (Köpping *et al.* 2020). This must then be carried away from the filter by the flow created. The purpose of this technique is to maintain an acceptable average performance over time for the user. The efficiency of this process is linked to many parameters such as the backwash pressure and flow rate, the duration of the various steps that make up the backwashing procedure, and the surface speed of the water in the filter media. It is interesting to note that, although used in the vast majority of drinking water production plants, published studies concerning the optimization of the backwashing process are relatively rare. However, it has been shown that the efficiency of a

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backwashing procedure is intimately linked to the structure of the deposit created during the filtration phase (Cui *et al.* 2020; De Souza *et al.* 2021).

Many studies show that the effectiveness of a backwash when filtering natural water depends on the extent of adsorption clogging that is created during the filtration cycle preceding it. It is thus observed that an increase in the filtration pressure or in the duration of the filtration cycle can lead to a decrease in the efficiency of the backwashing because they both lead to the formation of clogging by adsorption (Crozes *et al.* 1997; Hong *et al.* 2005a, 2005b). This is why, with the same overall consumption of backwashing water, it is generally advisable to favor short but frequent backwashes, thus reducing the duration of the filtration cycles compared to longer but less frequent backwashes. This not only reduces the extent of the adsorption clogging created but also limits the pressure rise during the filtration cycle (Nakatsuka *et al.* 1996; Decarolis *et al.* 2001; Chen *et al.* 2003; Hong *et al.* 2005a, 2005b). The effective pressure difference between the backwashing pressure and the filtration pressure is indeed another major parameter for the efficiency of the backwashing: the backwashing pressure must therefore not be lower than that of filtration (Xu *et al.* 1995; Gamage *et al.* 2021; Tang *et al.* 2021) and a minimum pressure of 1.5 bars is necessary to be able to remove the deposit during filtration at 0.5 bar of natural water (Cabassud *et al.* 1997).

Drinking water production plants make extensive use of this filter bed cleaning process: their operation therefore consists of a succession of filtration phases and backwashing phases. But backwashing is a process that consumes a lot of clean water produced. This consumption, which can reach 30% of the permeate produced during filtration (about 33% for the Parakou water plant), represents a loss for the process. Likewise, although very short (30 s to 2 min), the time necessary for the backwashing of the filter media corresponds to a period of non-production. Thus, backwashing reduces the productivity of the installation through the water losses they generate.

The studies dealing with the use of air as a curative process; that is, to remove an already formed deposit, are much less numerous than those dealing with its use as a preventive process. In fact, air has long been used to improve the efficiency of the washing phases of sand filters (Degrémont 2012). It can be seen that different air injection modes have been studied: with circulation of raw water (Laborie 1998; Mougenot & Al-Shakhis 1999; Richter *et al.* 1999) or with counter-current of permeate (Laborie 1998). During each study, the effectiveness of the air-assisted backwashing procedure was evaluated by different criteria, which can be classified into two groups: backwash water was collected either to assess the total amount of particles removed during backwashing, by carrying out a material balance between the filtration step and the backwashing step, or to evaluate the kinetics of particle elimination. In this case, the turbidity of the backwashing water is measured at regular time intervals throughout the procedure (Mougenot & Al-Shakhis 1999). The influence of the backwashing procedure on two overall process operating criteria, namely water loss (Laborie 1998) and net product flow (Laborie 1998) was evaluated. As a result, it is not necessary for the air + water phases to be long (>20 s) if there is then a sufficiently long water-only backwashing phase. During the study of a backwashing consisting first of a circulation of raw water with air then a simple backwashing with water, Mougenot & Al-Shakhis (1999) notes that the effectiveness of this backwashing procedure assisted by the air is independent of the duration of the water circulation phase with the air.

Particle elimination kinetics studies during this phase indeed reveal that a peak of turbidity in the backwashing waters is obtained around 5 s and that the turbidity of these waters after 20 s is very low. Thus, it is not necessary to operate with long air + water phases if the next water backwash phase is long enough. In addition, the peak height increases with air speed, confirming the previous finding that particle removal increases with air speed. The air injection also seems to have an influence on the filtration cycle by allowing a reduction in the rate of clogging or by extending the duration of the filtration cycles compared to a conventional backwash. Most of the backwashing parameters are not optimized: water injection conditions (flow rate, pressure, duration), air (surface speed, duration) and backwashing sequence. This work only provides a global view of the air-assisted backwashing process, while an understanding of the physical phenomena remains fundamental in order to explain the influence of certain operating parameters on the efficiency of the process. Many aspects of this backwashing process therefore remain to be studied, both from the point of view of understanding the phenomena of unclogging by air-water flows, and from the evaluation of the performance of this type of backwashing under conditions. close to real drinking water production conditions. However, these washing methods and sequences have been studied and are considered to be inefficient and therefore affect the regeneration of the filter material, when the filter is very dirty or when there are aggregates of dirt. Indeed, inadequate regeneration can greatly affect process performance and significantly reduce filter bed life (Erika 2013; Yu *et al.* 2018; Saleh 2020; Yin *et al.* 2021). This is the case for the Banikanni water treatment plant in the town of Parakou in northern Benin, which supported this work. It is therefore a question of analyzing the dynamics of the washing water through the filter material to assess the performance of washing and regeneration. In addition, it being understood that water reuse and sustainability are a topical issue (Nazari *et al.* 2012), the objective of this study is therefore to analyze the dynamics of the washing water through the filter material to assess the performance of washing and regeneration.

2. MATERIALS AND METHODS

2.1. Model of filtration in granular media

The principle behind filtration is to use a granular medium through which water circulates and helps retain suspended matter. The possibility of using these filters for water treatment is often limited by the low regeneration efficiency of the filter bed. The dirt retained by the filter material forms deposits, the structure of which depends on the properties of the dirt aggregates, the flow of water through the filter material, the geometry of the filter bed and the surface properties of the grains of materials (Erika 2013). When the suspension is fairly heavily loaded with solids, it is brought above the support on which the particles will be deposited in the form of a cake or cake of increasing thickness. An experiment was carried out on the Parakou water treatment plant, which is designed for a capacity of 600 $m^3 h^{-1}$ (Figure 1).

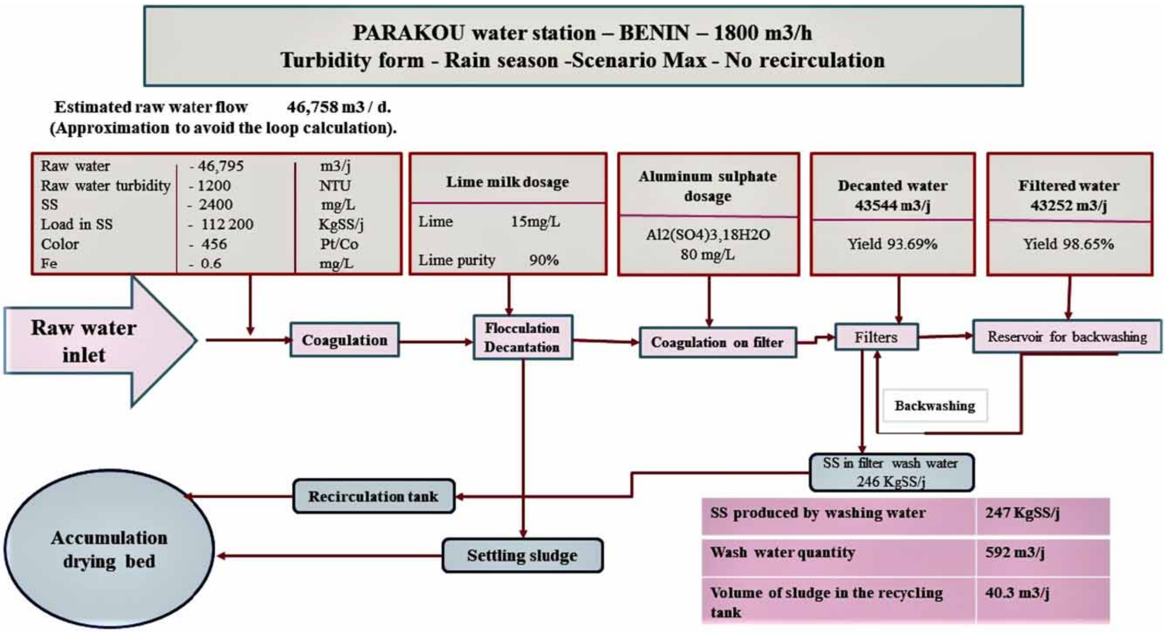

Figure 1 | Block diagram of the drinking water treatment plant in the city of Parakou, Benin.

2.2. Washing sequences

After settling, the water is distributed by gravity over 8 rapid filters with sand beds of 15 m^2 each. The water level above the filter layer was initially kept constant by the float, which operates a regulating valve – this system no longer works. Based on a filtration speed of 5 $m \cdot h^{-1}$, the capacity of each filter is 75 $m^3 \cdot h^{-1}$, for a total capacity of 600 $m^3 \cdot h^{-1}$. While washing a filter, the other three filters in the same series of four operate with a filtration speed of 5.7 $m \cdot h^{-1}$.

The effort required for the removal of dirt aggregates and the disturbance of their cohesive forces with the grain surface for regeneration of the filter material depends on the resistance of the dirt aggregates, the adhesion forces and the character of fixing of dirt on the grains. In addition, conditions for transport and disposal of dirt separated from the filter material must be created. This problem is solved with the help of the washing water stream, which ensures the expansion of the filter bed and the transport of dirt by a sedimentation rate from the lower layers of the filter bed to its upper part and even to the bottom, beyond the filter. However, the process can be complicated so that when washing, on the surface of the filter bed and at its top, a sludge packet forms having a speed close to the speed of sedimentation of the grains of the filter material. Therefore, the removal of such dirt is linked to the need to increase the flow rate of the wash water and the use of processes that would avoid the probable loss of filter material.

2.3. Hydrodynamic parameters and flow conditions

The occurrence of normal and shear forces is of prime importance for the destruction and removal of the deposit, formed in the space between the pores at the boundary of the 'grains of sand-dirt' phases. The main role in the separation of the large mass of dirt is played by the normal forces that appear with the expansion of the filter bed and the increase in its porosity. The cleaning of the grains of impurity particles occurs only in the presence of the process of self-separation and friction between the grains or by a sufficient value of the shear stress that appears with the flow of the washing water . Rather, some authors believe that the cleaning of dirt from the surface of the grains in the widening bed is carried out by the process of their collision during their movement characterized by different speeds. However, it is established that at the time of washing, the role of self-separation can be neglected, since with the expansion of the bed each grain is surrounded by a film of water that serves as a barrier against contact with other neighboring grains. (Appiah 1978; Cornet 1981). In fact, the tangential forces that arise from the action of the flow of water between the grains of the expanding bed is the major parameter that influences the removal of impurities from the surface of the grains.

It is established (Kawamura 2000; Baruth 2005; Trussell & Hand 2012) that during the filtration of natural waters, the value of the tangential forces of the deposits formed in the spaces between the grains of the sand bed varies from 0.2 to 0.7 Pa. Its maximum value is observed on the surface of the filter bed and decreases with increasing bed depth (Kawamura 2000). Thus, the force of cohesion of the particles of impurities between them was found to be twice smaller than that of their adhesion with the surface of the grains of sand and this is in perfect agreement with the results previously found (Trussell & Hand 2012). The tangential forces of movement of the deposits resulting from the filtration of wastewater, having different types of impurities, can considerably exceed the indicated value and this is why in the choice of the method of regeneration of the filter bed, the determination of the tangential forces which appear in view of the hydrodynamic forces around the grains by the flow of the wash water is of paramount importance.

2.4. Materials and Banikanni water treatment plant in Parakou, Benin

The equipment used in this study is made up of a hydrocyclone, a hydro-elevator and an ultrasonic chamber. The hydrocyclone used is Lama hydrociclon HID3P2D Ø6″, with a flow rate of 74 $m^3 \cdot h^{-1}$ and 100 $m^3 \cdot h^{-1}$. It performs its function as a separator by using the centrifugal force generated by the entry of water at high speed and the tangential path. Particles with a specific gravity heavier than water are trapped by the internal walls of the hydrocyclone and then fall into a reservoir located at the bottom. The conditions of use are reached from 0.2 bar pressure drop. The recommended pressure loss range is 0.2 to 0.5 bar. The separation efficiency of the device increases with speed (decrease in diameter) and pressure loss.

An ultrasonic chamber, model JP-2072T semi-automatic, is an ultrasonic cleaning machine. This machine is a 2,400 mm long ultrasonic blind cleaner consisting of a tank and a drying tank. The washing process begins with a water-filled tank that uses sound waves through the water to remove dirt, smoke and other debris followed by a drying tub. This tank has a capacity of 330 L with an ultrasonic power of 3,600 W and a heating power of 12,000 W.

The Banikanni water treatment plant is designed for a capacity of 600 $m^3 \cdot h^{-1}$. It consists of the following elements:

- two (2) identical settling tanks, round 'accelerator' type, 12.4 m in diameter;
- an aluminum sulphate dosing station, as a coagulant, equipped with 2 dosing pumps;
- a slaked lime metering station, as a coagulation/flocculation adjuvant, equipped with 2 metering pumps;
- a chlorine dosing station, for post-chlorination, equipped with 2 dosing pumps;
- two (2) series of 4 fast open filters each having a capacity of 75 $m^3 \cdot h^{-1}$ on the basis of a surface load of 5 $m \cdot h^{-1}$ or a capacity of 300 $m^3 \cdot h^{-1}$ for each series of 4 filters;
- a treated water tank with a volume of 850 m^3;

– a treated water delivery station made up of a series of five (5) surface pumps;
– a 100 m^3 concrete sludge settling tank.

After settling, the water is distributed by gravity over 8 rapid filters with sand beds of 15 m^2 each. The water level above the filter layer was initially maintained at a constant level by the float, which operates a control valve. Based on a filtration speed of 5 $m \cdot h^{-1}$, the capacity of each filter is 75 $m^3 \cdot h^{-1}$, for a total capacity of 600 $m^3 \cdot h^{-1}$. While washing a filter, the other three filters in the same series of four operate with a filtration speed of 5.7 $m \cdot h^{-1}$. The filtered water is stored in the treated water tank with a volume of 850 m^3, located below the filters.

2.5. Methods

Before performing the quantitative analysis of the laws that describe the flow of liquid in the filter bed, it is necessary to establish the Navier-Stokes equation, which takes the form (Schwartz & Zhang 2015):

$$\rho\left(\frac{\partial w_i}{\partial t}+w_k\frac{\partial w_i}{\partial x_k}\right)=-\frac{\partial p_p}{\partial x_i}+\mu\nabla^2 w_i \tag{1}$$

For a permanent flow of the incompressible liquid

$$\rho w_k\frac{\partial w_i}{\partial x_k}=-\frac{\partial p_p}{\partial x_i}+\mu\frac{\partial^2 w_i}{\partial x_k\partial x_k} \tag{2}$$

By integrating new dimensionless variables into (2),

$$x'_k=\frac{x_k}{L};\quad p'=\frac{p}{P};\quad w'_k=\frac{w_k}{W}\text{ and } w'_i=\frac{w_i}{W}$$

where L, P and W – respectively the characteristic length, pressure and velocity, the Navier-Stokes equations will take the form

$$\frac{\rho W^2}{L}w'_k\frac{\partial w'_i}{\partial x'_k}=-\frac{P}{L}\frac{\partial p'}{\partial x'_i}+\mu\frac{W}{L^2}\frac{\partial^2 w'_i}{\partial x'_k\partial x'_k}$$

By designating by $\frac{P}{\rho W^2}=Eu$; $\frac{\rho WL}{\mu}=\mathrm{Re}$ then it is found:

$$w'\frac{\partial w'_i}{\partial x'_k}=Eu\frac{\partial p'}{\partial x'_i}+\frac{1}{\mathrm{Re}}\frac{\partial^2 w'_i}{\partial x'_k\partial x'_k} \tag{3}$$

where Eu – Euler's number; Re – Reynolds number.

The determination of the resistance of the profiled grain or of the pressure drop at the moment of the flow of the washing water on the grain for characteristic values of flow rate, length, physical constants of viscosity and density of water, the Euler number containing the unknown characteristic pressure determining the resistance of the profiled grain, is a function of the Reynolds number including the predetermined values: Eu = f (Re). Given the relationship between the resistance coefficient λ and the Euler number, 2 Eu $=\lambda$, it can be written $\lambda=f(\mathrm{Re})$, whose expression can be found by solving the Navier-Stokes equation for the laminar flow case. The system of equations describing this flow reduces to the equation:

$$\nabla^2 w=\frac{\Delta P}{\mu l} \tag{4}$$

where ∇^2 – the operator of Laplace; ΔP – the drop in pressure on the section of length l. This equation is obtained from the system (2), written for the case where $w_x=w_y=0$ and the primary and secondary differentials of the projections of the speed vector $\bar{w}$ also equal zero. However, the Navier-Stokes equation system is often supplemented by the incompressible liquid equation $div\overrightarrow{w}=0$, from which emerges $\partial w_z/\partial z=0$. Thus, Equation

(2) becomes

$$\frac{\partial p}{\partial z} = \mu\left(\frac{\partial^2 w_z}{\partial x^2} + \frac{\partial^2 w_z}{\partial y^2}\right) \tag{5}$$

The relationship between the characteristic pressure and the pressure drop ΔP over the length l of the pipe is determined by the equation $P = \Delta pd/l$, where d = the diameter of the pipe, then it can be written

$Eu = \Delta pd/\rho w_{moy}^2 l$ and $\mathrm{Re} = w_{moy} d\rho/\mu$

Using the relationship between the Euler number and the coefficient of resistance, it is obtained

$$\Delta p = \frac{\lambda l \rho w_{moy}^2}{2d} \tag{6}$$

The flow of wash water through the filter material is considered here as a flow that occurs in pipes of complex cross-section, which basically are pore channels. Analysis of the solutions of Equation (4) shows that the average velocity of flow in the pore channels of the filter material is defined by

$$w_{moy} = \frac{k' d_\varepsilon^2 \Delta p}{\mu l} \tag{7}$$

where k′ – numerical coefficient; d_ε = equivalent diameter of the pore channel, defined by the equation $d_\varepsilon = 2\varepsilon d_P \alpha_\phi / 3(1-\varepsilon)$, l = the length of the pore channel; ε = the porosity of the filter bed; d_P = the spherical grain of sand diameter, α_ϕ = form coefficient.

Thus, to determine the flow regime of the washing water in the space between the grains, the bed is considered to be crossed by a set of cylindrical pores of diameter $d\varepsilon$ and the Reynolds number is defined by:

$$\mathrm{Re}_\varepsilon = \frac{w_{moy} d_\varepsilon \rho}{\mu} \tag{8}$$

From Equations (6) and (7), the relation between the resistance coefficient and the Reynolds number is proportional to the Poiseuille monomial. Thus, the results of the experiments carried out by Mins & Choubert (1951) will be used for the laminar flow of the washing water of the filters, which make it possible to write:

$$\lambda = f(\mathrm{Re}) = \frac{A}{R_e^{0,7}} \tag{9}$$

where A = the universal constant $A = 3,73/\alpha^{1,7}$ and α = the shape coefficient of the material $\alpha = s/s_b > 1$, where s and s_b = respectively the surface of the grain and that of a sphere of the same volume.

The washing of the filter consists of fluidizing the media in order to remove the dirt that has lodged therein and return it to its initial state, a total expansion of the media is aimed at. This expansion depends on several parameters such as the type of filtering medium, the particle size, the sphericity of the grains, the density of the medium and of course the water flow rate used to fluidize the filter (Erika 2013). The relationships between these parameters show that due to the exchange of momentum of the particles between neighboring layers, tangential friction forces arise, which often, as in the case of laminar flow (Saint-Venant, Boussinesq and Prandtl) are expressed by Newton's law in terms of the turbulent mixing coefficient µT as a function of the type of liquid and the intensity of the mixing (Cornet 1981). Under these conditions, considering that at the center of the section where r = 0, the speed is maximum i.e. u = umax, the speed distribution function is expressed by:

$$\frac{u}{u_{Max}} = \left(1 - \frac{n^2}{r^2}\right)^m \tag{10}$$

where r = the driving radius.

From Equation (7), formula (10) can be written:

$$u = u_{\max}\left(1-\frac{n^2}{r^2}\right)^m = k'\frac{r^2\Delta P}{\mu l}\left(1-\frac{n^2}{r^2}\right)^m = k'\frac{\Delta P}{\mu l}\left(\frac{D_k^2}{4}-n^2\right)^m \tag{11}$$

where k′ is a numerical coefficient which depends on the flow regime, Dk = the capillary diameter. By expressing the flow as a function of the average speed v and the local speeds u, the relationship between the average speed and the speed umax (Dègan & Bacharou 2008):

$$\frac{v}{u_{\max}} = (1+m)^{-1} \text{ where } m = 1,3\sqrt{\lambda} \tag{12}$$

where λ – the coefficient of resistance in length.

The determination of the stresses, which appear at the moment of the permanent flow of viscous and incompressible liquid and directed along the tangent to the contour plane, can be carried out using as basic formula the expression (Schwartz & Zhang 2015).

$$\tau = \mu\frac{dv}{dn} \text{ or } \tau = \mu G \tag{13}$$

where τ : shear stress; μ – dynamic viscosity coefficient; $G = dv/dn$- velocity gradient expressing the rate of change of the velocity v of the liquid in the direction normal to movement. From studies (Maxime 2003; Schwartz & Zhang 2015), the speed gradient is defined by:

$$\frac{dv}{dn} = G = \left(\frac{W}{V\mu}\right)^{0,5} \tag{14}$$

where W = the dispersal power of the flow; V = the volume of the liquid.

From (14), it can be easily deduced that $W = G\mu VG$.

By considering the constant gradient G and replacing it with the ratio v/n where n = grain distance or pore size. Thus $W = \tau(V/n)v$ where $V/n = S$ is the grain surface of the filter bed, affected by the flow of washing water, $\tau Sv = F.v = W$.

Thus, the energy W diffused in the liquid is the product of the force of action of the flow on the surface of the grains and the speed of the current; this coincides with the work of the authors (Kawamura 2000; Erika 2013; Schwartz & Zhang 2015) who suppose that all the energy of the moving liquid agrees with the creation of tangential forces on the surface of the granular bed. Although these authors (Maxime 2003; Erika 2013; Schwartz & Zhang 2015) adopted a rectangular character of the velocity distribution in the pores whereas when the liquid flows in the pipes, the roughness distribution scheme has a curvilinear character (Schwartz & Zhang 2015), and therefore the numerical values of the speed gradient, calculated by formula (9) are overestimated and constitute the upper limit of this parameter. Representing the real porous medium as a set of cylindrical capillary tubes of diameter dε or interstices of characteristic dimension δ, the flow regime of the washing water in the intergranular space according to Armando (1999), the number of Reynolds is defined by Relation (8). Figure 2 and Figure 3 depict the velocity gradient Gk as function of coefficient of resistance λ for different values of ν.

However, at the Parakou Town Water Plant, the state of the washwater flow can be determined by the Reynolds number. For the 0.95 mm particle size filter, with a washing water speed of 20 m/h, and a water temperature of 20 °C (ν = 0.01 Stokes), the Reynolds number Re = 5.2 and with the speed of 7.5 m·h^{-1} (2 L·s^{-1}·m^{-2}), Re = 2. The calculated values of Re show that the filter washing with the expansion of the filter bed for the grains of sand of dimension 0.9 to 1 mm, takes place in a laminar regime of liquid flow around the grain and with the increase of the speed and the expansion of the bed, the Reynolds number increases, and thus its value announces the beginning of the transitional regime. By estimating the speed gradient according to formula (13), it is obtained:

$$\frac{dv}{dn} = k'\frac{\Delta P}{\mu l}(-2\text{mn}) \quad \text{that is to say} \quad |G| = k'\frac{\Delta P}{\mu l}mD_k \tag{15}$$

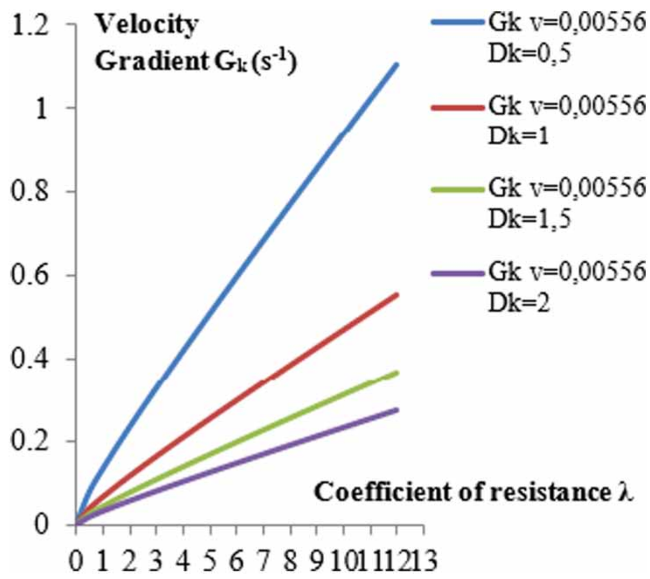

Figure 2 | Velocity gradient Gk as function of coefficient of resistance λ for $v = 0.00556$.

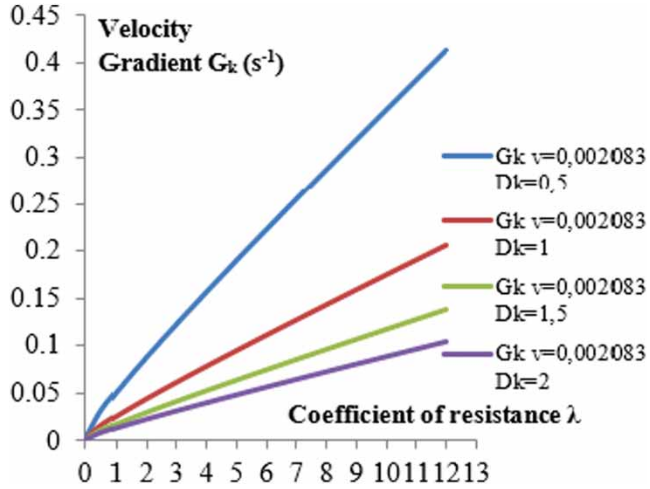

Figure 3 | Velocity gradient Gk as function of coefficient of resistance λ for $v = 0.002083$.

and so

$$\tau = k' \frac{\Delta P}{l} m D_k \tag{16}$$

If the average speed of the washing water in the pores is known, from relation (12) it is given:

$$v = k' \frac{\Delta P}{\mu l} r^2 (1+m)^{-1} = k' \frac{\Delta P}{4\mu l} D_k D_k (1+m)^{-1} = G_k \frac{D_k}{4m(1+m)};$$

From where $G_K = \dfrac{4mv(1+m)}{D_k}$ with $m = 1, 3\sqrt{\lambda}$, (17)

The value of the speed gradient G, calculated by formula (14), taking into account the regime of the flow of the liquid in the space between the pores is greater than that calculated by formula (17) from 20 to 25%. The passage of water around the grains of the bed for a sufficiently large distance between them, where their influence on each other is negligible, is possible for an upward flow speed of the washing water greater than the critical speed, when transporting grains from the bed using ejectors in the filter, outside the filter, as well as by separating the bed and the wash water in the hydrocyclone.

The grain cleaning effect in this case is defined by the interaction between the laminar layer of the incompressible liquid and the grain surface of the bed (Figure 4). The laminar layer is considered to be the layer of liquid of thickness δ, equal to the distance from the surface of the body to the point where the speed of movement of the liquid recovers to 99% or differs at 1% from the speed of the body. The boundary layer is laminar for $\mathrm{Re} \leq 3.10^5$ and turbulent for $\mathrm{Re} > 3.10^5$. For the above-mentioned filter bed grain washing methods, when the maximum relative speed of the current is about 1 m/s, the Reynolds number will have a large value, however it will not exceed the value of 3.10^5. This is why for the definition of the shear stresses one can use the equations of motion of the incompressible liquid in the boundary layer (Dègan & Bacharou 2008), which are of the following form:

$$v_x \frac{\partial v_x}{\partial x} + v_y \frac{\partial v_x}{\partial y} = -\frac{1}{\rho}\frac{\partial P}{\partial x} + \frac{\partial^2 v_x}{\partial y^2} \qquad (18)$$

$$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} = 0; \qquad \frac{\partial P}{\partial y} = 0$$

Solving these equations makes it possible to find the expression of the shear stress on the flat plate suspended in a uniform flow stream $u_{\max}$ (Dègan & Bacharou 2008).

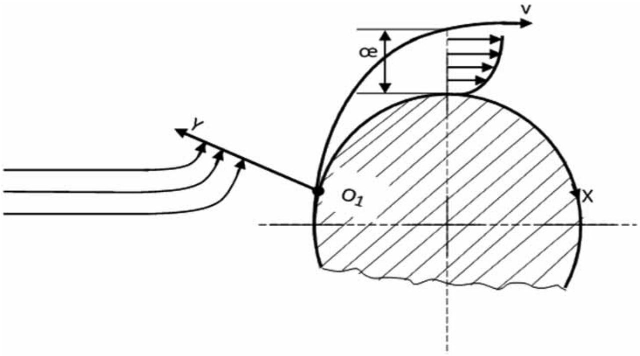

Figure 4 | Water velocity in the laminar boundary layer (Lauchle & Gurney 1984).

Let δ be the thickness of the thin layer covering the wall where the flow is laminar, in which the speed varies from 0 to u_τ and l the thickness of the zone of the free flow where the speed is maximum. Using the scale analysis method, the wall friction given by τ, it can be easily deduced:

$$\tau = \mu\left(\frac{\partial u}{\partial y}\right)_{y=0} = \mu\left(\frac{u_{\max}}{\delta}\right) \qquad (19)$$

By referring to Océane (2017) and to (19), the friction speed is given as:

$$u_\tau = \sqrt{\frac{\tau}{\rho}} = \sqrt{\frac{\mu u_{\max}}{\rho\delta}} = \left(\frac{\nu u_{\max}}{\delta}\right)^{1/2} \qquad (20)$$

Considering a free current of uniform pressure, dp/dx = 0; then from (20), it can be deduced that:

$$\frac{u_\tau^2}{\delta} = \frac{\nu u_{\max}}{\delta^2} = \frac{u_{\max}^2}{l} \Rightarrow \delta = \left(\frac{\nu l}{u_{\max}}\right)^{1/2}, \ \text{from where} \ \frac{\delta}{l} = R_{eL}^{-1/2} \qquad (21)$$

where R_{eL} is the Reynolds number based on the longitudinal dimension l of the laminar layer.

Equation (18) shows that the postulate of thinness of δ, on which the laminar layer theory is based, is based on the theory that δ is much less than l causes that δ is very small compared to l and therefore δ/l is much less than $l/l = 1$, is valid to give $R_{eL}^{1/2}$ much greater than 1, which is the condition for the existence of the dynamic laminar layer. Taking into account the above, Equation (19) becomes:

$$\tau = \mu\frac{u_{\max}}{\delta} = \mu\frac{u_{\max}}{l}R_{eL}^{1/2} = \rho\left(\frac{\nu u_{\max}}{l}\right)R_{eL}^{1/2} = \rho\left(\frac{\nu}{u_{\max}l}\right)u_{\max}^2 R_{eL}^{1/2} = \rho u_{\max}^2 R_{eL}^{-1}R_{eL}^{1/2}$$

$$\tau = \rho u_{\max}^2 R_{eL}^{-1/2} \tag{22}$$

Given that $R_{eL} = \frac{u_{\max}l}{\nu}$ and taking into account the relation (12), the relation (21) becomes for any speed v at a given point:

$$\tau = (1+m)^{\frac{3}{2}}\sqrt{\frac{\mu\rho v^3}{x}} \text{ where } m = 1,3\sqrt{\lambda} \tag{23}$$

where x – the coordinate along the contour surface, which begins to count from the point 0_1 where the current meets the surface (Figure 4).

3. RESULTS AND DISCUSSION

The formula (21) obtained for the laminar layer of the plate is qualitatively applicable to any material of any shape, for which it is possible to neglect the variations of all the values that enter it and their derivatives along the profiled surface (axis x) by comparison with the variations of these values in terms of thickness of the laminar layer (y axis). For this purpose, the value of the shear stresses is determined in the case of the flow around the surface of the grains of the 1 mm diameter bed at a large surface between the grains; that is to say, during the movement of the grains in the fluid flow. Formula (21) shows that the value of the shear stress varies as a function of the curvilinear x coordinate, the coordinate system of which is chosen at the point where the shear stresses are greater than the norms. At point 0_1, for which $x = 0$, theoretically the value of the shear stress is maximum; however, the micro flows that appear at this point of contact between the flow and the surface of the particles decrease its value.

The growth of the shear stress as a function of ΔP is linear for large values of x (Figure 5). On the other hand, the curves describing the evolution of the shear stress for small values are parabolic in shape. This difference in behavior is certainly due to the influence of the geometry of the pores, as well as a modification brought about by the flow between the pores of the filter medium. The shear stresses increase with the increase of ΔP (Figure 6) and therefore the washes are triggered when the shear stress is too high, allowing the particles accumulated on the grains of sand to loosen.

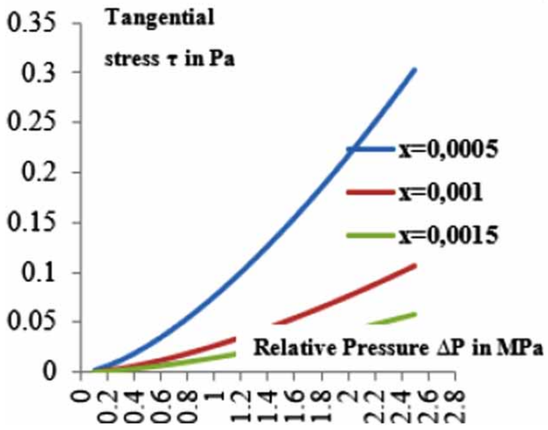

Figure 5 | Tangential stress as function of relative pressure for various values of $x = 0{,}5.10^{-3}$ m; $x = 10^{-3}$ m; $x = 1{,}5.10^{-3}$ m.

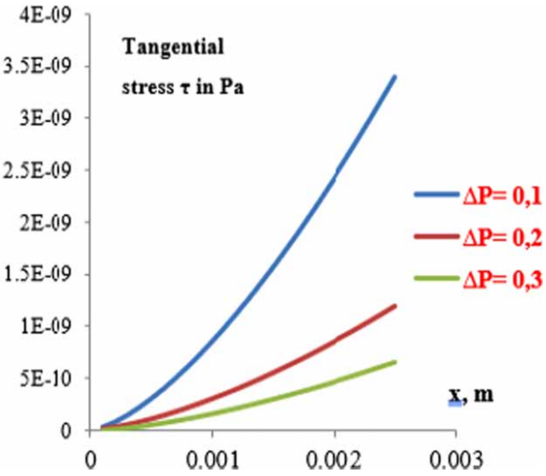

Figure 6 | Tangential stress as function of x for various values of $\Delta P = 0{,}1$; 0,2 ; 0,3 MPa.

For the definition of the shear stress, x was set at $x = 0.5.10^{-3}$ m; that is to say, about half the diameter of the particle. In laminar flow, the maximum velocity of the ambient liquid relative to the surface of the moving grain in the flow will be equal to the strained precipitation velocity of the grain regardless of the velocity of the current relative to the walls of the apparatus. At the Parakou treatment station, the grains of sand having on average a diameter dp = 1 mm and the relative speed of the flow of the washing water is $v = 10^{-1}\ \mathrm{m{\cdot}s^{-1}}$ and taken as equal to the speed of grain sedimentation. Thus, for $\mu = 10^{-3}$ Pa.s, $\rho = 10^{3}\ \mathrm{kg{\cdot}m^{-3}}$, the value of the tangential stress $\tau = 0.47$ Pa will decrease with the increase of x. The obtained value of τ characterizes the tangential stress, which has its place in laminar flow at the contour of the particle by the upward flow of the washing water or during the transport of filter material in the pipe under load. The maximum value of τ, which can be obtained by formula (23), appears when the grain has not yet been able to draw itself into the flow of water and the relative velocity v is high. This occurs, for example, in a hydro-elevator, when the grains settle in the mixing chamber. However, this tangential stress acts on the particle in various ways, since the velocities of the flow and the particles equalize, which is why the reliability of the process of cleaning the grain surface of the bed during its hydraulic overload with the help of the hydro-elevator is not high. Also, the increase in flow turbulence contributes to the increase in τ; for example, with the introduction of compressed air into the wash water.

Formula (23) determines the tangential stresses, which appear on the surface of the grains of the filtering bed for the case of their washing in the hydrocyclone when the grains of sand separated from the water are arranged on the walls of the apparatus and the flow of filtering water has an angular linear velocity of 0.8 $\mathrm{ms^{-1}}$ relative to the grain surface. By applying this value of the speed it is obtained $\tau = 10.62$ Pa. If, in reality the value of τ in the hydrocyclones will be lower, it is nevertheless an order of magnitude higher than the value of τ calculated for the washing in the upward flow. This testifies to the high washing efficiency of the filter material for impurities during the tests on hydrocyclones (Degrémont 2012). In addition, in this process, the forces of collision and friction of particles between themselves and on the wall of the apparatus, as well as the presence of a centrifugal field in the apparatus, acquire greater importance.

The use of ultrasonic waves is known to intensify the removal of particles from the surface of different materials (Pierre 2016), as well as grains from the filter media (Payant 2016). The ultrasonic field influences the hydrodynamics of the washing water flows and causes a qualitative leap in the degree of washing by means of the complex action of ultrasonic effects. These effects are determined by cavitation, acoustic flows, variable sound pressure, as well as the oscillation of filter bed particles and impurities. From experimental and industrial research of different methods of washing sand grains from the filter bed, the remainder of the particles in the filter bed related to the unit weight of the filter material is estimated, giving the following results: washing with water and in the air (standards) 11.0–12.3; Hydraulic overload using the hydro-elevator 8.3–10.3; washing in hydrocyclone 4.7–5.7; washing in the ultrasonic chamber 2.8–3.2. These results show that the efficiency of washing the grains of the filtering material in the ultrasonic chamber is higher than the washing with water and air, by its overloading using the hydro-elevator and by washing in the ultrasonic chamber. The future intensification of the ultrasonic regeneration process can be achieved by taking into account the increase in static pressure in the ultrasonic chamber, provided that the increase in static pressure causes an increase in the acoustic velocity of the currents, which can reach 1–2.6 m.s^{-1} (Pierre 2016). The calculation of the value of the tangential stress by formula (23) for such a speed of acoustic currents makes it possible to obtain $\tau = 62.5$ Pa, which is two orders of magnitude greater than the stresses that may arise during washing of the bed filtering in the upward flow of wash water.

Under laboratory conditions, research has been done on the influence of the value of the static pressure on the washing quality of the filter bed. For this, the sample from the filter bed of sand, clogged with filters in operation, was mixed in the ultrasonic washing chamber, where a well-defined volume of liquid was added. The frequency of ultrasonic waves is 18 kGs. The duration of the ultrasonic action varies from 5 to 60 s, and the relative static pressure value reaches 0.3 MPa. After the ultrasonic action, the concentration of particles is determined for a given size, which are transferred from the surfaces of the grains to the liquid (Figures 7 and 8).

Figures 7 and 8 show the fact that with the increase in the relative static pressure and the duration of the ultrasonic production, the concentration of pollution increases in the water; that is to say, the quality of the washing of the surface of the grains of sand, and for this the most effective washing is that which is carried out in the first 30 seconds of the ultrasonic elaboration. When tends towards infinity, the concentration reaches a maximum and becomes constant. The maximum concentration is lower and is reached after a while for small particles rather

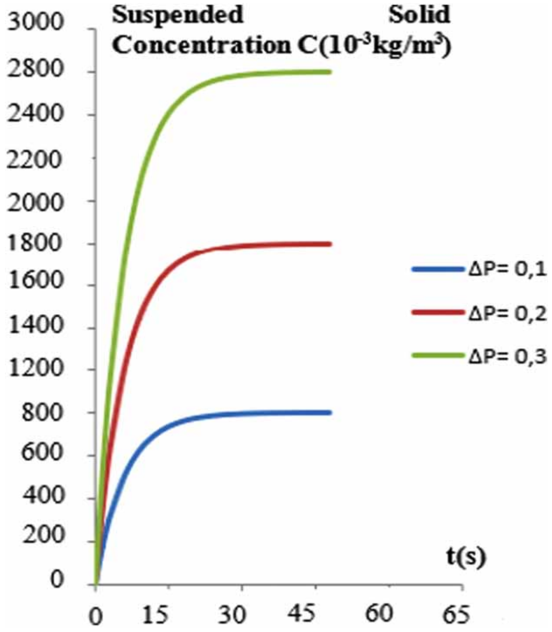

Figure 7 | Influence of the relative pressure on the change in the concentration of suspended solids in the washing water during washing of the filter bed in an ultrasonic field (frequency 18 kHz) for $\Delta P = 0.1$; $\Delta P = 0.2$; $\Delta P = 0.3$ MPa.

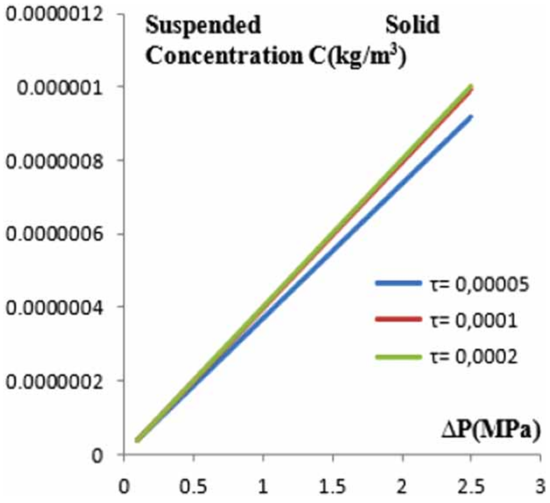

Figure 8 | Suspended solid (SS) concentration as a function of ΔP for $\tau = 0.00005$; $\tau = 0.0001$; $\tau = 0.0002$ and $x = 0.5.10^{-3}$ m.

than for large ones. The use of filters in industrial wastewater treatment schemes, the pollution of which can have different natures and have a strong adhesion with the grain surface of the filter bed, causes the need for performance of the filter bed regeneration method. With the choice of the regeneration method, it is advisable to study the conformity of the value of the tangential stresses created by the flow of washing water and the resistance of the pollution to the grains of the filtering material.

4. CONCLUSION

One of the causes of the poor performance of the methods used with water and water mixed with the washing air of the filters during the treatment of wastewater is the insufficient value of the shear stresses of the movement, created by the washing flows in the filter bed. The washing water flow regime at the Parakou town water plant is defined for a 0.95 mm particle size filter, with a washing water speed of 20 m/h, and a water temperature of 20 °C ($\nu = 0.01$ Stokes), the Reynolds number $\mathrm{Re} = 5.2$ and with a speed of 7.5 m/h (2 l/s.m^2), $\mathrm{Re} = 2$. These values of the Reynolds number show that the washing of the filter with the expansion of the filter bed for sand grains of dimension 0.9 to 1 mm is carried out in a laminar regime of liquid flow around the grain and with increasing speed and expansion of the bed, the Reynolds number increases. The value of the velocity gradient G, expressed from the average velocity, is greater than that expressed from the average and local velocities of the liquid flow in the space between the pores, by 20 to 25%. The use of hydro-elevators and hydrocyclones for washing the surface of the grains of the filtering material under hydraulic load makes it possible to reduce the amount of remaining impurities respectively by 1.5 to 2.5 times compared to the combined washing of water and air; for this, the performance of the washing of the grains in the hydrocyclone can be explained by the presence in the apparatus of centrifugal field and self-separation and the friction of the particles between them and on the wall of the apparatus. Regeneration of the filter material under the action of ultrasonic waves reduces the remaining impurities compared to washing with water and air about 6 times.

The perspectives opened up by this work are manifold. First of all, it would be important to confirm the preponderant role that temperature plays on all the experimental situations of removal of clogged particles in the pores of filter media, given that the shear rate is a function of the viscosity, which depends of the temperature. In particular, by systematically carrying out the experiments in a controlled convective medium, it should be possible to make a clear demonstration of the existence of a temperature-based removal mechanism. In addition, this approach would determine the optimum amount of liquid for efficient removal by this process.

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CONFLICT OF INTEREST

The authors declare no competing financial interest.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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