Color Removal of Reactive Dyes from Water by Clinoptilolite

ARTICLE *in* JOURNAL OF ENVIRONMENTAL SCIENCE AND HEALTH PART A · FEBRUARY 2004

Impact Factor: 1.16 · DOI: 10.1081/ESE-120030329 · Source: PubMed

Mustafa Turan
Istanbul Technical University

Orhan Ozdemir
Istanbul University

Mehmet S Celik
Istanbul Technical University

Influence of Media Characteristics on Energy Dissipation in Filter Backwashing

MUSTAFA TURAN,*,† EYUP SABAH,‡ HAKKI GULSEN,† AND MEHMET S. CELIK§

Environmental Engineering Department, Civil Engineering Faculty, and Mineral and Coal Processing Department, Mining Engineering Faculty, Istanbul Technical University, Ayazaga, Istanbul, 80626 Turkey, and Mining Engineering Department, Afyon Kocatepe University, Afyon, 03000 Turkey

Effective cleaning of granular filters during backwashing processes needs maximum turbulence and maximum shear in the fluid particle field. The energy dissipation in a backwashed filter as a particulate fluidized bed arises due to the suspending and random motions of particles and turbulent fluctuations in the bed. Size, density, and sphericity of the filter materials greatly influence the fluidization behavior of the media. In this study, a new model is proposed for predicting the energy dissipation parameters namely the hydrodynamic shear stress (τ_a), the velocity gradient (G_a), the turbulence dissipation coefficient (C_a), and the turbulence parameter ($C_a^{0.5}$/Re) in backwashing of filters for different types of filter materials (sand, anthracite, and glass ball). The hydrodynamic shear stress is the dominant mechanism of filter cleaning and appears to increase with increasing the density and size of the filter media particles. Using the basic set of data, a step by step procedure is developed to compute the velocity gradient G_a, the turbulence dissipation coefficient C_a, the hydrodynamic shear stress τ_a, and the turbulent parameter ($C_a^{0.5}$/Re).

Introduction

Granular media filtration has growing importance in drinking water production and generally is applied prior to disinfection in the water treatment process. The effectiveness of a filter depends on physical and chemical parameters of the filtration system such as size and surface properties of the granular media, depth of media, and the accumulation of particulate suspensions (*1*). The deposition of particulate materials on the surface of the granular media causes clogging of the filter pores and is the major parameter determining the headloss against time (*2, 3*). Besides, initial deposit removal is controlled by the attachment and collision efficiencies between the particulate materials and media (*4*−*6*). Hydrodynamic shear on the attached particulates dominates the release only at very high flow velocities (*7*). The detachment efficiency of deposits is higher with lower ionic strength waters which exhibit increased electrostatic repulsion and in turn particulate release (*8, 9*).

After a selected effluent quality, the filtration process is terminated and the filter is backwashed; this is a more critical process than filtration. An incorrect backwash rate and inadequate design of filters cause operational problems (*10*). Washing with water preceded by an air scour also increases the effectiveness of backwashing process (*11, 12*). In addition, the recycle of backwash solids did not affect the overall treatment process on a pilot scale (*13*).

A backwashed filter is classified as a particulate fluidized bed in fluidization terminology (*14*). The expansion and particle mixing characteristics of a fluidized bed composed of different particles is a complicated function of many variables, including hydrodynamics, particle characteristics, and turbulence effects of the fluid (*15*). The total energy dissipation during backwashing is formed with the power necessary to suspend the filter particles, the energy removal due to random motions of suspended particles, and the power dissipated by the turbulent fluctuations (*16*−*18*). The purpose of the present study is to develop a backwashing model which describes the influence of different types of filter media on the energy dissipation in a backwashed filter.

Model Development

Expansion Characteristics of Granular Media Filters. The Richardson−Zaki correlation (*19*) is widely used to describe the expansion characteristics of fluidized beds for spherical particles as

$$U/U_i = \epsilon^n \qquad (1a)$$

where U is the superficial (upflow) velocity, U_i is the intercept velocity, n is the bed expansion coefficient, and ϵ is the fluidized bed porosity. Since particles in the filter bed are nonspherical, backwashing of the filter media differs from the fluidization of beds with spherical particles. Therefore, the following equation can be given (*20*) as

$$U_i/U_t = 0.91\,\psi^{-0.400} \qquad (1b)$$

where U_t is the terminal settling velocity and ψ is the particle sphericity that is the ratio of the surface area of an equal volume sphere to the actual surface area of the particle (*21, 22*).

The characteristics of the upflow conditions at the intersection of the fixed bed and fluidized bed are compatible with one another, and, also, the minimum fluidization velocity, U_{mf} describes a transition point between these two types of flow conditions (*21*). Since the superficial (upflow) velocity of fluidized bed is always greater than that of fixed bed, the criteria for this position can be stated as follows

$$U_{mf} > U_i\epsilon_s^{\,n} \quad \text{for } U_{mf} < U \text{ and } \epsilon_s < \epsilon < 1 \qquad (2)$$

where ϵ_s is the fixed bed porosity. Since the total volume of particles becomes constant both in fixed and fluidized beds, the relative bed height can be written as

$$L/L_s = (1 - \epsilon_s)/(1 - \epsilon) \qquad (3)$$

where L_s is the fixed bed height, and ϵ_s is the fixed bed porosity. Also, the bed expansion coefficient of the nonspherical

* Corresponding author phone: +90 212 285 65 68; fax: +90 285 65 87; e-mail: mturan@ins.itu.edu.tr.

† Environmental Engineering Department, Istanbul Technical University.

‡ Afyon Kocatepe University.

§ Mineral and Coal Processing Department, Istanbul Technical University.

10.1021/es020661r CCC: $25.00

Published on Web 08/15/2003

TABLE 1. Physical Properties of Media Used in Filter Bed (*20, 22, 28*)[a]

sieve size	particle size range mm	particle density ρ_s (g/cm^3)	fixed bed porosity ϵ_s	particle diameter d_{eq} (mm)	T. settling velocity U_t (cm/s)	sphericity ψ	Re_t
A. sand-10/12	2.00/1.68	2.65	0.446	1.962	19.13	0.71	420
A. sand-14/16	1.41/1.19	2.65	0.465	1.463	16.35	0.71	290
A. sand −18/20	1.00/0.84	2.65	0.467	1.006	12.58	0.73	143
A. sand −30/35	0.59/0.50	2.65	0.468	0.598	8.17	0.77	54.7
A. anthracite-5/6	4.00/3.36	1.73	0.581	3.663	12.25	0.48	503
A. anthracite-6/7	3.36/2.83	1.73	0.586	3.115	11.12	0.45	388
A. anthracite-7/8	2.83/2.38	1.73	0.587	2.826	10.46	0.44	331
A. anthracite-12/14	1.68/1.41	1.73	0.597	1.516	6.95	0.46	118
E. anthracite-18/22	0.853/0.699	1.46	0.564	0.815	3.94	0.64	35.7
E. anthracite-25/30	0.599/0.500	1.46	0.565	0.505	2.83	0.61	15.9
E. glass ball-18/22	0.853/0.699	2.96	0.425	0.783	14.80	0.96	129

[a] A. = American, E. = English, selected values: $D = 15$ cm, $\mu = 0.9 \times 10^{-3}$ Ns/m^2 ($T = 25$ °C).

particles is given as

$$n = (4.45 + 18d_{eq}/D)\mathrm{Re_t}^{-0.1}\,\psi^{a} \quad \text{for } 15 < \mathrm{Re_t} < 200 \tag{4a}$$

$$n = 4.45\,\mathrm{Re_t}^{-0.1}\,\psi^{a} \quad \text{for } 200 < \mathrm{Re_t} < 503 \tag{4b}$$

$$a = -2.9237\,\psi^{0.884}\,\mathrm{Re_t}^{-0.363} \tag{4c}$$

$$\mathrm{Re_t} = \rho U_t d_{eq}/\mu \tag{4d}$$

where d_{eq} is the equivalent diameter which is the particle diameter of sphere of equal volume, D is the filter column diameter, ρ is the liquid density, and μ is the dynamic viscosity of liquid.

The wide range of filter particles used in this study such as the particle densities ranged from 1.46 g/cm^3 to 2.96 g/cm^3, the particle diameters ranged from 0.815 mm to 3.663 mm, and the sphericities ranged from 0.44 to 0.96. Therefore, the particle Reynolds number $\mathrm{Re_t}$ for the filter media used in this study varied between 35.3 and 503 (Table 1). Besides, the backwashing flow regime is in the transition region, i.e., between laminar and turbulent conditions (*10, 20*).

Energy Dissipation during Backwashing. Filtration performance reveals the mechanisms governing the particulate deposition on the particle surfaces and pores of filter and, consequently, headloss increase in the granular bed. Besides, the smaller particulate suspensions cause more headloss than larger particulate suspensions for the same mass deposited. Removal of deposits depends strongly on the water chemistry and the attachment and collision efficiencies between particulates and media (*4, 7*). Effectiveness of a backwashing process depends on a number of physical parameters such as size and density of the granular particles, superficial velocity, bed porosity, and amount of deposited materials. In multiparticle systems such as fluidized beds, the drag force acting on one particle is affected by the presence of other particles. Although energy loss (head loss) across the fixed bed is a function of superficial velocity (*3, 20*), the head loss in the fluidized bed (backwashing process) is proportional to the buoyant weight of the bed particles as expressed in the following equation (*14, 20, 21*):

$$H/L = (\rho_s/\rho - 1)(1 - \epsilon) \tag{5}$$

In the turbulent flows, the power produced locally due to turbulent fluctuations equals the power dissipation by turbulent motion (*23*). The total power dissipation in a unit volume P_v can be written as

$$P_v = \phi_1 + \phi_2 = \mu(1 + C)(\mathrm{d}u/\mathrm{d}y)^2 \tag{6}$$

where ϕ_1 and ϕ_2 are the power dissipations in a unit volume by time-mean motion and in a unit volume by turbulent motion, respectively, u is the point velocity in x direction, y is the coordinate perpendicular to x, and C is the turbulence dissipation coefficient which indicates the effect of turbulence in the total power dissipation (*18*). The velocity gradient is a useful tool in water and wastewater treatment and for laminar flow is presented by Camp as a function of power dissipation (*24*). The velocity gradient and the hydrodynamic shear stress are also very important for predicting optimum cleaning of a backwashed filter. However, for the backwashing flow of filters in the transitional state, the velocity gradient at a point G is obtained from eq 6

$$G = \mathrm{d}u/\mathrm{d}y = (P_v/\mu(1 + C))^{0.5} \tag{7}$$

On the other hand, the energy equation for flows in a backwashed filter is given by Turan (*18*) as follows

$$\tau\,\mathrm{d}u/\mathrm{d}y = (\alpha_1\rho U_*^{\,3}/KL_m + \beta\alpha_1\rho U_*^{\,3}/KL_m + \rho U_*^{\,3}/Ky)\epsilon^{(n-1)} \tag{8}$$

While the left-hand side of eq 8 shows the energy produced by the Reynolds stresses, the right-hand side indicates the power necessary to suspend particles in a unit volume, the rate of energy removal due to random motions of suspended particles such as rotation, rectilinear motion relative to the fluid, and the power dissipated by a turbulent motion of liquid phase, respectively. Coefficient β characterizes random motions of particles, and $\alpha_1 = U_i/U_t$ is a coefficient related to particle characteristics (*17, 18, 25*). The von Karman universal constant of flow with suspended particles, K and Monin-Obukhov length, L_m, are given, respectively, as follows

$$K = K_o/(1 + 2(1 - \epsilon)) \tag{9}$$

$$L_m = U_*^{\,3}/(KgU_t(\rho_s/\rho - 1)(1 - \epsilon)) \tag{10}$$

where K_o is the von Karman universal constant for pure water flow (0.4), and $(1-\epsilon)$ is the fraction solids or concentration (*26, 27*). Also the specific density of fluid and particle mixture ρ_a and the friction velocity U_* are respectively defined as

$$\rho_a = \rho(1 + (\rho_s/\rho - 1)(1 - \epsilon)) \tag{11}$$

$$U_* = (g\rho(\rho_s/\rho - 1)(1 - \epsilon)D/4\rho_a)^{0.5} \tag{12}$$

Energy Dissipation Parameters. A new model is developed to describe the influence of different types of filter materials (sand, anthracite, and glass ball) on the energy dissipation parameters such as the hydrodynamic shear stress, the velocity gradient, the turbulence dissipation coefficient, and the turbulence parameter ($C_a^{0.5}/\mathrm{Re}$), in a backwashed filter. In this study, fluidization in a circular cross-section column is presented, and the existence of a viscous sublayer around solid particles is neglected. Also, the transition flow regime consists of a transition core at the center of the fluidized bed and laminar sublayer near the wall. From eq 7, the arithmetic mean velocity gradient G_a was calculated by integrating over the cross section of the fluidization column given elsewhere (*18*) and modified for the model developed in the present study:

$$G_a = 8U_* (\ln(\rho U_* D/23.2\mu) - 1)/KD \tag{13}$$

Using the energy dissipation equation for backwashing of filter (eq 8), the hydrodynamic shear stress τ can be obtained in an arithmetic mean form at the same way as follows

$$\tau_a = \rho U_*^{2} \epsilon^{(n-1)}((\alpha D/6L_m) + 1) \tag{14}$$

where the coefficient α is given as (*17, 18*)

$$\alpha = \alpha_1(1 + \beta) = 7U_i/U_t \tag{15}$$

If eq 7 is rearranged in an arithmetic mean form, the following equation can be given for the calculation the turbulence dissipation coefficient C_a after calculating the τ_a and the G_a values for this model:

$$C_a = (\tau_a/\mu G_a - 1) \tag{16}$$

Using the same way, the turbulence parameter ($C_a^{0.5}$/Re) that describes the turbulence effects of the liquid-phase analogous to the turbulence intensity $(\bar{u}'^2)^{0.5}/U$ in a fluidized bed (*16*) is calculated as

$$C_a^{0.5}/\mathrm{Re} = (\tau_a/\mu G_a - 1)^{0.5}/\mathrm{Re} \tag{17}$$

where u' is the fluctuating velocity of turbulent flow. The Reynolds number of the flow Re also can be expressed as follows

$$\mathrm{Re} = \rho U d_{eq}/\mu \tag{18}$$

Results and Discussion

The energy dissipation model for filter backwashing was applied to predict the energy dissipation parameters namely the velocity gradient G_a, the turbulence dissipation coefficient C_a, the hydrodynamic shear stress τ_a, and the turbulent parameter ($C_a^{0.5}$/Re) for different types of filter materials (sand, anthracite, and glass ball). The use of such materials produced a wide range of particle diameters d_{eq} (0.815−3.663 mm), particle densities ρ_s (1.46−2.96 g/cm^3), and sphericities ψ (0.44−0.96), as shown in Table 1. The corrected values for the sphericities given by Dharmarajah and Cleasby (*22*) were used. Also, the values selected in this study were the column diameter D = 15 cm and the dynamic viscosity μ = 0.009 Ns/m^2 at 25 °C. Since the superficial (upflow) velocity of fluidized bed is always greater than that of fixed bed, the superficial velocity was applied according to the criteria given in eq 2. Using the specifications of filter bed, specifications of raw water, and superficial velocity, a step by step procedure to compute the velocity gradient G_a, the turbulence dissipation coefficient C_a, the hydrodynamic shear stress τ_a, and the turbulent parameter ($C_a^{0.5}$/Re) is presented in the flow scheme in Figure 1.

Hydrodynamic Shear Stress. At high superficial velocities in the filter column, hydrodynamic shear contributes to the detachment of deposited material from the filter particles (*7*). Similarly, hydrodynamic shear stress also plays a dominant role in the cleaning of granular media during backwashing of filters (*14*). Figure 2 shows the variation of arithmetic mean shear τ_a as a function of porosity ϵ. Hydrodynamic shear forces appear to increase with increasing density and size of filter particles during backwashing. The maximum shear stress varied in the porosity range of 0.75−0.85 (fraction of 0.15−0.25) for the typical values of

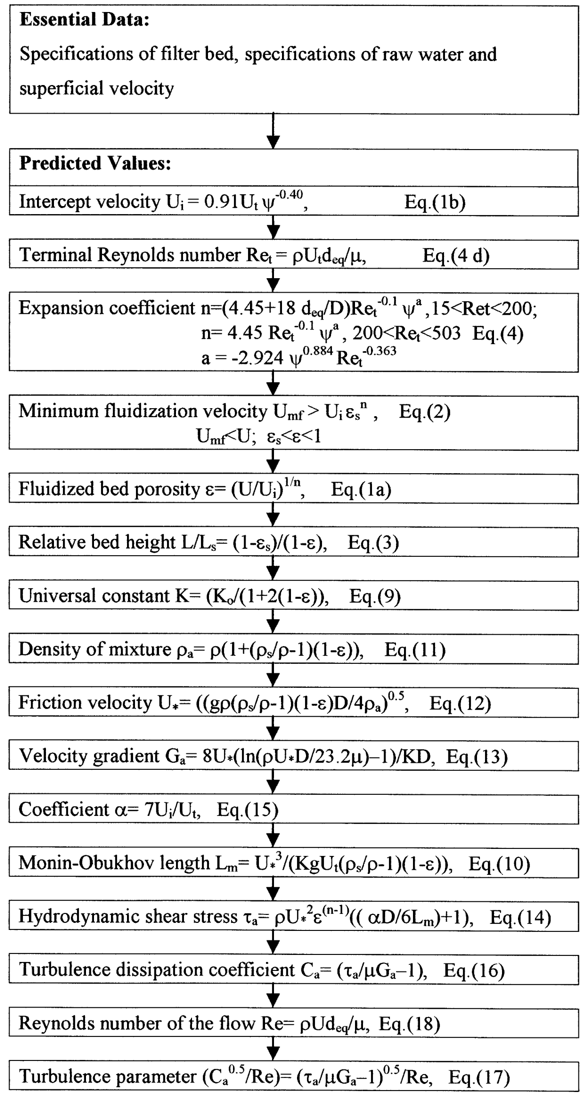

FIGURE 1. Flow scheme developed for energy dissipation modeling in filter backwashing.

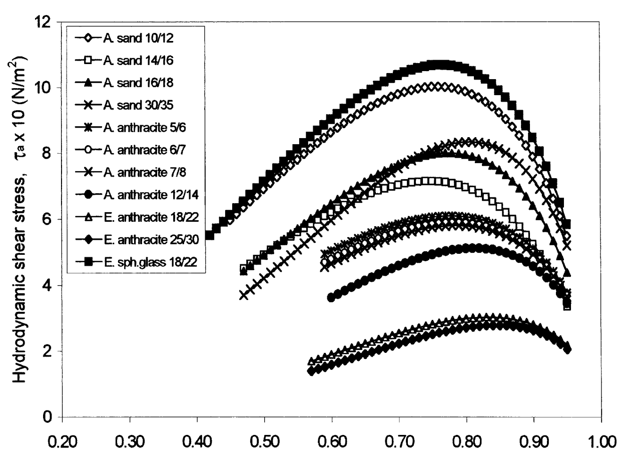

FIGURE 2. Variation of hydrodynamic shear stress as a function of porosity.

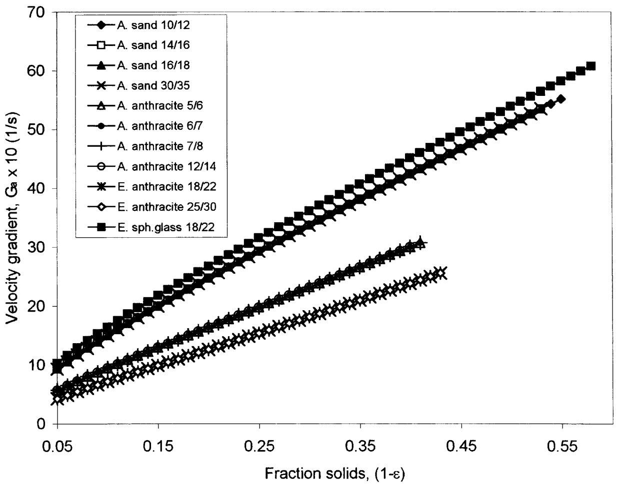

FIGURE 3. Velocity gradient versus fraction solids.

bed expansion coefficients ranging from 3.1 to 3.4. The maximum point becomes smoother for filter media having smaller and lighter particles. It was realized that the effectiveness of backwash could be improved by analyzing the total wash water usage to a given wash water turbidity. The optimum porosity for which minimum total wash water consumption is around 0.70 (*18, 25*). The maximum τ_a is also varied between 30.2 and 106.7 N/m^2 for English anthracite (18/22) (d_{eq}= 0.815 mm) at $\epsilon = 0.85$ and English spherical ball (18/22) (d_{eq}= 0.783 mm) at $\epsilon = 0.75$, respectively.

Velocity Gradient. The velocity gradient is the most effective factor in the granular bed filters. The velocity gradient is given as a function of the power dissipated in a unit volume and in the transitional flow regime (*14, 20*). The mean velocity gradient G_a (eq 13) developed for the present model is plotted versus fraction solids ($1-\epsilon$) in Figure 3. The G_a value increased with increasing fraction solids and density of the filter media particles but appeared to be influenced with independent of particles sizes. At the optimum backwashing conditions (or maximum shear forces) as fraction solids of 0.25, the G_a varied between 154 and 315 1/s for English anthracite (18/22) (ρ_s = 1.46 g/cm^3) and English glass ball (18/22) (ρ_s = 2.96 g/cm^3), respectively.

Turbulence Dissipation Coefficient. The C_a value indicates the contribution of turbulence fluctuations to the total power dissipation in a backwashed filter. This coefficient decreases with an increment of fraction solids. Conversely, an increase of density and size of particles causes a decrease in the C_a (Figure 4). At the same fraction solids, the C_a varied in the range of 171 and 366 for English anthracite (25/30) (ρ_s = 1.46 g/cm^3, d_{eq} = 0.505 mm) and American sand (10/12) (ρ_s = 2.65 g/cm^3, d_{eq} = 1.962 mm), respectively.

Variation of Turbulence Fluctuations in the Bed. Turbulence parameter ($C_a^{0.5}$/Re) characterizes the turbulence fluctuation effects similar to the turbulence intensity $(\bar{u}'^2)^{0.5}/U$ since both are the functions of $(\bar{u}'^2)^{0.5}$. The turbulence intensity increases with increasing particle population in a particulate fluidized bed (*16*). Similarly, the turbulence parameter increases with increasing fraction solids and decreases with increasing density and sizes of filter particles (Figure 5). Lighter particles appear to cause a higher rate of increase in turbulence for the same particle size compared to heavier particles. At fraction solids of 0.25 under the optimum cleaning conditions, the turbulence parameters $C_a^{0.5}$/Re is found as 0.4×10^{-3}, 1×10^{-3}, and 3×10^{-3} for American sand (14/16), American sand (30/35), and English anthracite (25/30), respectively.

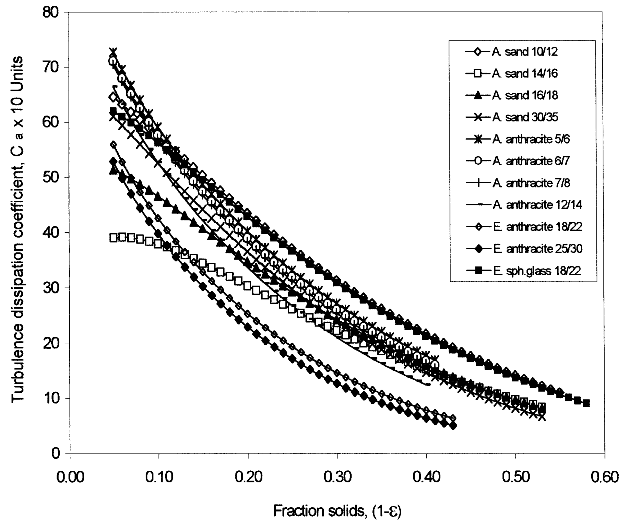

FIGURE 4. Turbulence dissipation coefficient versus fraction solids.

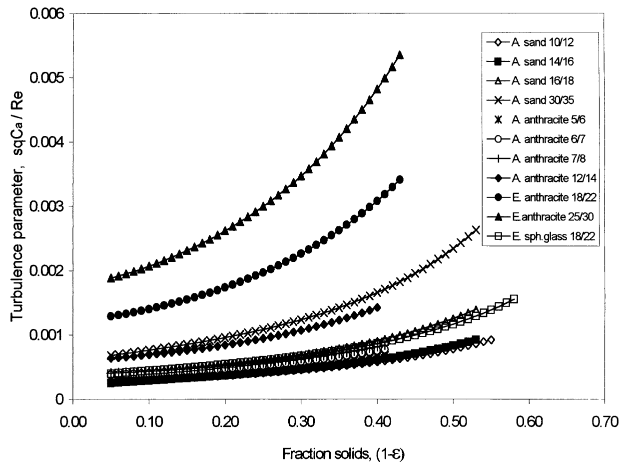

FIGURE 5. Turbulence parameter versus fraction solids.

Nomenclature

C	turbulence dissipation coefficient
$C_a^{0.5}$/Re	turbulence parameter
D	filter column diameter (m)
d	particle diameter (m)
G	velocity gradient (s^{-1})
H	head loss (m)
K	von Karman universal constant
L	bed height (m)
L_m	Monin-Obukhov length (m)
n	bed expansion coefficient
P_v	total power dissipation in a unit volume (N m^{-2} s^{-1})
U	superficial velocity (m s^{-1})
U_i	intercept velocity (m s^{-1})
U_t	terminal settling velocity (m s^{-1})
u	point velocity in x direction at y (m s^{-1})
u'	fluctuating velocity of turbulent flow (m s^{-1})
y	coordinate perpendicular to x (m)
α, β	energy dissipation constants

ϵ	porosity of fluidized bed
ϵ_s	porosity of filter bed
μ	dynamic viscosity of liquid (N m^{-2} s)
ρ	liquid density (kg m^{-3})
ρ_s	particle density (kg m^{-3})
τ	hydrodynamic shear stress (N m^{-2})
ψ	particle sphericity

Dimensionless Numbers

Re	Reynolds number of flow
Re_t	particle Reynolds number

Literature Cited

(1) Darby, J. L.; Lawler, D. F. *Environ. Sci. Technol.* **1990**, *24*(*7*), 1069−1079.
(2) Boller, M. A.; Kavanaugh, M. C. *Water Res.* **1995,** *29*(4), 1139−1149.
(3) Trussell, R. R.; Chang, M. *J. Environ. Engrg. ASCE* **1999,** *125*(11), 998−1006.
(4) Elimelech, M.; O'Melia, C. R. *Environ. Sci. Technol.* **1990**, *24*(10), 1528−1536.
(5) Tobiason, J. E.; Vigneswaran, B. *Water Res.* **1994**, *28*(2), 335−342.
(6) Wiesner, M. R. *J. Environ. Engrg. ASCE* **1999,** *125*(2), 1124−1132.
(7) Abadzic, S. D.; Ryan, J. N. *Environ. Sci. Technol.* **2001**, *35*(22), 4502−4508.
(8) Amirtharajah, A.; Raveendran, P. *Colloids Surf. A* **1993**, *73*, 211−227.
(9) Roy, S. B.; Dzombak, D. A. *Colloids Surf. A* **1996**, *107*, 245−262.
(10) Kawamura, S. *J. Am. Water Works Assoc.* **1999**, *91*(12), 77−90.
(11) Hewitt, S. R.; Amirtharajah, A. *J. Environ. Engrg. ASCE* **1984,** *110*(3), 591−606.
(12) Stevenson, D. G. *Water Res.* **1995**, *29*(11), 2594−2597.
(13) Cocchia, S.; Carlson, K. H.; Marinelli, F. *J. Environ. Engrg. ASCE* **2002**, *128*(3), 220−227.
(14) Amirtharajah, A. *J. Environ. Engrg. ASCE* **1978**, *104*(5), 917−932.
(15) Turan, M.; Eroglu, V. *J. Environ. Sci. Health* **2001**, *A 36*(9), 1735−1746.
(16) Hanratty, T. J.; Latinen, G.; Wilhelm, R. H. *J. Am. Inst. Chem. Engrs.* **1956**, *2*(3), 372−380.
(17) Itakura, T.; Kishi, T. *J. Hydr. Engrg. ASCE* **1980**, *106*(8), 1325−1343.
(18) Turan, M. *J. Environ. Engrg. ASCE* **1992**, *118*(5), 776−790.
(19) Richardson, J. F.; Zaki, W. N. *Trans. Inst. Chem. Engrg.* **1954**, *32*(1), 35−53.
(20) Cleasby, J. L.; Fan, K. *J. Environ. Engrg. ASCE* **1981**, *107* (3), 455−471.
(21) Wen, C. Y.; Yu, Y. H. *Chem. Engrg. Progress Symp. Ser.* **1966**, *62*, 100−111.
(22) Dharmarajah, A. H.; Cleasby, J. L. *J. Am. Water Works Assoc.* **1986**, *Dec.*, 66−76.
(23) Hinze, J. O. *Turbulence*; McGraw-Hill: New York. 1959.
(24) Camp, T. R. *J. Sanitary Engrg. ASCE* **1964**, *90* (4), 1−30.
(25) Turan, M. *Optimum porosity in a backwashed filter*, Ph.D. Thesis, Istanbul Technical University, Istanbul, Turkey, 1986 (in Turkish).
(26) Hino, M. *J. Hydr. Engrg. ASCE* **1963,** *89* (4), 161−185.
(27) Monin, A. S.; Obukhov, A. M. In *Buoyancy effects in fluids*; Cambridge University Press: Cambridge, England, 1973.
(28) Cleasby, J. L.; Ives, K. J.; Saatci, A. M. *Filtration in water treatment*; Istanbul Technical University Press: Istanbul, Turkey, 1979 (in Turkish).

Received for review March 27, 2002. Revised manuscript received May 13, 2003. Accepted June 16, 2003.

ES020661R