Chemical Engineering Journal 221 (2013) 292–299

Contents lists available at SciVerse ScienceDirect

Chemical Engineering Journal

journal homepage: www.elsevier.com/locate/cej

Water flow exchange characteristics in coarse granular filter media

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HIGHLIGHTS

- ▶ We measured the inter media water flow exchange distribution.
- ▶ Elution rate decreases at increasing dynamic holdup.
- ▶ High surface area and wide particle size distribution cause low elution rate.
- ▶ High irrigation velocity cause high elution rate and reduced water utilization.
- ▶ We model contaminant elution from particle characteristics and operation settings.

ARTICLE INFO

Article history:
Received 18 October 2012
Received in revised form 30 January 2013
Accepted 1 February 2013
Available online 10 February 2013

Keywords:
Specific surface area related elution velocity distribution
Granular biofilter media
Particle size distribution
Water irrigation rate
Filter moisture content
Liquid holdup

ABSTRACT

Elution of inhibitory metabolites is a key parameter controlling the efficiency of air cleaning bio- and biotrickling filters. To the authors knowledge no studies have yet considered the relationship between specific surface area related elution velocity and physical media characteristics, which constitutes a scientific gap. This study investigates the impact of particle size distribution (considering materials with multiple particle sizes) and irrigation rate on the overall specific surface area related elution velocity distribution in porous granular media. The elution measurements performed in this study are performed at a concurrent airflow of 0.3 m s^{-1}, water irrigation rates of 1–21 cm h^{-1} in materials with particle diameters ranging from 2 to 14 mm to represent media and operation conditions relevant for low flow biotrickling filter design. Specific surface area related elution velocity distribution was closely related to the filter water content, water irrigation rate, media specific surface area and particle size distribution. A predictive model linking the specific surface area related elution velocity distribution to irrigation rate, specific surface area and particle size distribution was developed and predicted the observed specific surface area related elution velocity distributions with a mean error of 9%.

1. Introduction

Biofiltration is a cost effective air pollution control technology [1,2]. A frequent cause of poor biofilter performance is insufficient moisture content and non-uniform moisture distribution within the biofilter medium [3]. Controlling biofilter moisture level is important for biofilter efficiency, as drying of the biofilter medium can reduce biofilter efficiency due to gas flow channeling and localized dry spots with low microbial activity [4–11]. To maintain suitable biofilter moisture content, biofilters often receive pre-humidified air and/or irrigation [6,8,10–12]. Strictly speaking irrigated biofilters becomes biotrickling filters as soon as a moving water phase is present, however, as this study focus on low flow biotrickling filters the term biofilter will be applied to indicate the low irrigation velocity. Irrigation of biofilters can further be utilized for distribution of nutrients, controlling pH and removal of toxic degradation products, all crucial parameters for biofilm activity and biofilter performance [13–15]. In contrast, high volumetric water content (caused by high irrigation rates) can reduce biofilter efficiency by reducing oxygen and substrate supply to the biofilm (especially hydrophobic gaseous compounds) [16–19]. Even in irrigated biofilters, if the water is not evenly distributed in the filter bed, local dry areas or areas with reduced water flow can develop [20], resulting in reduced biomass activity which can lead to decreased overall biofilter performance. Media which facilitates homogeneous distribution of the water flow/water exchange across the complete media specific surface areas therefore seem optimal.

Although water supply to the media specific surface area is known to be a crucial biofilter property relatively little is known about this phenomenon. Distribution of water/air in biofilters is often described through the so-called residence time distribution (RTD), a distribution obtained through tracer tests, where pulses

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http://dx.doi.org/10.1016/j.cej.2013.02.002

Nomenclature

a_t	filter medium specific surface area ($L^2\ L^{-3}$)
C	concentration ($M\ L^{-3}$)
C_d	drainage water salt concentration ($M\ L^{-3}$)
$C_{\text{im-w}}$	immersion water salt concentration ($M\ L^{-3}$)
d_p	particle diameter (L)
d	particle diameter (L)
d_m	mean particle diameter (L)
K_0	empirical constant (–)
K_1	empirical constant (–)
L	filter length (L)
MRE	mean relative error (–)
M_d	mass of drained water (M)
M_{wet}	mass of wet filter media (M)
M_{dry}	mass of dry filter media (M)
M_R	mass of residual salt in the filter media at experiment termination (M)
M_E	eluted salt mass (M)
M_0	initial salt mass (M)
RTD	residence time distribution (–)
S-RTD	specific surface area water retention time distribution
n	number of measurements (–)
q	elution quantile (–)
Q	flow rate ($L^3\ T^{-1}$)
R	particle size range (L)
N_q	number of eluted water filled pore volumes at a given quantile, q = 10%, q = 50% and q = 90% (–)
V	superficial liquid velocity ($L\ T^{-1}$)
WFPV	water filled pore volume (–)
$V_{\text{im-w}}$	volume of immersion water (L^3)
P	parameter for empirical fit
q	quantile (eluted salt/total salt) (–)
t	time (T)
$t_q, t_{10}, t_{50}, t_{90}$	quantile elution time for: any q, q = 10%, q = 50% and q = 90% (T)

Greek letters

α	empirical constant (–)
β	empirical constant (–)
κ_1	empirical constant (–)
κ_2	empirical constant (–)
γ	empirical constant (–)
θ	volumetric water content ($L^3\ L^{-3}$)
μ	viscosity ($M\ T\ L^{-3}$)
ρ	density ($M\ L^{-3}$)
Φ	porosity ($L^3\ L^{-3}$)
Δt	Time interval between measurements (T)

Sub and super scripts

$'$	aggregated empirical constant
N	parameter for N
dyn	dynamic
st	static
b	bulk
w	water
p	particle

of tracer are led through saturated as well as unsaturated columns [21–24]. Simplified RTD in a porous media is an artifact of the presence of mobile and immobile water volumes as well as their internal mass transfer. This means that RTD in theory only depend on these volumes and thereby only indirectly are connected to the media specific surface area. RTD's are therefore independent of inter media dry spots as these do not contribute to the transport nor the retention of tracer. This means that RTD cannot be directly applied for estimating the utilization potential (wetted surface area/total surface area) of the medium. In fact to the authors knowledge no study has addressed specific surface area water retention time distribution (S-RTD) as related to irrigation rate and filter medium particle size distribution in biofilters with air flow based on tracer elution measurements.

The objective of this study is therefore, to develop a method for estimating S-RTD and relate it to media particle size distribution and irrigation rate. The aim is to assess S-RTD as a function of irrigation rate and particle size distribution. S-RTD will be assessed based on breakthrough curves using chloride as a tracer for a range of seven different irrigation rates applied to media with 21 different particle size distributions with particle sizes of 2–14 mm.

As the focus of this study is on the relation between material physical properties and S-RTD, investigations will be carried out under conditions where no biomass is present. This is done to fully understand the link between the S-RTD and the physical properties of the utilized medium. It is recognized that biomass strongly affects biofilter water content as well as pore size distribution [25]. Therefore the results provided in this study cannot be applied directly to biofilters containing biomass, as the presence of biomass is likely to alter the distribution of water. However as this study mainly serves to understand and describe the link between S-RTD and medium physical characteristics, investigations based on clean media were preferred, as uneven distribution of biomass within the filter media will introduce additional uncertainties and complicate the understanding of the relationship.

2. Theory

Irrigation water added to the top of a biofilter will trickle down through the medium creating local regions with different water velocities. The distribution of these velocities depends on the quantity of water held in the filter defined as the total liquid holdup. The total liquid holdup (θ) in irrigated porous media constitutes the dynamic (θ_{dyn}) and static (θ_{st}) holdup. Traditionally the θ_{dyn} in a trickle bed reactor is defined as the drainable volume after gas and liquid flow through the bed are stopped, while the θ_{st} is the remaining volume after drainage [26]. This static holdup consists of the liquid in the intra-particle pores (only for porous particles) as well as the liquid held in the inter-particle pores [26]. Static and dynamic holdup in soils (often labeled water retention) have been investigated extensively [27–29], and a wide selection of predictive expressions are available [27–29]. Soils, however, consists of particles that are typically 2–5 orders of magnitude smaller than for biofilters, thus, flow and retention properties of soils are very different from those found in most biofilter materials. Several correlations relevant for biofilter materials have been proposed [30–35] for predicting these holdups which for materials consisting of spherical particles can be written as:

$$\mathbf{P} = K_1 V^{\alpha} a_t^{\beta} + K_o \qquad (1)$$

where **P** is either θ_{dyn} or θ, V is the superficial liquid velocity, a_t is the specific surface area = $6(1-\Phi)\ d_p^{-1}$, where Φ is total porosity and d_p is particle diameter and K_1 is a combined correlation specific constant including various parameters such as gas and liquid viscosity, gas and liquid density and media porosity. Parameters α, β