Modelling of a recirculating granular medium filter's processes

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Abstract The effluents of French small farm factories will soon be submitted to regulation. Only a few treatment techniques are available to deal with these kind of effluent (high concentration and small daily volumes). To allow the treatment, in the particular economic context of small food processing industries, Cemagref is trying to adapt a treatment based on attached growth cultures on fine media, a system known to be easy to operate and relatively inexpensive. A model, based on four sub-models (hydrodynamic characteristics, oxygen transport, solute transport in the mobile and immobile phases and bacterial evolution) describes this process. Based on wastewater concentration, hydraulic load, applied organic loads, feeding / rest cycles and recycling phases number, this model predicts:

- eliminated organic loads and the discharge concentration as a function of time,
- oxygen and biomass contents as a function of time and depth.

The determination of the model's parameters is based on a comparison between simulations and performances achieved on experimental columns. This model would be helpful in sizing full-scale filters treating different types of agro-food wastewater. The aim of this article is to present the model's structure, to give all parameter values and to compare the simulations with the results obtained on pilot and full scale plants.

Keywords Agro-food industries; attached-growth cultures; full-scale plant; modelling; pozzolana; wastewater treatment

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Introduction

The agro-food industries of rural areas (small dairy producing units, cheese shops, or wineries) produce specific wastewater with COD (Chemical Oxygen Demand) concentrations as high as 10 g L^{-1} for some m^3d^{-1}. For rural areas with a low density of population, this daily organic load (some dozens of kg BOD_5 (Biochemical Oxygen Demand) can get the upper hand on the domestic wastewater. Direct introduction into a collective network cannot always be possible:

- from the economic point of view, high overheads come from overdimensioning of the collective treatment works, particularly when the industrial load is generated in very short periods of time.
- from the technical point of view, the treatment of the mixture of domestic and agro-food wastewater decreases the number of possible treatment processes. If a connection is done afterwards to an existing treatment plant of the rural district, malfunctions often occur.

In some cases, even partial in-situ treatment can be the best technical and economical solution.

Nowadays treatment works with suspended cultures (activated sludge, aerated lagoons, …) are proposed for these types of effluents. But technical-economic possibilities of small agro-food units are not sufficient for such conventional technologies because of their complex and costly maintenance. Except for land spreading, only possible in the case of favourable pedological and hydrogeological context, there is currently a lack of alternative systems for the wastewater treatment of such units.

Reed bed filter treatment works (Boutin *et al.*, 1997) are currently being developed. They should soon be proposed to the smallest farms in order to treat only the washing water of milking equipment of which COD, without whey, reaches 2 g L^{-1}. The applied surface loading rate is not greater than 70 g GOD m^{-2} j^{-1} (GOD is Global Oxygen Demand, i.e. COD + 4.57N-Nk), but this process is suitable for the treatment of a few kg BOD_5 d^{-1}. This process doesn't fit well for higher units. Economically, even though available areas are present in rural districts, investment quickly becomes unaffordable for the owner. Technically, when infiltration surfaces are large, effluent distribution becomes more difficult when influent is concentrated and, by the way, when the volumes to be infiltrated (in the function of the filter surface) are low. In this context, Cemagref is doing development work on attached growth cultures by using media rougher than sand (gravel, pozzolana …).

Mechanisms and working principle

Purifying mechanisms which have been developed for these filters fall between:

- the Trickling Filters (TF) for which the available oxygen quantity is not a restrictive factor and the distribution of the biomass across the lining is almost homogeneous.
- the Sand Filters (SF) in which the major part of the purifying biomass concentrates in the first centimetres (Guilloteau *et al.*, 1993).

As in SF, feeding of the granular filters is done by batches. The disjointed wastewater feeding phases are followed by rest periods which contribute to the control of the development of the fixed biomass. This biomass drops because of lack of feeding. With such biomass self control conditions, there is no need of a settling device to separate treated water and sludge, which simplifies operation conditions.

As in TF, wastewater drips on the media, then is re-circulated several times a day.

Wastewater, after one day storage, accesses the filter, drips on it, goes into a recycling tank and is sent again to the filter's surface. This process is repeated several times a day in order to obtain a contact time "bacteria–wastewater" sufficient to achieve, at the end of the treatment, a sufficiently low COD concentration.

Thomas (1996) pointed out COD yields greater than 90% on dairy effluents with COD concentrations greater than 10 g L^{-1}. This was achieved through pozzolana filters (3 to 7 mm granulometry) at an applied load of 500 g GOD m^{-2} d^{-1} with a 4 times/day cycle. For loads above 300 g GOD m^{-2} d^{-1}, quality percolate recycling procedures seem to be needed. The slight complication of the resulting treatment work (additional pumps and automation) is widely compensated by the reactor's size reduction.

To confirm that this system, using materials coarser than sand, could be applied to a large variety of situations, setting of a numerical simulation model appeared necessary. The setting of this model supposes also a concept formalization in order to structure the experimental steps for use of materials of a granulometry rougher than sand. The model's description is the object of this article.

Model description

A non-saturated porous media is composed of 4 distinct phases (when being the base of the development of a metabolically active population): solid particles, liquid and gaseous phases, and biomass (Baveye and Valocchi, 1989). Except for the supposed inert media, the biofilm and the liquid and gaseous phases are continuously interacting and each phase configuration is constantly evolving. A global model comprising 4 sub-models has been proposed to characterise the purifying processes in the gravel filters.

Hydrodynamic model

There are 3 different types of humidity in porous media (Bear, 1979):

- mobile water, due to gravity, circulates into the macroporosity of the media.
- retention or capillary water stays in the media after all mobile water has been drained.
- microbial development behaves as an additional liquid phase. It comprises a developing active part of the biofilm, ρ^{biof}. But also, a non-active part, ρ^{accu}, comes from bacterial death. In fact, micro-organism death generates matter which can be either biodegradable (and reused by live bacteria) or non-biodegradable. This latter, ρ^{accu}, accumulates in the filter (Horn and Hempel, 1997; Henze *et al*., 1997).

  The microbial phase and the retention water constitute the stagnant liquid phase:

$$\begin{cases} \theta = \theta^{mob} + \theta^{stag} \\ \theta^{stag} = \theta^{res} + \lambda \cdot \left(\rho^{biof} + \rho^{accu}\right) \end{cases} \quad (1)$$

where θ[ad.] is the total volume humidity, θ^{mob}[ad.] the mobile volume humidity, θ^{stag}[ad.] the stagnant volume humidity, θ^{res}[ad.] the retention volume humidity, λ [$L^3\ M^{-1}$] the mass volume of the biomass and ρ^{biof} [$M\ L^{-3}$] and ρ^{accu} [$M\ L^{-3}$] the VSS concentrations of the active and accumulated biomass respectively. The process to be modelled is based on an intermittent non-saturated flow. A correlation can be established between the flow in a gravel media and the flow in the macro-pores (Beven and Germann, 1982). This leads to a non-dispersive model, piston flow type, described by Fokker-Plank:

$$\frac{\partial \theta_{mob}}{\partial t} = -\frac{\partial[q(\theta)]}{\partial z} \quad (2)$$

where $q(\theta)$ [$L.T^{-1}$] is the infiltration specific flow.

The specific flow is a function of the hydraulic conductivity $K(\theta)$[$L\ T^{-1}$] and also of the capillary diffusivity D_z [$L^2\ T^{-1}$] according to the following Eq. (3):

$$q(\theta) = -\left[Dz\frac{\partial \theta}{\partial z}\right] - K(\theta) \quad (3)$$

Because of the batch feeding and of the material's size, diffusion phenomena are negligible. Eqs (2) and (3) can be simplified by the flow equation of Richards:

$$\frac{\partial \theta_{mob}}{\partial t} = -\frac{\partial[K(\theta)]}{\partial z} \quad (4)$$

The model of hydraulic conductivity (Figure 1 and Eq. (5)) is the one proposed by Kozensy (Taylor and Jaffe, 1990):

$$K(\theta) = K_{so}\left[\frac{\theta - \theta^{res}}{\phi - \theta^{res}}\right]^{n_o} \quad (5)$$

where ϕ [ad.] is the total porosity or water content in saturated media, n_0 [ad.] a typical coefficient of the media (so called trail parameter) and K_{so} [$L\ T^{-1}$] the hydraulic conductivity at saturation.

To take account of the bacterial development, Chachuat (1998) proposed the hydraulic conductivity of a colonized porous media, when saturated, as the one of a virgin media of which the total porosity would be reduced by the biofilm humidity. It leads to a translation of a factor $\lambda.\ (\rho^{biof} + \rho^{accu})$ of the curve: $K = f(\theta)$ (Figures 1 and 2). The influence of the biofilm development on the hydraulic conductivity is described in Eqs. (6) and (7):

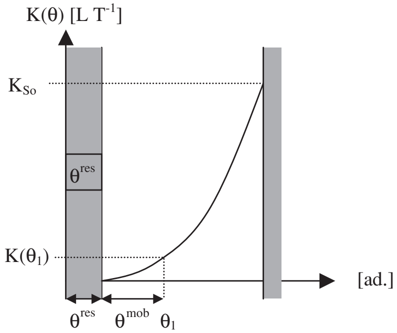

Figure 1 *K = f(θ)* for non-colonized media

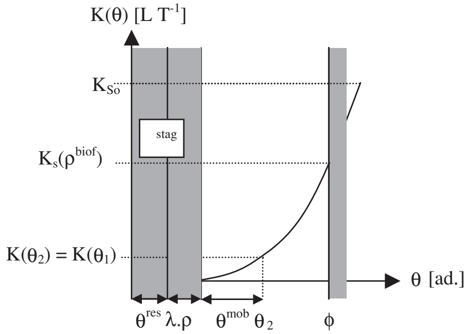

Figure 2 *K = f(θ)* for colonized media

$$K_S(\rho^{biof}) = K_{So}.\left[1-\frac{\lambda.\left(\rho^{biof}+\rho^{accu}\right)}{\phi-\theta^{res}}\right]^{n_0} \tag{6}$$

$$\text{So} \quad K(\theta) = K_{So}\cdot\left[\frac{\theta^{mob}}{\phi-\theta^{res}}\right]^{n_0} \tag{7}$$

Oxygen transfer model

Oxygen is supplied by the air phase; the dissolved oxygen brought the applied wastewater has not been taken into account (Zhu *et al.*, 2001). In these conditions, atmospheric oxygen transfer inside filters and its evolution by diffusion, convection and consumption (Schmitt, 1989) is represented by Eq. (8):

$$\frac{\partial\left[\Phi_a\cdot C_{oxy}^{gaz}\right]}{\partial t} = \frac{\partial}{\partial z}\left[D_{oxy}\cdot\frac{\partial C_{oxy}^{gaz}}{\partial z} - q_{air}.C_{oxy}^{gaz}\right] - R_{oxy} \tag{8}$$

where C_{oxy}^{gaz} [M L^{-3}] is the oxygen concentration in the gaseous phase, Φ_a [ad.] the free porosity in air, D_{OXY} [L^2 T^{-1}] the diffusion coefficient of oxygen in the air phase, q_{air} [L T^{-1}] the specific flow of air and R_{OXY} [M L^{-3} T^{-1}] the "oxygen uptake" corresponding to the biological degradation of the pollution.

No data about the diffusion coefficients in gravel media could be found in the literature. Xu *et al.* (1992) compared the diffusion functions from several writers concerning the utilized materials. The "glass balls" material (Currie, 1960) is the closest to the rough filters material. So a diffusion function has been retained:

$$D_{oxy}/D_o = K.\left(\Phi_a\right)^m \tag{9}$$

where D_o[L^2T^{-1}] is the diffusion coefficient in air at 273K at atmospheric pressure, K [ad.] and m [ad.] are experimental constants.

The convection Eq. (10) is the one proposed by Schmitt (1989) with α_{o_2}[T^{-1}] and α_{gaz} [T^{-1}] being respectively oxygen consumption and CO_2 discharge by time measure:

$$\frac{\partial q_{air}}{\partial z} = -\frac{\partial\Phi_a}{\partial t} - \alpha_{o_2} + \alpha_{gaz} \tag{10}$$

Bect (2000) supposed that the air flow was only due to the variation of the water quantity inside the filter. So, the consumed oxygen quantity is equilibrated with the discharge of produced CO_2. Eq. (10) is simplified and Eq. (8) becomes:

$$\Phi_a . \frac{\partial C_{oxy}^{gaz}}{\partial t} = \frac{\partial}{\partial z}\left[D_o . K . (\Phi_a)^m . \frac{\partial C_{oxy}^{gaz}}{\partial z}\right] - q_{air} . \frac{\partial C_{oxy}^{gaz}}{\partial z} - R_{oxy} \quad (11)$$

Solute-transfer model

As in the hydrodynamic model, the dichotomy between liquid mobile phase and stagnant phase is maintained (Figure 3). Assimilation of solutes by micro-organisms is supposed to happen exclusively in the stagnant zone. A linear diffusion model represents the solute flow between the two phases.

In the mobile part, the mass transport of the solutes, as described by Eq. (12), is composed of a convective part and a dispersive part, together with solutes exchanges between both phases.

$$\frac{\partial\left[\theta_{mob} . C_{COD}^{mob}\right]}{\partial t} = -\frac{\partial\left[q . C_{COD}^{mob}\right]}{\partial z} + \frac{\partial}{\partial z}\left[D_{COD} . \theta^{mob} . \frac{\partial C_{COD}^{mob}}{\partial z}\right] - \alpha\left[C_{COD}^{mob} - C_{COD}^{stag}\right] \quad (12)$$

where C_{COD}^{mob} [M L^{-3}] is the COD concentration in the mobile part, C_{COD}^{stag} [M L^{-3}] is the COD concentration in the stagnant part, D_{COD} [L^2 T^{-1}] the dispersion coefficient of the COD in the *z* direction and α [T^{-1}] the transfer coefficient between both phases.

In the stagnant part, the solute distribution is supposed to be uniform across the liquid film thickness. The mass transport of the solute results from solute exchanges with the mobile phase plus the degradation by the biomass.

In addition, as mentioned above, the micro-organisms' death produces solutes which add to the substrate. All these reactions can be summarized in Eq. (13) (Parouty, 2001).

$$\frac{\partial\left[\theta_{stag} . C_{COD}^{stag}\right]}{\partial t} = \alpha\left[C_{COD}^{mob} - C_{COD}^{stag}\right] - R_{COD} + R_{BIO} \quad (13)$$

R_{COD} [M L^{-3} T^{-1}] is the term substrate uptake which corresponds to the biological degradation of the pollution. R_{BIO} [M L^{-3} T^{-1}] is the part of dying microorganisms which is biodegradable.

Biological degradation model

The development of micro-organisms inside the filters is usually limited by some chemical substances (Baveye and Valocchi, 1989). For this study, limiting factors are substrate availability (measured by the COD) and oxygen availability. This duality (Widdowson *et al.*, 1988 ; Wood *et al.*, 1995) is described in Eq. (14):

$$R_{COD} = \frac{\mu_m}{Y} \cdot M_{COD} \cdot M_{OXY} . \rho^{biof} \quad (14)$$

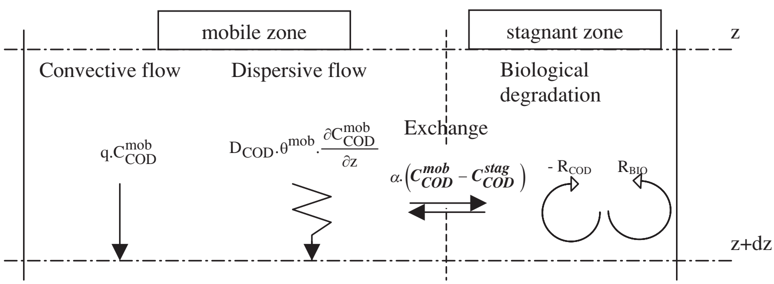

Figure 3 Schematic representation of a solute-transfer model

where μ_m [T^{-1}] is the maximal rate of bacterial development, Y [ad.] the yield of the conversion of the substrate into biomass, M_{COD}[ad.] and M_{OXY} [ad.] are Monod relations:

$$M_{COD} = \frac{C_{COD}^{stag}}{K_{COD}^{1/2} + C_{COD}^{stag}} \qquad M_{OXY} = \frac{C_{OXY}^{biof}}{K_{OXY}^{1/2} + C_{OXY}^{biof}}$$

$K_{COD}^{1/2}$ [M L^{-3}] and $K_{OXY}^{1/2}$ [M L^{-3}] are respectively the semi-activity concentrations compared with COD and oxygen in the biofilm and C_{oxy}^{biof} [M L^{-3}] the oxygen concentration in the biofilm.

The oxygen concentrations in the gaseous phase and in the biofilm are balanced and proportional. This is explained by the fact that the thin biofilm thickness allows sufficiently quick exchanges between both phases (Bect, 2000), so that Henry's law, where H[ad.] is the Henry constant, can be applied:

$$C_{oxy}^{gaz} = H.C_{oxy}^{biof} \qquad (15)$$

This proportionality allows the definition of all oxygen concentrations in the gaseous phase (Eq. (16)) which is the single parameter that can be easily measured thanks to an oxymeter.

$$M_{OXY} = \frac{C_{OXY}^{gaz}}{H.K_{OXY}^{1/2} + C_{OXY}^{gaz}} \qquad (16)$$

The oxygen consumption (Eq. (11)) results from the conversion of the substrate into biomass, but also from their maintenance. These two parameters are integrated in Eq. (17):

$$R_{OXY} = (\gamma.\mu_m.M_{COD} + \beta.K_d).M_{OXY}.\rho^{biof} \qquad (17)$$

where γ [ad.] is the oxygen utilization coefficient for the bacterial synthesis, K_d [T^{-1}] the self-regulation coefficient of the biomass and β [ad.] the oxygen utilization coefficient for the microorganisms' catabolism.

With the hypothesis that the convection transport of the biomass inside the liquid does not exist, the active biofilm development (Refsgaard *et al*, 1991; Wood *et al.*, 1995) can be expressed by:

$$\frac{\partial \rho^{biof}}{\partial t} = Y \cdot R_{COD} - K_d \cdot M_{OXY} \cdot \rho^{biof} \qquad (18)$$

The terms $K_d \cdot M_{OXY} \cdot \rho^{biof}$ in Eq. (18), represent the regression of the active biomass which means true bacterial death together with the simple utilization of the reserves during food shortage.

The accumulated biomass evolution (Eq. (19)) is supposed to be proportional to the evolution of the regressing active biomass (Parouty, 2001), f [ad.] being the proportionality factor.

$$\frac{\partial \rho^{accu}}{\partial t} = f.K_d.M_{OXY}.\rho^{biof} \qquad (19)$$

$R_{BIO,}$ being the substrate contribution because of micro-organisms' death is described by Eq. (20).

$$R_{BIO} = \delta.f'.K_d.M_{OXY}.\rho^{biof} \qquad (20)$$

δ [ad.] is the transformation coefficient of the biomass into COD and f' [ad.] the biodegradable part of the dying biomass. The sum of f and f' is not always equal to 1 because the biomass regression is subject to other phenomena than only bacterial death.

The 12 equations ((1), (4), (7), (11), (12), (13), (14), (17), (18), (19) and (20)) concerning 12 unknown factors constitute the structure of this model which has been written in FORTRAN 90. The retained discretization method is the finite differences, adopted schemes being in explicit terms for time, except Eqs. (4) and (12).

Results and discussion

Estimation of model parameters

Experimental studies on pozzolana-filled laboratory columns, already described by Ménoret *et al.* (2000, 2002), have led to the estimation of several parameters of the simulation model.

This calibration of the model, which is not the scope of this article, has been performed first on the hydrodynamic parameters, then on the parameters linked to the substrate transfer, then on those linked to the oxygen transfer and finally on the bacterial development. All these parameters are summarized in Table 1.

Comparison with columns

These columns are fed with an effluent reconstituted from powdered milk and whey in order to obtain a stable concentration of 8.4 g $COD_{filtered}$ L^{-1}. The applied organic load is 252 g $COD_{filtered}$ m^{-2} d^{-1}. Figures 4 and 5 compare the results of the model and the measures obtained from the columns and represent, at the end of the seventh feeding period, discharged volumes and COD load removal at the end of each feeding day. The process of both systems is based on 6 recycling and a 7 days feeding followed by 7 days rest period.

The average relative error calculated for the discharged volumes achieves about 10% and for the COD removal less than 1%. The first day final COD removal is the only one

Table 1 Parameters values taken in account in this model

Parameters		Symbols		Values
Dispersion coefficient of COD	(Bect, 2000)	D_{COD}	$[L^2 T^{-1}]$	0.07 $cm^2\ s^{-1}$
Air diffusion coefficient at 273°K and atmospheric pressure	(Bect, 2000)	D_o	$[L^2 T^{-1}]$	0.22 $cm^2\ s^{-1}$
Accumulation part of the biomass	(Parouty, 2001)	f	[ad.]	4.5 10^{-2}
Biodegradable part of the dying biomass	(Parouty, 2001)	f'	[ad.]	60 10^{-2}
Henry's constant	(Bect, 2000)	H	[ad.]	28
Parameter of oxygen diffusion function	(Bect, 2000)	K	[ad.]	1
Self regulation coefficient of the biomass	(Bect, 2000)	K_d	$[T^{-1}]$	0.2 j^{-1}
Semi-activity concentration compared with the COD	(Bect, 2000)	$K^{1/2}_{COD}$	$[M L^{-3}]$	0.12 $g\ L^{-1}$
Semi-activity concentration compared with the O_2 in the biofilm	(Bect, 2000)	$K^{1/2}_{OXY}$	$[M L^{-3}]$	10^{-3} $g\ L^{-1}$
Hydraulic conductivity at saturation	(Chachuat, 1998)	K_{so}	$[L T^{-1}]$	7 $cm\ s^{-1}$
Parameter of oxygen diffusion function	(Bect, 2000)	m	[ad.]	1.4
Trail parameter	(Parouty, 2001)	n_0	[ad.]	7.5
Yield of conversion of the substrate into biomass	(Bect, 2000)	Y	[ad.]	0,5
Transfer between mobile and stagnant phases	(Parouty, 2001)	α	$[T^{-1}]$	5.5 10^{-6} s^{-1}
Oxygen utilization for the micro organisms catabolism	(Parouty, 2001)	β	[ad.]	1
Oxygen utilization for the bacterial synthesis	(Parouty, 2001)	γ	[ad.]	0,5
Transformation coefficient of the biomass into COD	(Parouty, 2001)	δ	[ad.]	2 g COD $(g\ VSS)^{-1}$
Retention volume humidity	(Chachuat, 1998)	θ_{res}	[ad.]	8.7 10^{-2}
Mass volume (in MVS) of the biomass	(Parouty, 2001)	λ	$[L^3 M^{-1}]$	0.05 $L\ g^{-1}$
Maximal rate of bacterial development	(Bect, 2000)	μ_m	$[T^{-1}]$	10 j^{-1}
Total porosity	(Chachuat, 1998)	Φ	[ad.]	54 10^{-2}

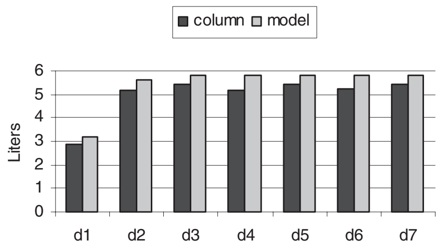

Figure 4 Discharged volumes each day

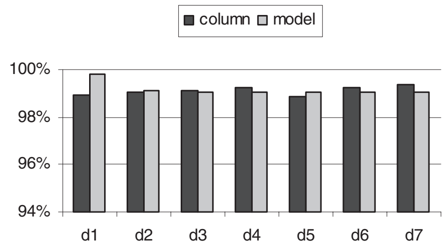

Figure 5 COD load removal each day

to be overestimated, but only slightly, the error being lower than 1%. When compared to the measures coming from the columns, the tuning of the model seems to be sufficiently precise to consider the model as a valid tool for future installation dimensioning.

Comparison with the wastewater plant of Pradel (France)

Since 1996, the experimental caprin farm of the Pradel has treated effluents according to this process. The system receives a mix of washing parlour effluents and the milk serum from the cheese dairy, the washing water of the dairy and domestic wastewater from the toilets. The average concentration of the influent, measured in June 2000 (Ménoret *et al.*, 2002) is 9.8 g. $COD_{filtered}$ $L^{-1}d^{-1}$ leads to a COD loading rate of 330 g m^{-2} d^{-1}. The standard deviation of the applied load (8.3 kg $COD_{filtered}$ d^{-1}) confirms the variability of the pollution to be treated. (Table 2). The average yield of COD removal reaches 98%.

Figure 6 compares the yields calculated from the loads on site and those calculated from the model integrating the daily load variations. The tuning is not fully satisfactory as the calculated yield is only about 92% versus the actual measurement of 98%. This can be explained by the existence of operating conditions different between the model and the plant: database of applied loads, flow and duration of feeding's phases, influent's quality, etc. Nevertheless the very different shapes of the curves indicate that the purifying mechanisms are not yet correctly modelled. What is surprising is the fact the model predicts the weakest yields at the beginning of the feeding week. A potential explanation could be an underestimation of the impact of the biological development on permeability.

Conclusion

An one-dimensional mathematical model allowing the simulation of the purifying mechanisms inside filters with rough material (pozzolana) has been developed. This model is composed of the assembling of four modules describing the effluent drainage in the filter, the solutes exchanges, the gaz exchanges and the biological degradation in function of time and depth. Compared to the column's results, our model is correctly calibrated. The

Table 2 Influent and effluent at Pradel farm

Days	COD_{raw} (mg L^{-1})	$COD_{filtered}$ (mg L^{-1})	Applied load (kg $COD_{filtered}$ d^{-1})	Discharged load (kg COD d^{-1})
D1	12,950	(11,000)*	36.50	0.72
D2	7,000	6,040	19.25	0.25
D3	6,860	6,030	17.95	0.22
D4	8,175	7,525	18.15	0.37
D5	12,880	11,420	22.25	0.52
D6	14,225	12,845	8.85	0.315
D7	16,050	(14,000)*	18.35	0.32
Average	11,600	9,835	20.20	0.40

* estimated value

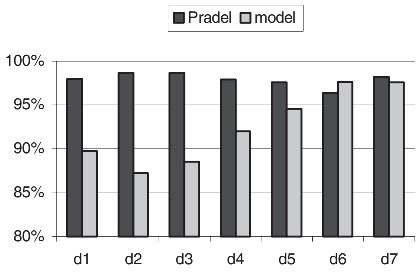

Figure 6 COD removal each day

predictive yield calculation, based on load, can be given with an error lower than 1%. But after comparison with the results coming from a full-scale plant, the model is still not sufficiently accurate.

Acknowledgements

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