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CFD study on hydraulic performance of subsurface flow constructed wetland: Effect of distribution and catchment area

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Abstract−A subsurface flow constructed wetland (SSFW) was simulated by using a commercial computational fluid dynamic (CFD) code (Fluent 6.22, Fluent Inc.). The liquid residence time distribution in the SSFW was obtained by the particle trajectory model. The simulation confirmed that the effect of the distribution and/or catchment area on the hydraulic efficiency is significant. An inappropriate horizontal distribution and/or catchment area can result in poor hydraulic efficiency. The hydraulic efficiency of the SSFW with the vertical distribution and/or catchment area can be kept at a high level (above 0.898). The design of the vertical distribution and/or catchment area in the SSFW is better than that of the horizontal. From the point of view of the engineering design, a small dimension distribution and/or catchment area in the SSFW is advisable, which maintains a considerable hydraulic efficiency of the SSFW (above 0.840), but also benefits the increase of the purge area.

Key words: Subsurface Flow Constructed Wetland, Computational Fluid Dynamics, Distribution Area, Catchment Area, Hydraulic Efficiency

INTRODUCTION

Subsurface flow constructed wetland (SSFW) has received much attention for the environmental engineering field, due to its low construction costs, simple operation and maintenance, little secondary pollution and a favorable environmental appearance [1,2]. In practice, the pre-treated wastewater flows through the SSFW and is treated by the various types of media and the biofilm formed on the media. Therefore, it is reasonable to regard the SSFW as a biochemical packed-bed macro-reactor.

The hydraulic performance of the SSFW, as the transfer performance of the reactor, has a significant influence on the efficiency of the SSFW. An appropriate hydraulic design not only improves the pollutant removal efficiency but also reduces the cost and volume of the wetland [3-5].

There are many factors that affect the hydraulic performance of the SSFW. Some impact parameters of the hydrodynamic behavior of constructed wetlands have been investigated, such as the vegetation [6,7], flow parameters [8], inlet and outlet location [9] and so on [10-12]. However, the distribution and catchment area in the SSFW, which may influence the development of preferential paths and dead zones, has not been explored prior to this study.

In addition, the traditional method to investigate the hydraulics of the SSFW is usually associated with the physical tracer experiment, which may be labor intensive, expensive and time consuming [13]. However, computational fluid dynamics (CFD), as a easy, inexpensive and sophisticated design and analysis tool, has been applied in a widespread field. At present, the majority of CFD research of wastewater treatment facilities is focused on wastewater ponds or sedimentation tanks [14-17]. None provide a CFD model for the SSFW. Thus, it is significant to investigate the hydraulics of the SSFW by using CFD.

In this paper, the CFD simulation technique is applied to an SSFW. By using a commercial CFD code, Fluent 6.22 (Fluent Inc.), this study reveals the flow patterns in the SSFW and evaluates the hydraulic performance of the SSFW with different designs of the distribution and catchment areas. This can provide references for engineers to optimize the design of the distribution and catchment areas in the SSFW.

CFD MODEL

1. Physical Model

Fig. 1 is a sketch of the SSFW. It can be seen that the inner of the SSFW is divided to many symmetric cells by the inlet conduit and outlet conduit. Therefore, it is appropriate to substitute the symmetric cell of the SSFW for the whole SSFW as the studied object.

The simplification of the symmetric cell of the SSFW can be seen in Fig. 2. Each cell of the SSFW consists of the plant-soil layer and media districts (Fig. 2(a)). In the SSFW, the inlet conduits are kept under the plant-soil layer and the effect of the plant-soil lay on the

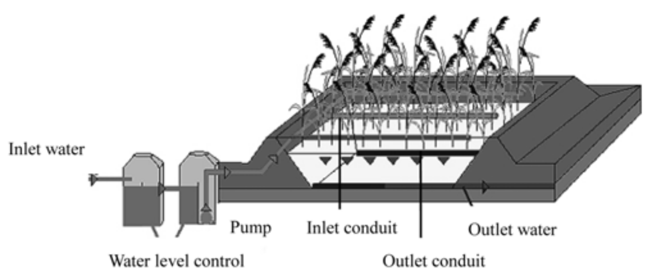

Fig. 1. The sketch of the subsurface flow constructed wetland (SSFW).

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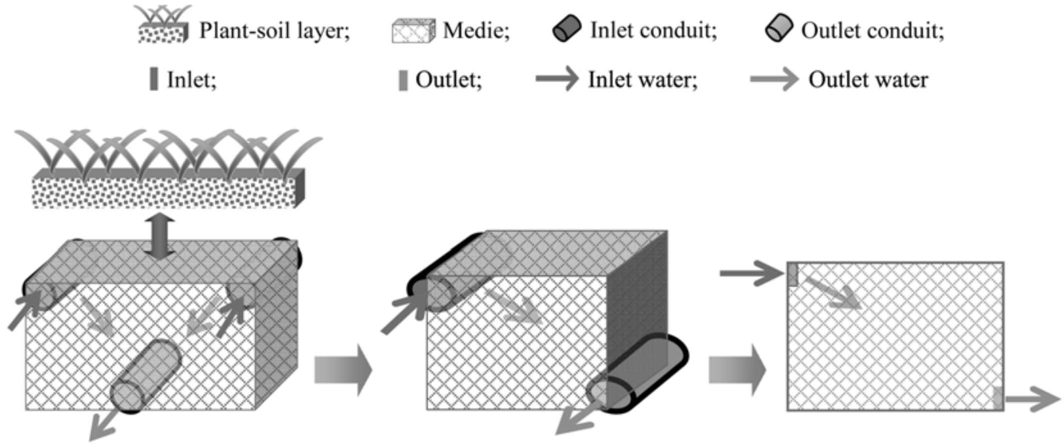
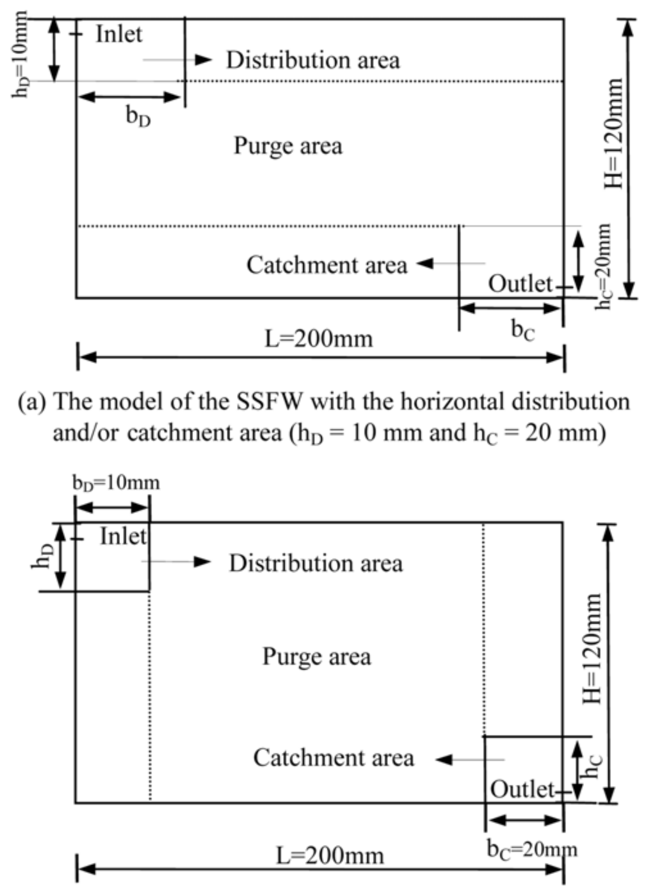


(a) A symmetric cell of the SSFW (b) Three-dimensional model of the media (c) Two-dimensional model of the media

Fig. 2. The simplification of the SSFW.



(a) The model of the SSFW with the horizontal distribution and/or catchment area (h_D = 10 mm and h_C = 20 mm)

(b) The model of the SSFW with the vertical distribution and/or catchment area (b_D = 10 mm and b_C = 20 mm)

Fig. 3. Two-dimensional models of the SSFW. The subscript of D: the distribution area; the subscript C: the catchment area; b: the width of area (distribution or catchment area); h: the height of area (distribution or catchment area).

flow of the wastewater is slight. Therefore, only the media district in the symmetric cell is studied in this paper (Fig. 2(b)). Lastly, a two-dimensional model of the media district in the symmetric cell is developed by reasonable simplifications (Fig. 2(c)).

To investigate the effect of the distribution and catchment area on the hydraulic performance of the SSFW, two models of the SSFW are set up according to the simplified SSFW (Fig. 3). The simulation conditions and geometric parameters of the models can be seen in Table 1.

2. Mathematical Model

2-1. Governing Equations

The following set of equations governs the mass and momentum of the flows in porous media [18,19].

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \bullet (\rho v_i) = 0 \tag{1}$$

Here ρ is the density of the liquid [kg m^{-3}]; v is the velocity vector [m s^{-1}].

Momentum balance equation:

$$\frac{\partial (\rho v_i)}{\partial t} + \nabla \bullet (\rho v_i v_i) = -\nabla p + \nabla \bullet [\mu(\nabla v_i + (\nabla v_i)^T)] + \rho g + S_i \tag{2}$$

Here p is the static pressure [Pa]; μ is the dynamic viscosity [Pa s]; S_i is the source term for the ith (x, y, or z) momentum equation.

For the case of simple homogeneous porous media, S_i is defined as:

$$S_i = -\left(\frac{\mu}{\alpha} v_i + C_2 \frac{1}{2} \rho |v_i| v_i\right) \tag{3}$$

Here α is the permeability [m^2]; C_2 is the inertial resistance factor [m^{-1}]. They can be estimated from:

$$\alpha = \frac{D_p^2}{150} \frac{\varepsilon^3}{(1-\varepsilon)^2} \tag{4}$$

$$C_2 = \frac{3.5}{D_p} \frac{(1-\varepsilon)}{\varepsilon^3} \tag{5}$$

Here D_p is the mean media diameter [m] and ε is the void fraction of the media (dimensionless). ε_1 and ε_3 is the void fractions of the gravel in the distribution area and catchment area, which value can be obtained by the empirical formulas (ε=0.039$D_p^{-0.51}$, D_p=5-50 mm). ε_2 is the void fraction of the sand in the purge area, which usually

Table 1. Simulation conditions and geometric parameters of the model

Parameters	Description	Value
Operating conditions	Feed component	H_2O
	Feed temperature (K)	293.15
	Inlet velocity (u, m/s)	8.8419×10^{-5}
	Outlet pressure (Pa)	102599
The SSFW	SSFW width (L , mm)	200
	SSFW height (H, mm)	120
	Inlet and outlet diameter (d, mm)	2
Distribution area in the SSFW	Mean diameter (d_1, mm)	30
	Void fraction (ε_1, %)	24
	Viscous resistance coefficient ($1/\alpha$,$1/m^2$)	6.96×10^6
	Inertial resistance coefficient (C_2, 1/m)	6.41×10^3
Purge area in the SSFW	Mean diameter (d_2, mm)	1
	Void fraction (ε_2, %)	43
	Viscous resistance coefficient ($1/\alpha$, $1/m^2$)	6.13×10^8
	Inertial resistance coefficient (C_2, 1/m)	2.51×10^4
Catchment area in the SSFW	Mean diameter (d_3, mm)	30
	Void fraction (ε_3, %)	24
	Viscous resistance coefficient ($1/\alpha$,$1/m^2$)	6.96×10^6
	Inertial resistance coefficient (C_2, 1/m)	6.41×10^3

is during 43-47%. In this paper, ε_2 is chosen as 43%.

2-2. Boundary Conditions

The boundary conditions of inlet and outlet are velocity inlet and pressure outlet, and the values of them are 8.8419×10^{-5} m s^{-1} and 102,599 Pa, respectively. The inlet velocity is calculated according to the conventional hydraulic load of the subsurface constructed wetland, which usually is from 0.02 to 0.15 m/d. In this paper, the flow area and inlet diameter are 240 mm2 (20*12 mm) and 2 mm, respectively. Therefore, when the hydraulic load is 0.076 m/d, the inlet velocity is 8.8419×10^{-5} m/s. The outlet pressure is equal to the sum of the atmosphere pressure and the outlet water pressure. When the atmosphere pressure is 101,325 Pa and the water pressure is 1,274 Pa (0.12H_2O m), the outlet pressure is 102,599 Pa. The boundary conditions are specified at all external boundaries based on the following assumptions:

- The liquid velocity and temperature are uniform at the entrance.
- A fully developed laminar flow characterizes the hydrodynamics among the porous media inside the wetland.
- The external wall of the wetland is adiabatic; there is no slip condition and zero radial concentration gradient at the wall of the wetland.

2-3. Model Solution

The numerical grids of the model were created by using Gambit 2.2.30 and adopting quadrangular elements. The solution of the model used a two-dimensional steady laminar segregated solver. In all the options in the code, the technique of finite volume was selected to solve the governing equations. Frequently, suitable values of the under-relaxation factors were adopted to ensure the smooth convergence of the numerical solution.

EVALUATION OF HYDRAULIC PERFORMANCE

CFD simulation presents the flow field, which has the advantage of qualitative analysis of hydraulic characteristics because it provides a visual display of the flow pattern in SSFWs. At the same time, the liquid resident time distribution (RTD) gotten by introducing the particle trajectory model provides parameters to quantitatively evaluate the hydraulic performance of SSFW. These parameters include normalized retention time (t_θ), normalized variance (σ_θ^2) and hydraulic efficiency (λ). They are defined by the following equations [9,16,20-22].

$$t_\theta=\frac{t_{mean}}{t_n} \tag{6}$$

$$t_{mean}=\frac{\int_0^\infty tf(t)dt}{\int_0^\infty f(t)dt} \tag{7}$$

$$t_n=\frac{V_R}{V_0} \tag{8}$$

$$\sigma_\theta^2=\frac{\sigma^2}{t_n^2}=\frac{(\sigma)^2}{t_n^2} \tag{9}$$

$$(\sigma)^2=\frac{\int_0^\infty (t_{mean}-t)^2 f(t)dt}{\int_0^\infty f(t)dt} \tag{10}$$

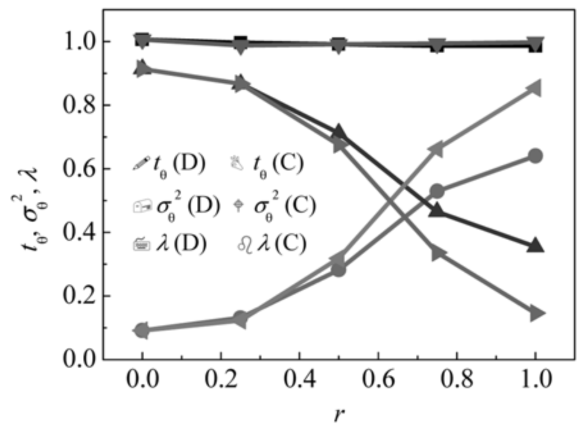
$$\lambda=t_\theta(1-\sigma_\theta^2) \tag{11}$$

Here t_n is the theoretical residence time [s]; V_R is the wetland volume [m^3]; V_0 is the inflow volume per time unit [m^3 s^{-1}]; t_{mean} is the average time; f(t) is the RTD function. σ is the standard deviation from the average time; σ^2 is the variance.

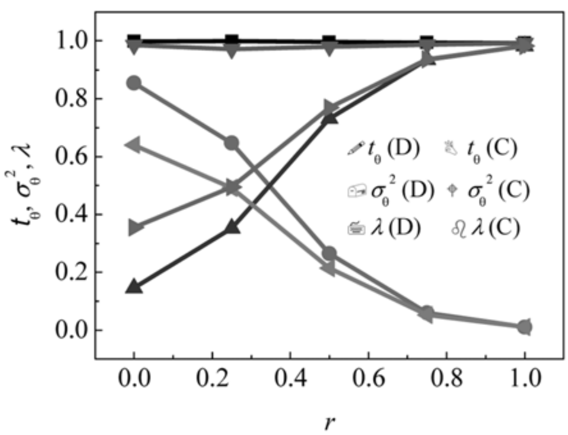
t_θ describes the amount of time that wastewater spends within the system, on which the amount of treatments occurring depends. Therefore, a larger t_θ benefits the treatment of pollutant.

σ_θ^2 provides information on the amount of dispersion and mixing present in an SSFW system. The SSFW can be regarded as a first-order biochemical reactor. According to the reactor theory, for a first-order reaction, compared to the reactor with complete stirred flow (σ_θ^2=1), the reactor with plug flow (σ_θ^2=0) has better efficiency. Hence, in the SSFW a smaller σ_θ^2 benefits the treatment of pollutant.

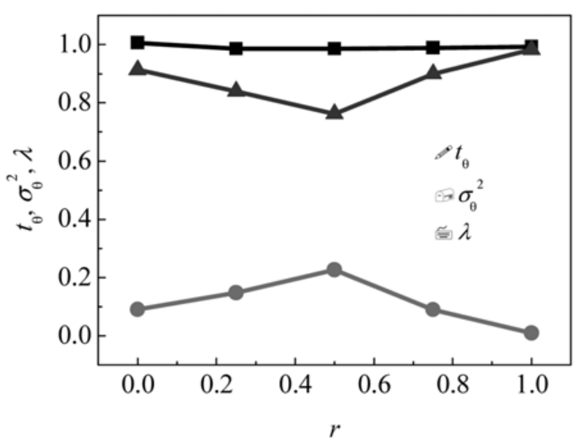
λ is a simple and effective parameter for characterizing the hydraulic performance of wetland [22]. The closer to 1 λ is, the better the hydraulic efficiency of the SSFW.



(a) Either horizontal distribution area or horizontal catchment area



(b) Horizontal distribution area with b_C = 200 mm or horizontal catchment area with with b_D = 200 mm



(c) Symmetrically horizontal distribution and catchment area

Fig. 4. Effect of the horizontal distribution and/or catchment area on the hydraulic performance of the SSFW. r: the ratio of b_D or b_C to L; (D) and (C): the variation of the distribution area and catchment area, respectively.

RESULTS AND DISCUSSION

1. Effect of the Horizontal Distribution and/or Catchment Area

With the height of the distribution area at 10 mm and catchment area at 20 mm, the effect of the horizontal distribution and/or catchment area on the hydraulic efficiency of the SSFW was studied. Three cases were considered: (a) either horizontal distribution area or horizontal catchment area; (b) horizontal distribution area with b_C=200 mm or horizontal catchment area with b_D=200 mm; and (c) symmetrically horizontal distribution and catchment area. The results are shown in Fig. 4.

It can be observed in Fig. 4 that the residence time (t_θ) remained at a steady level in all reviewed cases, and the hydraulic efficiency (λ), which is in inverse proportion to the variance (σ_θ^2), was markedly affected by the change of the horizontal distribution and/or catchment area. In addition, the SSFW with symmetrically horizontal distribution and catchment area all had considerable hydraulic efficiency (Fig. 4(c)).

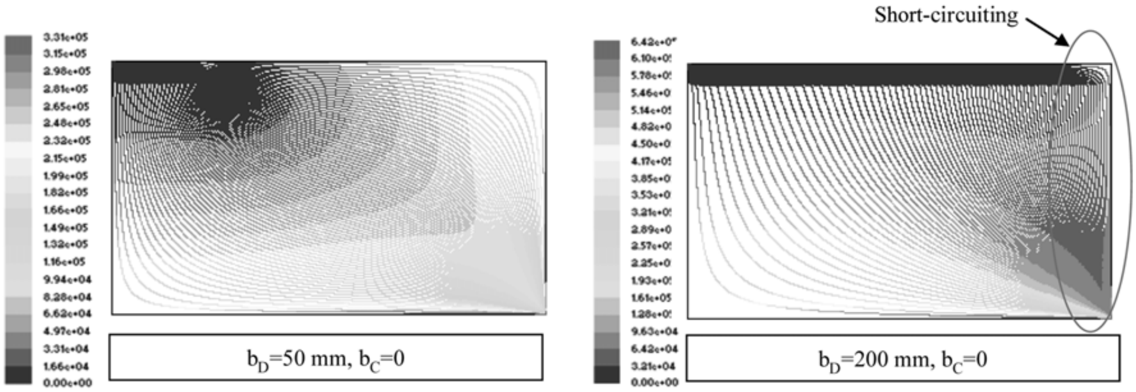
In Fig. 4(a), the hydraulic efficiency of the SSFW reduced with the introduction of horizontal distribution area or catchment area and decreased with the increase of r (the ratio of b_D or b_C to L). Fig. 5 presents the path-line profile of the SSFW. It indicates that the increase of the horizontal distribution area and catchment area resulted in the increase of the short-circuiting, and this may be the reason for the decrease of the hydraulic efficiency of the SSFW.

In Fig. 4(b), the introduction of the horizontal distribution area to the SSFW with b_C=200 mm, or catchment area to the SSFW with b_D=200 mm, improved the hydraulic efficiency. Moreover, the hydraulic efficiency increased with the increase of r. This was because the flow pattern in the purge area was closer to a vertical plug flow (Fig. 6) and the σ_θ^2 decreased, with the increase of r.

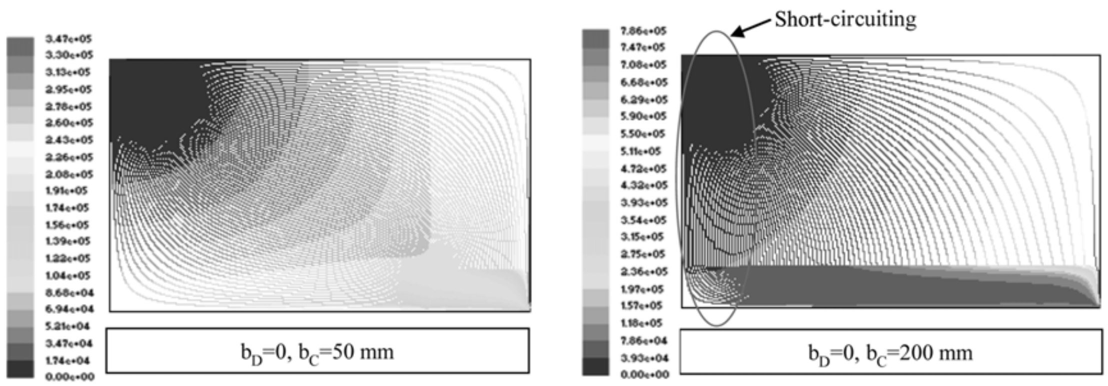
In Fig. 4(c), the SSFW with the symmetrically horizontal distribution and catchment areas had considerable hydraulic efficiency (λ>0.762) due to the low value of σ_θ^2. The reason was that when the distribution and catchment area was symmetrical, the flow field of the SSFW also had high symmetry, which induced the low value of σ_θ^2. Whereas, when b_D=b_C=100 mm, short-circuiting occurred between the distribution area and the catchment area in the SSFW (Fig. 7), which induced the relatively lower hydraulic efficiency of λ=0.762.

2. Effect of the Vertical Distribution and/or Catchment Area

With the width of the distribution area at 10 mm and catchment area at 20 mm, the effect of the vertical distribution and/or catchment area on the hydraulic efficiency of the SSFW was studied. Similar to the design of the horizontal distribution and/or catchment area, three cases were considered: (a) either vertical distribution area or vertical catchment area; (b) vertical distribution area with h_C=120 mm or vertical catchment area with h_D=120 mm; and (c) symmetrically vertical distribution and catchment area. The results are shown in Fig. 8.



(a) Path-line profile of the SSFW with horizontal distribution area



(b) Path-line profile of the SSFW with horizontal catchment area

Fig. 5. Path-line profile of the SSFW with either horizontal distribution area or horizontal catchment area.

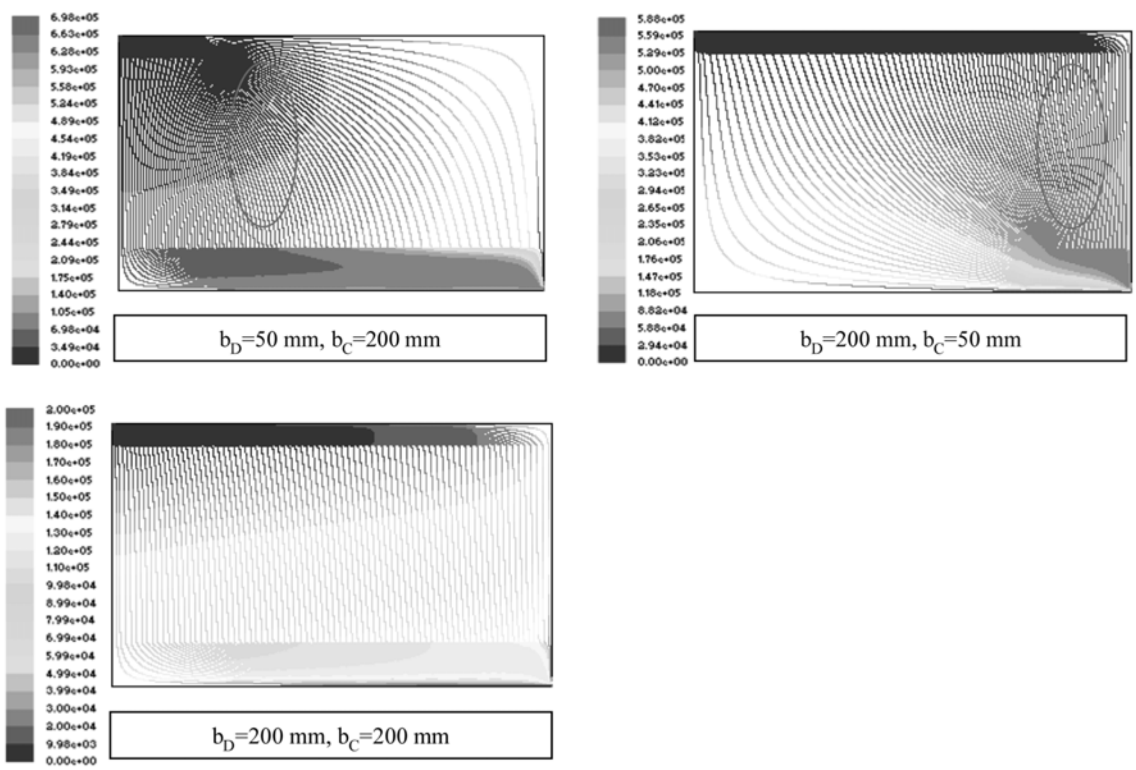


Fig. 6. Path-line profile of the SSFW with horizontal distribution area and horizontal catchment area.

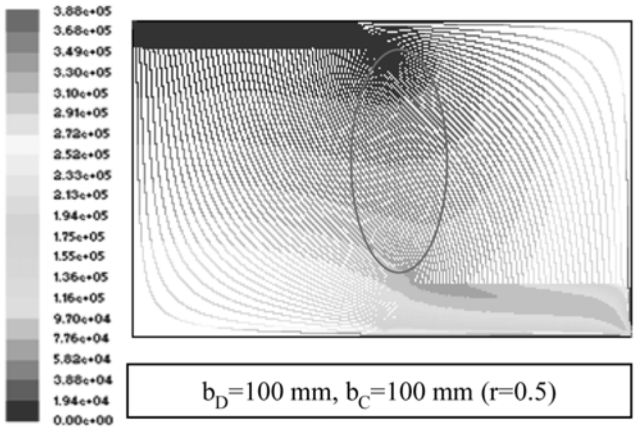


Fig. 7. Path-line profile of the SSFW with symmetrically horizontal distribution and catchment area.

In Fig. 8, the hydraulic efficiency was maintained at a high level (λ>0.898) in all reviewed cases. In addition, it can be noted that the hydraulic performance (t_θ, σ_θ^2, λ) of the SSFW was slightly affected by the vertical distribution and/or catchment area in cases (a), (b) and (c), especially in case (a) (Fig. 8(a)). The hydraulic efficiency in Fig. 8(b), similar to that in Fig. 8(c), increased with the increase of r (the ratio of h_D or h_C to H). When h_D=h_C=100 mm, the hydraulic efficiency was highest due to the occurrence of a horizontal plug flow in the SSFW (Fig. 9).

Comparing Figs. 4 and 8 indicates that the design of the vertical distribution and/or catchment area was better than that of the horizontal. With the vertical distribution and/or catchment area, the hydraulic efficiency of the SSFW was kept at a high level (above 0.898), and was slightly affected by the change of r. On the contrary, an inappropriate design of the horizontal distribution and/or catchment area may result in poor hydraulic efficiency, such as the cases of b_D=100-200 mm and b_C=0, b_D=0 and b_C=100-200 mm, b_D=0-100 mm and b_C=200 mm and so on.

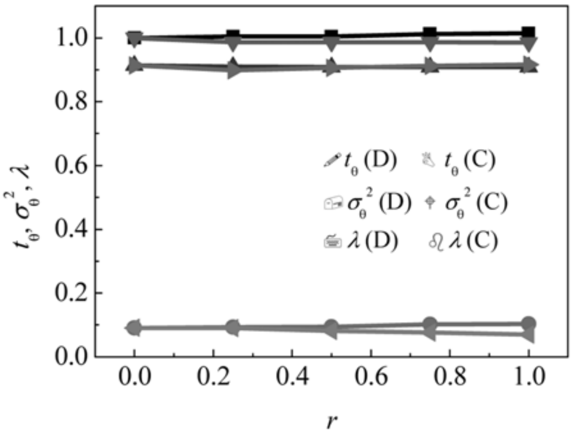
In addition, Figs. 4(a), (c) and Figs. 8(a), (c) show that the SSFW with small dimension distribution and/or catchment area (r≥0.25) also had good hydraulic efficiency (above 0.840). Therefore, the design of the small dimension distribution and/or catchment area is adopted frequently in practice to get good hydraulic efficiency and increase the purge area at the same time.

CONCLUSIONS

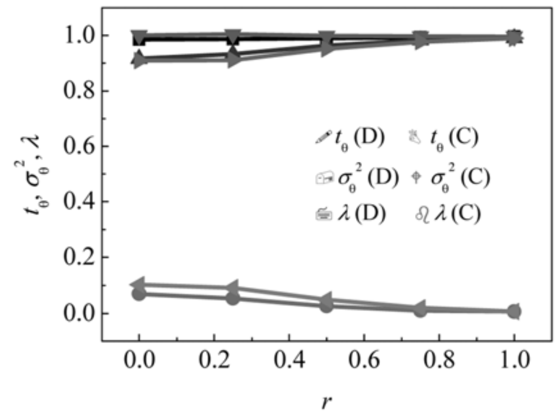
The SSFW was simulated by the means of CFD, and the effect of the distribution and/or catchment area on the hydraulic performance of the SSFW was investigated. The important conclusions are the following.

(1) The hydraulic efficiency of the SSFW is markedly affected by the horizontal distribution and/or catchment area. An inappropriate horizontal distribution and/or catchment area can result in poor hydraulic efficiency.

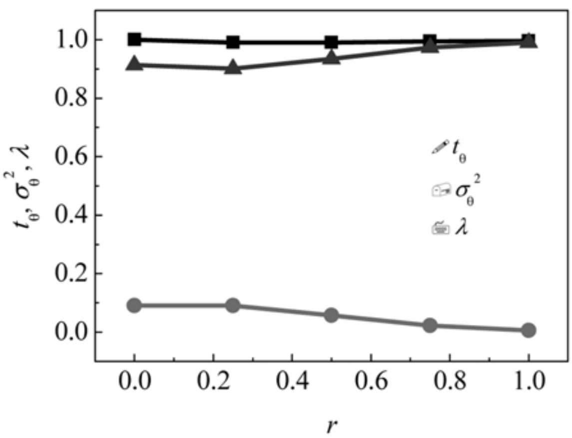
(2) The hydraulic efficiency of the SSFW with the vertical distribution and/or catchment area can be kept at a high level (above 0.898), and is slightly affected by the vertical distribution and/or catchment area.



(a) Either vertical distribution area or vertical catchment area



(b) Vertical distribution area with h_C = 120 mm or vertical catchment area with with h_D = 120 mm



(c) Symmetrically vertical distribution and catchment area

Fig. 8. Effect of the vertical distribution and/or catchment area on the hydraulic performance of the SSFW. r: the ratio of h_D or h_C to H; (D) and (C): the variation of the distribution area and catchment area, respectively.

(3) The design of the vertical distribution and/or catchment area in the SSFW is better than that of the horizontal, considering the

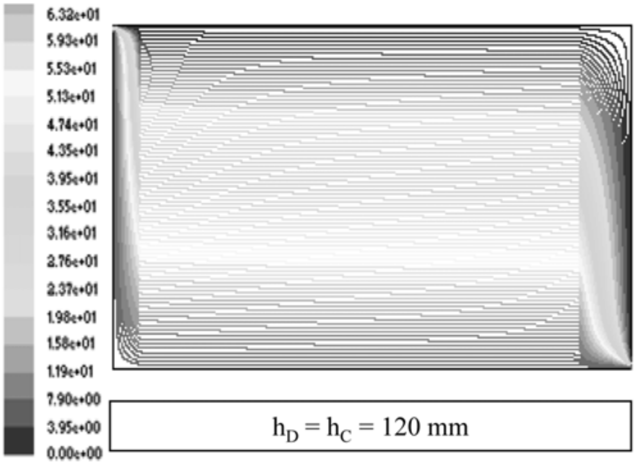


Fig. 9. Path-line profile of the SSFW with h_D=h_C=120 mm.

hydraulic efficiency of the SSFW.

(4) From the point of view of the engineering design, a small dimension distribution and/or catchment area (r≤0.25) in the SSFW is advisable, which maintains a considerable hydraulic efficiency of the SSFW (above 0.840) but also benefits the increase of the purge area.

NOMENCLATURE

C_2 : the inertial resistance coefficient [1/m]
D_p : constructed media diameter [m]
f(t) : the RTD function
g : acceleration of gravity [m s^{-2}]
p : static pressure [Pa]
S_i : source term for the *i*th (x, y, or z) momentum
t_n : nominal detention time [s]
t_{mean} : mean residence time [s]
t_Θ : normalized resident time (dimensionless)
V_R : wetland volume [m^3]
V_0 : inflow volume per time unit [m^3/s]
α : the permeability [m^2]
$1/\alpha$: the viscous resistance coefficient [1/m^2]
ε : the void fraction of media [%]
λ : hydraulic efficiency (dimensionless)
μ : dynamic viscosity [Pa s]
v : velocity vector [m s^{-1}]
r : density of the liquid [kg m^{-3}]
s : the standard deviation from the average time
σ^2 : the variance
σ_θ^2 : normalized variance (dimensionless)

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