Separation and Purification Technology 169 (2016) 137–150

Contents lists available at ScienceDirect

Separation and Purification Technology

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

Assessment of a novel spiral hydraulic flocculation/sedimentation system by CFD simulation, fuzzy inference system, and response surface methodology

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ARTICLE INFO

Article history:
Received 28 November 2015
Accepted 5 June 2016
Available online 6 June 2016

Keywords:
Computational fluid dynamics (CFD)
Dissolved organic carbon (DOC)
Hydraulic flocculation
Natural organic matter (NOM)
Response surface methodology (RSM)

ABSTRACT

Computational fluid dynamics (CFD) was used for hydrodynamic modeling of flocculation and sedimentation experiments in a novel spiral hydraulic flocculation/sedimentation system. The experiments were conducted by different flow rates and different internal geometry to obtain different flocculation times and velocity gradients. In all experiments, the velocity gradient was gradually decreased with depth showing very smooth tapered flocculation which is preferred in hydraulic flocculation. The results of velocity gradient that obtained from the CFD simulation were used to investigate the influence of velocity gradient on turbidity and NOM removal in terms of specific ultraviolet absorbance (SUVA) and dissolved organic carbon (DOC). The experimental results revealed high influence of velocity gradient on reduction of NOM and turbidity. Fuzzy inference system (FIS) and response surface methodology (RSM) were used for modeling the influence of initial SUVA, DOC, and turbidity with velocity gradient and flocculation time on the treatment efficiency. Both methods were suitable for describing the treatment process, however, fuzzy inference model validated the experimental results with higher correlation.

1. Introduction

Coagulation by metal salts is the most prevalent method for treatment of drinking water due its high efficiency for removal of turbidity and suspended solids [1,2]. In recent years, many researchers studied the enhancement of coagulation process for removal of natural organic matter (NOM) by adjustment of water pH and optimizing of coagulant dose [3–5]. NOM exists in most of drinking water resources such as rivers and canals. The main components of NOM in surface water are humic and fulvic acids [6,7]. NOM reacts with the chlorine during the disinfection process resulting in disinfection by-products (DBPs) which cause many dangerous health problems [8,9].

Coagulation/Flocculation process occurs because of differential electrostatic charges on the different faces of suspended particulates. The mixing of a coagulant provides spreading of positive charged ions which causes neutralization of the charge on the particulates. Consequently, the repulsive forces between particles are reduced, allowing them to agglomerate together forming larger flocs [10]. The concern about hydraulic flocculation has been risen because it needs lower maintenance and operating cost comparing to mechanical flocculation [11]. Many researchers evaluated different types of hydraulic flocculation in which the water is agitated by being routed around complex geometry [12,13]. This process induces the turbulence needed for flocs formation.

Unfortunately, the criteria for appropriate design and operation of hydraulic flocculation are incomplete. Conventional designs utilize the product of the average velocity gradient (G) and hydraulic residence time (T) as a measure of the extent of flocculation in a reactor. Theoretically, any combination of G and T that gives the same product should work with the same performance [11]. Consequently, hydraulic flocculators often operate well at low flow conditions even if average velocity gradient is as low as 10 s^{-1}, because the longer detention time still provides for an adequate GT value [14]. The geometrical complexity of hydraulic flocculation tanks makes the determination of velocity gradient by the energy dissipation governing equations for the macroscopic flow field a very difficult task [13,15].

Due to the convenience of increasingly faster digital computers and the efficient implementation of accurate numerical algorithms, computational fluid dynamics (CFD) is a valuable tool for quickly extracting accurate information about turbulent flow and mixing

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http://dx.doi.org/10.1016/j.seppur.2016.06.019
1383-5866/

in water and wastewater treatment systems [14,16]. CFD is distinguished over conventional modeling approaches as it is a proportionately cheap, high-speed technique for evaluating fluid systems that are difficult to simulate or measure in a laboratory or under field conditions [17]. CFD has the prospect of yielding a "virtual prototype" for water and wastewater treatment reactors. Moreover, it can simulate the three-dimensional fluid flow inside a reactor and thus help to optimize the operational conditions of treatment processes [18,19].

Mathematical and statistical methodologies have been used for modeling and optimizing a variety of water and wastewater treatment technologies [20,21]. Among the several modeling methods, fuzzy inference system (FIS) is distinguished from probabilities because the former deals with uncertainty in concepts of definitions rather than the frequency of occurrence of a phenomenon [22]. Fuzzy theory has been reported to be very effective for describing engineering problems because it attains linking between qualitative decision making and numerical values [23,24]. In addition, response surface methodology (RSM) has been used for modeling and optimizing of water processes. RSM is a combination of mathematical and statistical methods for constructing models, assessment the influence of several parameters, and obtaining the values of process variables that produce desirable values of the response [25].

In the present study, a novel hydraulic flocculation/settling reactor depends on the spiral movement of water around an internal cone was evaluated for removal of turbidity and NOM from water. A CFD simulation with (Fluent) software was used for modeling of flocculation process and computation of velocity gradient. The experimental results were used for investigation the influence of velocity gradient on the efficiency of NOM and turbidity removal. In addition, FIS and RSM were used for modeling the removal of turbidity and NOM.

2. Materials and methods

2.1. Chemicals

Aluminum sulphate ($Al_2(SO_4)_3{\cdot}18H_2O$), and kaolinite ($Al_2(SO_4)_3{\cdot}18H_2O$) were obtained from Algomhuria Co. An organic compound of 68% Humic acid and 17% fulvic acid was purchased from Eden. Hydrochloric acid (27%, w/v) was obtained from Sigma-Aldrich.

2.2. Lab experiments

For preparation of synthetic water, kaolinite was used to cause turbidity and the humic/fulvic acids compound was added as a NOM source. The initial DOC of water after adding a certain amount of humic and fulvic acids was 11.5 mg/L. The initial pH of water was adjusted to 5.5 which previously reported to be the optimal pH for the same synthetic water [26]. The synthetic water was prepared and stored in a 200 L tank provided with a stirrer. The water was discharged in a continuous flow to the reactor by a centrifugal pump as shown in Fig. 1(a). The aluminum sulphate solution was continuously injected in the water path before the centrifugal pump so that the flash mixing was occurred inside the pump. The reactor consists of stainless steel cylinder, internal cone, and effluent flow weir as shown in Fig. 1(b). The water entered the reactor through a copper nozzle in the tangential direction so that it provided a high tangential velocity in a helical (spiral) path around the inner cone. The flocculation process occurred during the spiral movement of water around the inner cone, while the sedimentation of flocs was occurred inside the inner cone.

Two different cones were used. Cone 1 has (D1/D2) 560/530 mm, and cone 2 has (D1/D2) 550/480 mm, where D1 is the upper diameter and D2 is the lower diameter. The system was operated using different flow rates to obtain different retention time and velocity gradient as shown in Table 1.

Turbidity was measured by turbiditymeter (Hanna HI93703). UV_{254} was measured by spectrophotometer Unico2100. To determine dissolved organic carbon (DOC), samples were first filtered by 0.45 μm Millipore filter papers then total organic carbon (TOC) was measured by TOC analyzer (Analytik Jena AG Co., Germany). Specific ultraviolet absorbance (SUVA) was determined by the Eq. (1) [27]:

$$SUVA = \frac{UV_{254}\ (\mathrm{cm}^{-1})}{DOC\ (\mathrm{mg/L})} \quad (1)$$

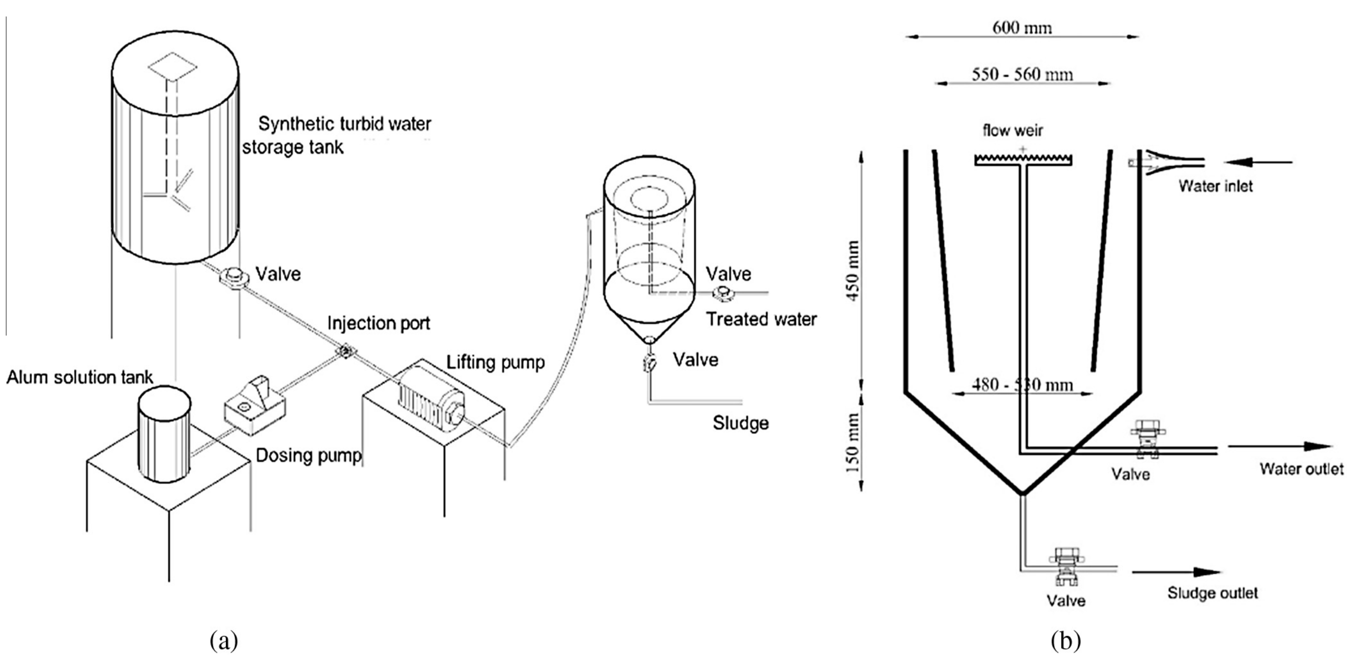

Fig. 1. (a) Schematic diagram for treatment system and (b) Clari-flocculator dimensions.