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Impact of asymmetric lamp positioning on the performance of a closed-conduit UV reactor

Tipu Sultan [a,*], Zeshan Ahmad [a], Zahid Anwar [b], Muhammad Shahzad Khurram [c]

[a] School of Engineering (SEN), Department of Mechanical Engineering, University of Management & Technology, C-II Johar Town, Lahore 54770, Pakistan
[b] Mechanical, Mechatronics and Manufacturing Engineering Department KSK-Campus, UET Lahore, Pakistan
[c] Department of Chemical Engineering, COMSATS Institute of Information Technology, Lahore, Pakistan

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ABSTRACT

Computational fluid dynamics (CFD) analyses for the performance improvement of a closed-conduit ultraviolet (UV) reactor were performed by changing the lamp positions from symmetric to asymmetric. The asymmetric lamp positioning can be useful for UV reactor design and optimization. This goal was achieved by incorporating the two performance factors, namely reduction equivalent dose (RED) and system dose performance. Four cases were carried out for asymmetric lamp positioning within the UV reactor chamber and each case consisted of four UV lamps that were simulated once symmetrically and four times asymmetrically. The results of the four asymmetric cases were compared with the symmetric one. Moreover, these results were evaluated by using CFD simulations of a closed-conduit UV reactor. The fluence rate model, UVCalc3D was employed to validate the simulations results. The simulation results provide detailed information about the dose distribution, pathogen track modeling and RED. The RED value was increased by approximately 15% by using UVCalc3D fluence rate model. Additionally, the asymmetric lamp positioning of the UV lamps had more than 50% of the pathogens received a better and a higher UV dose than in the symmetric case. Consequently, the system dose performance was improved by asymmetric lamp positioning. It was concluded that the performance parameters (higher RED and system dose performance) were improved by using asymmetric lamp positioning.

1. Introduction

Millions of people suffer from diseases by drinking dirty water each year. Public health data shows that 85% of child and 65% of adult diseases are due to waterborne pathogens and this disease rate is increasing [1]. This systemic problem calls for more stringent standards on the microbiological pollution of water effluents. Several approaches are used for the water disinfection including ozonation, membrane filtration, advanced oxidation processes (AOP), chlorination and ultraviolet (UV) irradiation.

The UV disinfection treatment has an advantage over chlorination/dechlorination is the absence of toxicity and by-product formation, with comparable costs. UV treatment does not alter water chemically; nothing is added except energy. The use of chlorine gas for the disinfection of wastewater treatment effluents causes several safety and environmental concerns including undesirable by-products that pose a hazard to humans and the environment. Furthermore, it does not provide a solution for the protozoa present in water [2]. The other advantage of UV disinfection is it can also inactivate chlorine resistant pathogens (*Cryptosporidium* and *Giardia*) [3,4]. The application of the UV disinfection is not limited to the drinking water, but it is equally important for ballast water [5]. Despite many advantages UV disinfection also has some disadvantages such as: ineffective against adenovirus, fouling of the reactor's tube, high turbidity and total dissolved and suspended solid can render UV disinfection ineffective and reactivation of microorganisms or repair [2].

It is expressed in literature that the UV light is the best mutagenicity agent for water disinfection [6]. UV light used for water disinfection can be produced by low-pressure high output (LPHO) mercury vapor lamps, low-pressure (LP) mercury vapor lamps, or medium-pressure (MP) mercury vapor lamps [2].

A UV reactor is composed of a UV chamber that contains UV lamps. The UV lamps are enclosed in quartz sleeves to irradiate the pathogens present in drinking water. The UV dose acquired

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* Corresponding author at: School of Engineering (SEN), Department of Mechanical Engineering, University of Management & Technology, C-II Johar Town, Lahore 54770, Pakistan.

E-mail address: sultan.sindhu@gmail.com (T. Sultan).

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Nomenclature

A and B	constants in logarithm microbial inactivation rate function (–)
dt	pathogens residing time (s)
I	irradiance of UV radiation (W/m^2)
k	inactivation rate constant (m^2/J)
K_{in}	turbulent kinetic energy (m^2/s^2)
N	pathogen influent (–)
N_0	pathogens effluent (–)
N/N_0	log inactivation (–)
$\bar{p}$	means pressure (Pa)
t	time (s)
u_i *and* u_j	velocity components (m/s^2)
u_{in}	velocity at inlet (m/s^2)
u_iu_j	Reynolds stress tensor (m^2/s^2)
δ_{ij}	kronecker delta function (–)
ε_{in}	turbulent dissipation at inlet (m^2/s^3)
ν	laminar kinematic viscosity (m^2/s)
ν_t	turbulent kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
σ_k	Prandtl-Schmidt number for K_{in} (–)
σ_ε	Prandtl-Schmidt number for K_ε (–)

Subscripts

i, j	position of a cell
in	inlet

by the pathogens depends on two factors: the fluence rate and the residence time [7].

The fluence rate distribution gives details about UV light movement from UV lamp to the pathogens. Several numerical models have been developed for fluence rate determination such as the Point Source Summation (PSS) [8], the Line Source Integration (LSI) [9] and the extension models based on PSS and LSI [10,11]. Bolton [11] investigated that the models neglecting the reflection and refraction effects can over-predict more than 25%.

The performance of the UV reactor was analyzed by using several computational fluid dynamics (CFD) techniques and CFD has great potential as a powerful and cost-efficient tool for UV water disinfection [12]. Sultan and Cho [13] proposed a methodology to incorporate the surface roughness effects for water disinfection UV reactor. In addition, the performance of the UV water disinfection was enhanced by considering the surface roughness in the literature [14]. Zaho et al. [15] studies the impact of influent pipe configuration on the UV reactor performance. They found that the straight pipe configuration results in a shift in the UV dose distribution to higher UV dose range corresponding to elbow configuration. Sozzi and Taghipour [16] studied the UV reactor performance by employing Eulerian and Lagrangian approaches. They found a good agreement between them at high flow rates. Pan and Orava [17] evaluated the performance of UV reactor by employing the concept of UV disinfection efficiency. Qualls et al. [18] found that the proximity of the lamps to the walls and to each other causes UV energy loss due to light absorption. Furthermore, excessively close lamp spacing results in a reduction of the performance.

In addition, few studies, have examined the performance of the UV reactor by considering different parameters. But the effects of asymmetric lamp positioning on the UV reactor performance are not broad enough described in the literature. Therefore, in this paper, four asymmetric lamp positionings are compared to one symmetric lamp positioning in order to achieve a better UV reactor performance. The better UV reactor performance implies a higher Reduction Equivalent Dose (RED) value and a better dose distribution (system dose performance) for the pathogens inactivation. The fluence rate simulation model UVCalc3D was used to evaluate a higher RED value and a better dose distribution. There are two reasons for the use of UVCalc3D: first the facility of multiple band modeling, and second UVCalc3D is the only fluence rate model that is verified experimentally [19].

In this research four asymmetric lamp positions were compared with one symmetric position. The hydrodynamics and movement of the pathogens in UV reactor was considered predominant idea for the entire model selection. First case was selected by providing double UV intensity focused at one point near the inlet and at a distance on the tail. In second case at the inlet region two lamps were placed at smaller vertical distances so that it can retard the flow at start and more time will be available for disinfection. Furthermore, two lamps near the outlet were kept at large distances in order to irradiate the pathogens that pass close to the wall. In the third case the lamps were positioned the shape of a rhombus in order to check the angular position irradiation effects. In the fourth case the lamps were positioned diagonally and the diagonal was maintained at 45° to inactivate the pathogens diagonally. These symmetrical and asymmetrical configurations were compared in order to determine the best one.

2. CFD analyses of the water disinfection

UV water disinfection consists of three sub-processes: flow modeling, fluence rate modeling and kinetic modeling. In order to better disinfect the water a detailed understanding of all these sub-processes is very important.

2.1. The flow model

The flow through a closed-conduit UV reactor is categorized into two types namely laminar flow and turbulent flow. The boundary-layer effects significantly reduce the effectiveness of UV disinfection by decreasing flow velocities [20]. Turbulent flow conditions are considered good for the UV disinfection process as they results in better UV delivery to the pathogens [21]. In this study the flow through the close conduit UV reactor was simulated using the Reynolds Average Navier–Stokes (RANS) governing Eqs. (1) and (2), in conjunction with a k-ε turbulence model at discrete locations within the physical domain.

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial \overline{u_i}}{\partial t} + \frac{\partial}{\partial x_j}(\overline{u_i}\overline{u_j}) = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_j} + \frac{\partial}{\partial x_j}\left[\nu\left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i}\right) - \overline{u'_i u'_j}\right] \tag{2}$$

$$-\overline{u'_i u'_j} = \nu_t\left(\frac{\partial \overline{U}_i}{\partial x_j} + \frac{\partial \overline{U}_j}{\partial x_i}\right) - \frac{2}{3}k\delta_{ij} \tag{3}$$

$$\nu_t = C_\mu k^2/\varepsilon \tag{4}$$

Here ρ is the density, $\bar{p}$ is the mean pressure, $-\overline{u_i u_j}$ is the Reynolds stresses tensor (Eq. (3)), ν laminar kinematic viscosity and ν_t is turbulent kinematic viscosity of water (Eq. (4)). The governing equations used for the turbulent kinetic energy "K" and turbulent dissipation "ε" are given in Eqs. (5) and (6)

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