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Lamp emission and quartz sleeve modelling in slurry photocatalytic reactors

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HIGHLIGHTS

- Determination of best emission model to use for UV lamps.
- Explored the effects of lamp length to lamp radius ratios and lamp ageing on the type of model used.
- Determined the effect of reflection, refraction and absorption by the quartz sleeve in slurry photocatalytic reactors.
- Results obtained conveniently presented in dimensionless form.

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ABSTRACT

Modelling of incident radiation intensity in a reaction medium or at catalyst surface is a necessity for kinetics modelling of pollutant degradation in photocatalytic reactors. In slurry photoreactors, the incident radiation within the reacting medium is calculated via the radiative transport equation (RTE) which considers the absorption and scattering of light due to the catalyst particles. As a result, a proper lamp emission model is required so as to obtain boundary conditions of the incident radiation entering the reacting medium. In this paper, we examine the validity of line, surface and volumetric source models at describing the incident radiation around a UV lamp. We then examine the effects of different lamp length to lamp radius ratios ($2L/r_{lamp}$) and lamp ageing on the lamp emission model, with respect to the more descriptive and accurate volume source model. Finally, computational fluid dynamics (CFD) simulations are performed to determine the effect of light reflection, refraction and absorption at the air–quartz–water interfaces on incident radiation entering the reaction medium, for three quartz tube radius to lamp radius ratios (r_{quartz}/r_{lamp}) and two typical quartz tube thicknesses. The results obtained in this study are conveniently presented in dimensionless form and could be used as correction factors in the setting up of the radiation boundary condition in the modelling of cylindrical slurry photocatalytic reactors.

1. Introduction

Heterogeneous photocatalysis is a promising advanced oxidation process (AOP) for the removal of organic pollutants from air and wastewater. Photocatalysis involves the use of UV light to excite a semiconductor catalysts (most usually TiO_2), leading to the formation of electron–hole pairs. The electrons and holes then, through a chain of reactions, produce the very reactive hydroxyl radical which has the ability to destroy many robust toxic organic pollutants.

Photocatalytic reactors can be illuminated via three main ways: (1) directly shone upon at a distance such as in immobilised type reactors, (2) with the lamp directly immersed into the reaction space as in slurry cylindrical reactors and (3) by using reflecting devices. Therefore, in photoreactor simulations, the proper modelling of the irradiation reaching the reaction space is of paramount importance. This starts with choosing an appropriate lamp emission model.

The choice of a lamp model does not depend on the researcher's preference but rather is imposed by the type of source that is used. Some lamps produce an arc within the lamp tubes that emits radiation by itself; hence emission is made by the whole lamp volume. We speak in this case of voluminal emission, which is atypical of low, medium and high pressure mercury arc lamps. Other lamps such as fluorescent tubes are coated with a fluorescent substance which emits radiation that is induced by the discharged arc inside the lamp. In such cases, we speak of surface emission, i.e. emission is produced by the lamp envelope. An approximation to

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the volume and surface source models is the linear model, which considers the whole lamp as being an emitting line.

Romero et al. (1983) determined that the linear model gave reliable results when the values the ratio of the inner wall radius to lamp length and the ratio of the lamp radius to inner wall radius were high and low respectively (here, the inner radius can be taken as the radius of the quartz tube separating the lamp from the reaction region). Furthermore they found that the linear approximation approached the more complete volume source model when the ratio of the lamp radius to lamp length was low. However, with increase in the lamp radius, errors as large as 15% could be introduced. Irazoqui et al. (1973) showed that the line source model gave results close to the volumetric model in an annular reactor. On the other hand, other studies (Alfano et al., 1986; Alfano et al., 1990; Cerda et al., 1973) have confirmed that the linear model is inadequate whenever reflecting devices are used. In such instances, the volume source model should be utilised.

Nevertheless in the literature the line source model has been used preferentially to model photocatalytic reactors (Elyasi and Taghipour, 2010b; Pareek and Adesina, 2004; Qi et al., 2011; Salvadó-Estivill et al., 2007; Toepfer et al., 2006; Yang et al., 2005). Some researchers (Elyasi and Taghipour, 2010b; Qi et al., 2011; Toepfer et al., 2006) have even used the line source model to describe radiation emission at the quartz surface in slurry photocatalytic reactors, despite the fact that in such reactors, the ratio of lamp radius to inner wall radius is relatively high. Pareek et al. (2003) on the other hand, opted to use a surface source model as boundary condition to simulate radiation emission at the quartz surface in a slurry photocatalytic reactor.

In photocatalytic reactors, a light ray has to pass through different media before reaching the catalyst particles. In slurry photocatalytic reactors for instance, the light goes through the air space separating the lamp from the quartz tube, then through the quartz tube and into the slurry. The incident radiation at the outer surface of the quartz tube is then used in the radiation transport equation (RTE) (Boyjoo et al., 2013) so as to model absorption and scattering of light in the reaction medium. The solution of the RTE allows for the calculation of the local volumetric rate of energy absorption (LVREA) which is an important parameter in the kinetics modelling of pollutant degradation. Hence, the effects of Fresnel reflection, refraction and absorption (by the quartz tube only) due to the air–quartz–water interfaces have to be taken into account so as to obtain a proper boundary condition for use in the solving of the RTE.

Bolton (2000) used a model to account for reflection and refraction due to the air–quartz–water interfaces and showed that up to 25% overestimation of the average fluence rate could be made if those effects were neglected. Elyasi and Taghipour (2010a) modified the line, surface and volumetric source models to incorporate reflection, refraction and absorption using low pressure UV lamps. They found that the modified linear model showed reasonable accuracy and was adequate for engineering applications. Similarly, Zhang and Anderson (2010) and Duran et al. (2010) showed that the effects of reflection, refraction and absorption could be non-negligible factors in the prediction of the radiation field in a photoreactor.

In this work, we will establish the best lamp emission model to be used for a UV lamp by validation of the experimental data of Yang et al. (2005). We then deduce the validity of each model (with respect to the more complete volume source emission model) at different lamp length to lamp radius ratios ($2L/r_{\text{lamp}}$). We also examine whether lamp ageing has any effect on the type of emission model used. Finally, CFD simulations are carried out to determine the effect of reflection, refraction and absorption due to the air–quartz–water interfaces in a cylindrical slurry photocatalytic reactor. Three different quartz tube radii were simulated at two typical wall thicknesses. The results are presented in dimensionless form and compared to results obtained if the effects of reflection, refraction and absorption were neglected (i.e. by using a lamp emission model only). The results obtained in this study could be used as correction factors in the setting up of the radiation boundary condition in the modelling of slurry photocatalytic reactors.

2. Theory

This section briefly discussed the main types of emission models available and introduces the radiative transport equation which is used in the modelling of radiation transport in an absorbing and scattering medium.

2.1. Lamp emission models

The choice of a proper lamp emission model is of paramount importance in the modelling of photocatalytic reactors. Depending on the type of lamp used, various models exist to describe the radiation distribution produced around the lamp. The basic models regard the lamp as an emitting line, a surface source or a volume source (Boyjoo et al., 2013; Pareek et al., 2008). The line and surface source models can be further classified as emitting diffusely or specularly. In diffuse emission, the magnitude of intensity vectors at the point of emission shows a strong dependence on the angle of emission while in specular emission, the magnitude of the light intensity vectors is independent of the angle of emission (Pareek et al., 2008). Diffuse light is displayed by most fluorescent lamps while specular emission is more representative of mercury arc and neon lamps. More detailed treatment of the lamp models are presented elsewhere (Boyjoo et al., 2013; Pareek et al., 2008).

The line source model regards the whole lamp as an emitting line whereby the incident intensity at a point in space is integrated over the whole lamp length. For specular emission, the incident radiation intensity according to the line source specular emission (LSSE) model is

$$E = \frac{K_l}{4\pi}\int_{-L}^{L}\frac{dh}{(r^2+(z-h)^2)} \tag{1}$$

while for diffuse emission, the magnitude of intensity vectors at the point of emission shows a strong dependence on the angle of emission. The incident radiation intensity according to the line source diffuse emission (LSDE) model follows a cosine law relative to the LSSE model and can be simplified to

$$E = \frac{K_l}{4\pi}\int_{-L}^{L}\frac{r\,dh}{(r^2+(z-h)^2)^{3/2}} \tag{2}$$

where K_l rate of radiation emitted per unit length of lamp ($\mathrm{W\,m^{-1}}$).

The surface source model regards the outer lamp surface as emitting radiation. In this model, the incident intensity at a point in space is integrated over the whole lamp outer surface area. This type of emission is typical in fluorescent lamps where the arc discharged between the electrodes of the lamp acts on a fluorescent coating on the surface of the lamp, which in turn emits radiation. For specular emission, the incident radiation intensity according to the surface source specular emission (SSSE) model is

$$E = \frac{K_s}{4\pi}\int_{h=-L}^{h=+L}\int_{\phi=-\pi/2}^{\phi=+\pi/2}\frac{R\,d\phi\,dh}{[(r\cos\theta-R\cos\phi)^2+(r\sin\theta-R\sin\phi)^2+(z-h)^2]} \tag{3}$$