



## Research article

## Model for attrition-enhanced char combustion in fluidized beds



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## ABSTRACT

Attrition in fluidized beds can be important due to particle collisions removing fines from the surface of a large char particle. A model for the attrition enhanced combustion of a char particle is presented. When oxygen penetrates the surface of a particle and reacts with the solid, the surface layer becomes more fragile. Fine particles are generated due to percolation and attrition contributing to the mass loss from the mother particle in addition to burning. A shrinking particle model including the effects of attrition and gasification has been developed. The oxidation is assumed to take place at the particle external surface in the classical shrinking particle model i.e. in a layer with zero thickness. The basis for the shrinking particle model is explained by studying the diffusion and reaction processes taking place in a narrow layer on the particle surface in more detail. The Arrhenius-type chemical reaction kinetics parameters (pre-exponential coefficient, activation energy, reaction order) are not purely of chemical nature but they are apparent in the classical shrinking particle model. A more realistic model, where oxidation takes place in a thin layer instead of taking place at the surface and gasification takes place in the core region, is discussed. The model predicts the thickness of this layer and oxygen concentration and char conversion (or density) profiles in this layer. The classical shrinking particle model is, however, applicable with modifications. Pore diffusivity, intrinsic reaction rate and attrition all contribute to the apparent parameters for kinetics calculated with respect to outer surface.

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## 1. Introduction

Small fragments are erased from the surface of a particle in attrition. This phenomenon is enhanced by combustion and also by gasification. Attrition and percolation have been studied for different fuels and different conditions [1–17]. Attrition enhances the combustion rate of a single char particle by removing small fragments from the surface. In circulating fluidized bed the efficiency is higher due to recirculation of fines back to the bed. These fragments can escape the riser reactor partly as unburned reducing the combustion efficiency. The fate of them is not considered here, but attention is only on the mother particle.

The reaction of char with an oxidizer is commonly characterized by combustion zones (see e.g. [18]). The reaction is controlled by the kinetics in zone I whereas in zone III the reaction is controlled by the external mass transfer to the surface of the particle. In zone II the combustion is controlled by the external mass transfer, kinetics and pore diffusion. The combustion of a char particle in zones II and III (see e.g. [18]) takes place with reducing diameter and density, whereas gasification takes place more in zone I with reducing density. The pore enlargement due to reaction is more rapid close to the particle surface and modelling of such case has been carried out [19,20].

The shrinking particle model is an approximation, where oxygen is assumed to react at the particle surface. It is especially applicable for large particles at high temperatures for which the burning rate is mainly limited by the diffusion of oxygen in the particle's boundary layer. In reality, if the char particle is porous, oxygen will also penetrate into the particle and a narrow reaction zone is formed. The surface of the particle will become more porous and fragile due to reactions and, ultimately, when a limiting porosity is exceeded, fine particles will escape from the surface of the mother particle. Such attrition phenomena have usually been accounted in models by summing up its effect to the reduction of the particle size due to reaction rate (see e.g. [21]). However, these processes are interlinked and a model giving the combined effect of boundary layer diffusion, attrition, intra-particle diffusion and reaction in the particle surface layer is presented in this paper. The particle size decreases due to the combined effect of reaction and attrition as illustrated in Fig. 1. Soon after the start a quasi-steady reaction zone is formed in the outer layer of the particle (Fig. 2). This reaction zone, which is a hollow sphere with a narrow thickness, can be approximated as a plate (Fig. 3). Furthermore, even the reaction rate of gasification is slow compared to that of combustion; it can have some effect for a large particle, since it can take place in a larger inner volume as the zone I type of reaction. It can have a considerable effect in some conditions discussed later.

The shrinking core model utilizes the resistance analogy, where the resistance due to diffusion is added to the surface resistance due to chemistry. This surface treatment is simple and the chemistry is

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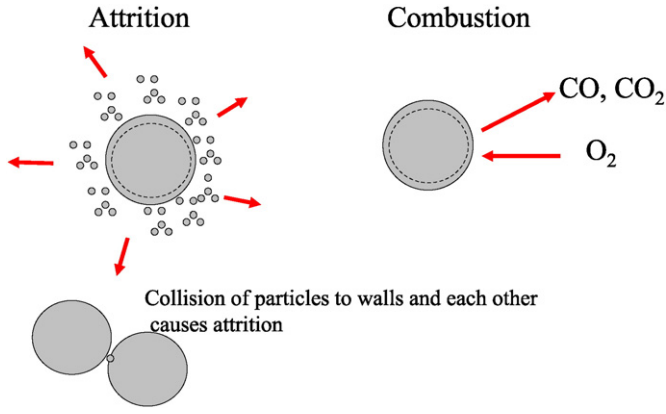


Fig. 1. Size reduction by attrition and combustion.

accounted for by using apparent kinetical constants. In the present model we go more deep into diffusion and reaction processes that are actually taking place in the narrow surface layer (Fig. 3).

There are some analogous processes in engineering such as surface abrasion and corrosion, where surface is removed by abrasion, which promotes the diffusion of corroding substance into the surface. The reaction of limestone or lime with sulphur dioxide is another example, where the surface is removed by attrition [22].

Thiele modulus and effectiveness factor (see e.g. [23]) are frequently applied when the reactions take place inside the particle. However, this treatment applies when the reaction rate coefficient and diffusivity are constant. In practical combustion conditions the process is non-linear [24]. The diffusivity of reacting gas in the char increases with local conversion.

A model accounting for the dependence of reaction rate and diffusivity on conversion and attrition is developed. The model is especially suitable for fluidized bed combustion conditions, where particle size is usually relatively large compared to pulverized combustion and the particles frequently collide with other bed particles increasing attrition.

Gasification can enhance combustion-induced attrition. In oxy-fuel combustion CO<sub>2</sub> replaces N<sub>2</sub>. Gasification of char with CO<sub>2</sub> can be important especially when the particle size is large, since it can take place throughout a larger volume whereas oxidation with O<sub>2</sub> takes place at outer surface. An extreme case has been discussed [25].

## 2. Model

The diffusion and reaction of oxidizing gas inside a burning particle can be described by the equation

$$\frac{\partial \rho_i}{\partial t} = \frac{1}{r^2} \frac{\partial}{\partial r} \left( D_i r^2 \frac{\partial \rho_i}{\partial r} \right) + \dot{\rho}_i \quad (1)$$

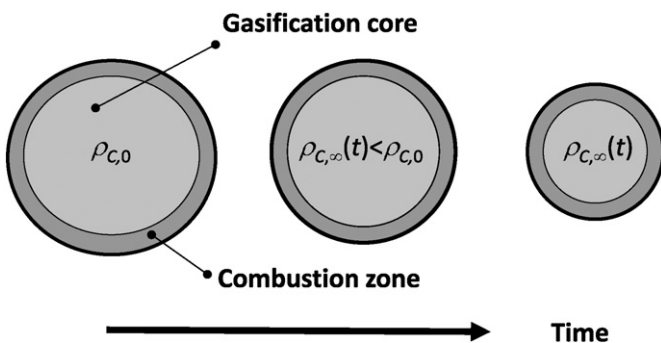


Fig. 2. Shrinking particle with decreasing particle radius due to combustion and attrition and decreasing density due to gasification.

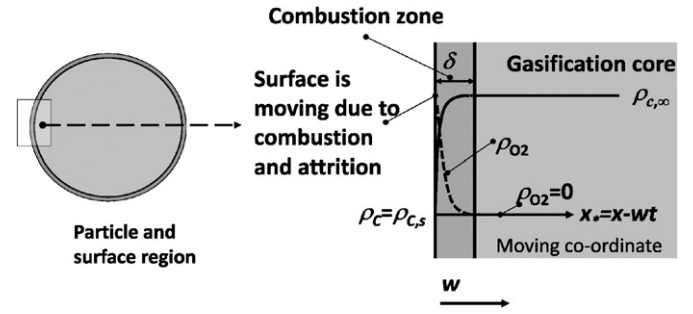


Fig. 3. Moving asymptotic reaction zone in simultaneous attrition, diffusion and reaction for a combusting particle. Left a particle, right a cut of particle surface region approximated as a semi-infinite solid.

where  $i$  denotes O<sub>2</sub>, CO<sub>2</sub> or H<sub>2</sub>O, respectively. The term on the left describes the storage. The first term on the right hand side describes diffusion inside the particle. The second term describes the local disappearance of gas reacting with solid. The chemical reaction rate  $\dot{\rho}_i = -k_i \rho_i^n$  depends on the local concentration of reactant gas. The reaction rate coefficient  $k$  may also depend on the local conversion  $k_i = k_{0,i} g(X)$ , which is accounted for by function  $g(X)$ . Function  $g(X)$  includes effects such as local pore surface area, change of reaction rate by catalysis, annealing and increase in local ash content. Initially with zero conversion  $f(0) = g(0) = 1$ .

The boundary condition at the surface of the particle and the symmetry condition in the centre of the particle are

$$h(\rho_{i,g} - \rho_{i,r=R}) = D_i \left( \frac{\partial \rho_i}{\partial r} \right)_{r=R}, \quad \left( \frac{\partial \rho_i}{\partial r} \right)_{r=0} = 0 \quad (2)$$

We consider a process that has been taken place for some time so that it has reached a quasi-steady state. In the shrinking particle model the reactions between oxygen and char are assumed to take place at the surface of the particle. Here we consider them to take place in a surface layer that is thin compared to the particle radius. Gasification reactions of char with CO<sub>2</sub> and H<sub>2</sub>O are slow and their concentrations inside the particles are quite constant. Their contribution is neglected in the narrow surface layer (Fig. 2) in comparison to the reaction between char and oxygen. However, their contribution in the inner region, where no oxygen reaches, can be considerable, since the reaction volume is large compared to that of the narrow oxidation zone. Using these assumptions the rate of conversion for the outer surface zone is

$$\frac{dX}{dt} = k_0 g(X) f \rho_{O_2}^n / \rho_{C,0} \quad (3)$$

where  $X = 1 - \rho_C / \rho_{C,0}$  and  $k_0 = k_{0,O_2}$ . Gasification is assumed to take place in regime I i.e. the concentration of the reactants CO<sub>2</sub> and H<sub>2</sub>O are constant inside the particle. In a more accurate analysis, if effect of diffusion cannot be neglected, the reaction rate coefficient of gasification is multiplied with the effectiveness factor. The density of char in the inner region (denoted by  $\infty$ ) is decreasing

$$\frac{d\rho_{C,\infty}}{dt} = -\rho_{C,0} \frac{dX_\infty}{dt} = \rho_{C,0} g(X_\infty) / \tau_G \quad (4)$$

The time constant for gasification  $\tau_G = \rho_{C,0} / (k_{0,CO_2} f_{CO_2} \rho_{CO_2}^n + k_{0,H_2O} f_{H_2O} \rho_{H_2O}^n)$  can be determined experimentally in atmosphere containing no oxygen. In the case when gasification is neglected  $X_\infty = 0$ . Since the reactions take place in a surface narrow zone, the surface

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