



The image furnace for studying thermal reactions involving solids. Application to wood pyrolysis and gasification, and vapours catalytic cracking

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ABSTRACT

The aim of the present paper is to show that the image furnace is an efficient laboratory device for studying fundamental aspects of high temperature reactions involving a solid. The basic principle relies of solid heating by a concentrated radiation in very clean conditions. The available heat flux densities can be quantitatively controlled inside very large domains, which are quite similar as those encountered in usual pilot plant reactors. The image furnace qualities are experimentally studied in the particular case of biomass thermal conversion. Many results have been already published in the field of pyrolysis reactions. The present paper reports its ability to study also basic reactions of char steam gasification and of catalytic (olivine) cracking of vapours produced by biomass thermal degradation. These three types of reactions (decomposition of a solid; reaction of a gas with a solid; interaction of a vapour with a catalyst) can be studied independently from each other and in the same heat flux densities conditions. The results can be efficiently used for further worthwhile modelling of biomass gasifiers.

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1. Generalities. Purpose of the paper

Solids are involved in many thermochemical reactions. The various domains of applications include for example: decomposition of inorganic compounds, ores treatments, drying, sulphides roasting, wastes treatments (e.g. pyrolysis, gasification), operations involving a catalyst, ceramics, combustion of solids (e.g. wood, charcoal), etc. Studying the kinetics of these reactions is a difficult task because of the existence of close couplings inside the high temperature reactor between chemical kinetics, heat and mass transfer resistances and complex hydrodynamics of all the involved phases (solid, gas). Different facilities can be used at the laboratory scale for studying these phenomena. Unfortunately the operating conditions can be very different according to the cases, making difficult the use of derived results for pilot plant up scaling. The aim of the present paper is to show that the image furnace is an efficient tool for studying, in the same conditions, different types of thermal reactions involving a solid (solid decomposition, solid/gas reactions, catalytic reactions). The study is made in the context of biomass pyrolysis/gasification processes where all these types of reactions take place.

Some general remarks are presented in the following introduction: main general lumped kinetic mechanisms involved in solids

thermal reactions; related kinetic studies; principle, advantages and drawbacks of the image furnace; biomass thermal conversion processes.

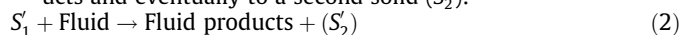
1.1. Thermal solid and gas–solid reactions

The thermal reactions involving a solid can be roughly classified into 3 classes:

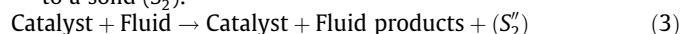
- A reacting solid (S_1) decomposes inside an inert atmosphere for giving rise to fluid products and eventually to a second solid (S_2):



- A solid (S'_1) reacts with a fluid for giving rise to new fluid products and eventually to a second solid (S'_2):



- Catalytic reaction where the solid is a catalyst that interacts with a fluid for giving rise to new fluid products and eventually to a solid (S''_2):



In each of these cases, the desired fluid products can undergo secondary reactions occurring in the gas phase or in the presence of catalysts:

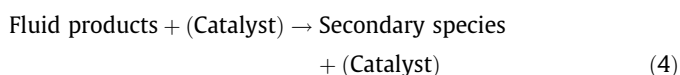
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Nomenclature

CSTR	continuous stirred tank reactor	μ	dynamic viscosity (Pa s)
D	diffusivity ($\text{m}^2 \text{s}^{-1}$)	ρ	mass density (kg m^{-3})
DFB	dual fluidized bed	τ	time constant (s)
d	solid sample diameter (m)		
f	gas species molar fraction (%)	<i>Subscripts</i>	
GC	gas chromatography	1	type (1) experiments
HC	hydrocarbon (C_2 and C_3)	2	type (2) experiments
IF	image furnace	1 + 2	type (1) + (2) experiments
K	mass transfer conductance (m s^{-1})	3	type (3) experiments
k	heterogeneous kinetic constant (s^{-1})	B	biomass
L	characteristic sample size (m)	C	char
M	molar mass (kg mol^{-1})	Cat	catalyst
MB	mass balance (%)		
m	mass (kg)	<i>Carbon</i>	
P	pressure (Pa)	Ch	chemical reaction
R	gas constant ($8.314 \text{ J mol}^{-1} \text{ K}^{-1}$)	Cr	cracking
Ra	ratio of H_2 to CO molar (%) fractions	f	fluid
Re	Reynolds number	G	gases
RTD	residence time distribution	g	gasification
r	radius of the reactor (m)	<i>Hydrogen</i>	
S	sample surface submitted to the radiation (m^2)	j	gas species
Sc	Schmidt number	mt	mass transfer
SEM	scanning electron microscopy		
Sh	Sherwood number	<i>Oxygen</i>	
T	temperature (K)	pc	pyrolysis + cracking
t	time (s)	P	pyrolysis
u	mean velocity (m s^{-1})	R	reactor
v	specific mass loss rate ($\text{kg m}^{-2} \text{ s}^{-1}$)	r	reacting species
V	volume (m^3)	V	vapours
X	conversion (%)	x, y, z	index of C, H, O of char molar formula
Y	mass yield (%)	<i>Superscripts</i>	
Y'	pseudo mass yield (%)	o	exit of the pyrolysis section (tubular reactor)
<i>Greek symbols</i>		s	exit of the cracking reactor
ϕ	value of the heat flux density which is available at the focus F3 (W m^{-2})		



It is often difficult to prevent such reactions that may reduce the yields and qualities of desired fluid products.

1.2. Kinetic studies. Solid heating

The kinetics of reactions (1)–(3) can be studied at the laboratory scale in different types of facilities.

- Some ones are designed for the only purpose of basic research. They often rely on the use of a given mass of S_1 , S'_1 or catalyst and operate in non-steady state conditions. The reactions (2) and (3) are performed in the presence of a known flowrate of reacting fluid. In any case the reaction rate is followed by measuring the rates of S_1 or S'_1 mass losses and/or the conversion rates of the fluid reactants. These informations are usually studied as a function of sample temperature or heating rate, two parameters that are often difficult to define and measure with good accuracies [1,2]. The reacting solid masses are usually small in order to prevent internal temperature gradients. In the case of slow reactions of types (1) and (2), thermogravimetric analysis [3] is frequently used (imposed heating rates roughly between 0.1 and 100 K min^{-1} [4]). Very high imposed

heating rates (thousands K s^{-1}) can be reached in other types of systems. For example, a small solid sample can be deposited on a rapidly heated metallic wire [5,6], associated to online analysis of products. However actual temperature reached by the solid is difficult to define and measure. In other intermediate systems, the solid sample is settled inside a horizontal tube [7] heated inside a hot furnace in conditions allowing the determination of complete mass balances.

In the case of type (3) reactions, a given flowrate of fluid reactant crosses, during given times, a fixed catalyst bed heated at different temperatures [8–13].

- Other laboratory devices operate with small scale continuous reactors fed by steady state flowrates of gases (inert gas in the case of (1) and reacting gas in the case of (2)) and of reacting solids. Many types of contactors can be used such as fluidized beds, drop tubes, entrained flowreactors. The actual reacting solid temperature is also difficult to obtain and important temperature gradients may exist between the particles and the surrounding gas as well as inside the particles.
- Practically, the solids can be heated according to different possible heat transfer processes: convection (hot gas), radiation (hot neutral or catalytic medium, vessel walls) and/or conduction (more or less contact with a hot surface). According to

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