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Study of heat and mass transfer in a chemical moving bed reactor for gasification of carbon using an external radiative source

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Abstract—A theoretical model of a chemical moving bed reactor for gasifying carbon with CO_2 using an external radiative source (concentrated solar radiation) is proposed. It permits the determination of the temperature profile for gas and solid and the concentration profile in the gas as a function of control parameters: gas flow rate, warm surface temperature, diameter of particles. Comparison of model results with experiment gives satisfactory agreement.

1. INTRODUCTION

VARIOUS technical approaches use coal for conversion to gaseous and liquid fuels. The energy necessary to drive endothermic coal gasification reactions can be supplied by partial coal combustion, by preheating the reactant gas, or from an external radiative source, such as the sun.

The use of high-temperature solar energy to drive the endothermic reactions associated with coal and other carbonaceous materials for gasification has been studied by several investigators [1–5].

Recently, a moving bed reactor, shown in Fig. 1, for gasifying coconut charcoal (it is nearly pure carbon: 1.5 ± 0.5 wt% H with a low ash content of 1.2 wt%) with CO_2 was studied experimentally [6]. Experiments were carried out on a vertical solar furnace located at the C.N.R.S. Laboratory in Odeillo, France.

These tests were made with incident solar intensities ϕ_i of 290–690 kW m^{-2}, temperatures T_0 of 900–1200°C, gas flow rates F_{CO_2} of 1–11 l min^{-1} and particles with a diameter of 0.32 cm.

The performance of the reactor was defined on the

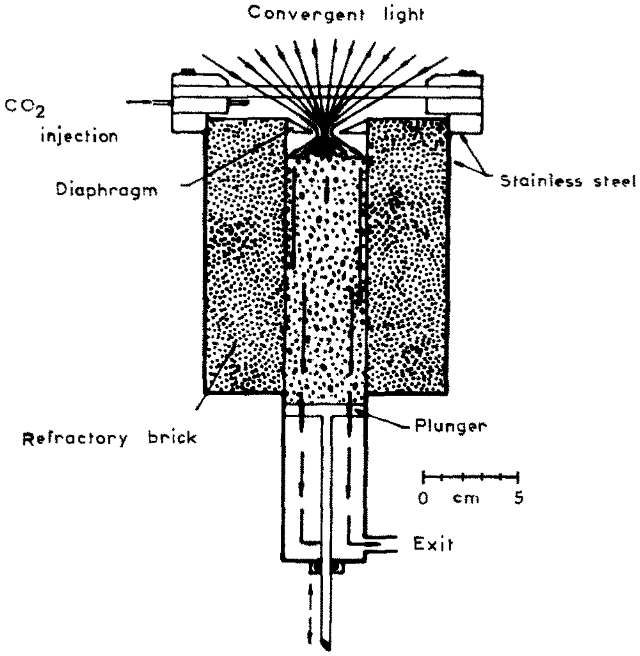

FIG. 1. Reactor used for solar gasification. As the packed bed was consumed it was pushed toward the focal plane.

NOMENCLATURE

A	(particle surface area)/(unit bed volume) [m^{-1}]
C	mass fraction of CO_2 in the gas mixture
c_p	heat capacity [J kg^{-1} K^{-1}]
d	particle diameter [m]
D	diffusion coefficient of CO_2 in the gas [m^2 s^{-1}]
D_0	diameter of the cylinder containing the porous medium [m]
F_{CO_2}	CO_2 flow rate at the entry of the reactor [m s^{-1}]
h	particle–fluid heat transfer coefficient [W m^{-2} K^{-1}]
ΔH	molar enthalpy of reaction [J mol^{-1}]
K	extinction coefficient [m^{-1}]
k_g	mass transfer coefficient [m s^{-1}]
L	length of the packed bed [m]
M	molar density [kg mol^{-1}]
p	pressure inside the reactor [Pa]
q_r	radiation flux density in the solid
T	temperature of the solid [K]
v	fluid velocity [m s^{-1}]
V	volume of the packed bed [m^3]
v_s	solid velocity [m s^{-1}]
x	axial coordinate (positive in the flow direction) [m]
X	degree of advancement of reaction.

Greek symbols

ε	bed void fraction
η	thermochemical efficiency of the process
θ	gas temperature [K]
λ	thermal conductivity [W m^{-1} K^{-1}]
μ	viscosity [N s m^{-2}]
ρ	density [kg m^{-3}]
σ	Stefan–Boltzmann constant [W m^{-2} K^{-4}]
ϕ_i	incident radiative flux [W m^{-2}].

Dimensionless variables

Nu	Nusselt number, hd/λ
Pr	Prandtl number, $\mu c_p/\lambda$
Re	Reynolds number, $v_0 d\rho/\mu$
Sc	Schmidt number, $\mu/\rho D$
Sh	Sherwood number, $k_g d/D$
X^+	dimensionless axial coordinate, x/d.

Subscripts

a	ambient conditions
C	carbon
cal	calculated value
meas	measured value
p	particle
s	solid, superficial
0	reference value.

basis of the amount of solar energy stored (efficiency of the process, η) and the fraction of reactant gas consumed. The efficiency can be determined from the fuel value (heat of combustion) of the product gas (ΔH_p), the heat of combustion of the fuel gasified (ΔH_F) and the solar energy (ΔH_s) used during gasification as follows:

$$\eta = \left(\frac{\Delta H_p - \Delta H_F}{\Delta H_s}\right) \times 100.$$

In the above tests, the maximum of the fraction of reactant gas (CO_2) consumed was found to be 98% for $F_{CO_2} = 4$ l min^{-1} and $T_0 = 1150$°C, and the maximum efficiency was found to be 50% for $F_{CO_2} = 8.2$ l min^{-1} and $T_0 = 950$°C.

A major parameter in the study of transfer in this reactor is the overall rate of gasification, which is determined by a chemical, mass transport or mixed control, depending on experimental conditions.

A gravimetric analysis has determined a control of the reaction process by mass transport (diffusion through the gas film around a solid particle) for temperatures above 1000°C.

In addition to this work, a theoretical model of the functioning of the moving bed reactor with mass transport control is presented here.

2. HEAT AND MASS TRANSFER EQUATIONS

The reactor is assumed to be composed of a stacking of identical non-porous carbon grains regularly distributed in a drum. Its section is large enough that its sides may be considered as adiabatic; the flow is one-dimensional and the physical properties are the same for all points located in the same section.

Compared to other exchange modes (conduction, radiation and convection), viscous friction and pressure drops are considered as negligible. The flow is assumed to be steady and the gas flow rate constant. Heat and mass transfer equations are [6]:

for the gas

$$\rho v \frac{\partial C}{\partial x} = \frac{\partial}{\partial x}\left(\rho D \frac{\partial C}{\partial x}\right) + \sigma_C \tag{1}$$

$$\rho c_p v \frac{\partial \theta}{\partial x} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial \theta}{\partial x}\right) + \sigma_\theta ; \tag{2}$$

for the solid

$$-\rho_s \frac{\partial v_s}{\partial x} + \sigma_s = 0 \tag{3}$$