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Axial dispersion and mixing phenomena of the gas phase in a packed pebble-bed reactor

Rahman S. Abdulmohsin [a,*], Muthanna H. Al-Dahhan [b,c,1]

[a] Department of Chemical and Biochemical Engineering, Missouri University of Science and Technology, 1101 North State Street/210-R Bertelsmeyer Hall, Rolla, MO 65409-1230, USA
[b] Department of Chemical and Biochemical Engineering, Missouri University of Science and Technology, 1101 North State Street/110-E Bertelsmeyer Hall, Rolla, MO 65409-1230, USA
[c] Department of Nuclear Engineering, Missouri University of Science and Technology, 301 W. 14th St./222 Fulton Hall, Rolla MO 65409-0170 USA

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ABSTRACT

The knowledge and proper analyses of axial dispersion and the mixing phenomena of the coolant gas flow in the dynamic core of pebble-bed nuclear reactors are useful for safe design and efficient operation of these reactors. These processes can be characterized in terms of the residence time distribution and quantified in terms of the axial dispersion coefficient. Therefore, in this work, the axial dispersion coefficients of the gas phase and their residence time distributions were measured experimentally in a separate effect pilot-plant scale and cold-flow experimental setup of 0.3 m in diameter, using a sophisticated and advanced gaseous tracer technique. The non-ideal flow of the gas phase in the pebble bed was described using the axial dispersion model (ADM). The effect of the gas velocity on the axial dispersion was investigated using a range of velocities from 0.01 to 2 m/s, covering both the laminar and turbulent flow regimes. The effect of the bed structure (pebble size) on the axial dispersion coefficient was investigated, and the results indicate that the pebble size strongly affects axial dispersion and mixing in the packed pebble-bed reactor. The results show that the flow pattern of the gas phase does not deviate much from the idealized plug-flow condition at high flow rate, which depends on the gas flow rate and the bed structure of the pebble-bed. The present work provides insight on the extent of mixing and dispersion in the gas phase in the studied bed using an advanced gas dynamics technique and methodology that properly accounts for the external dispersion.

1. Introduction

A pebble-bed-type of very high-temperature gas-cooled reactor (VHTR) is one of the most probable solutions (Goodjohn, 1991) to fulfill the future energy demand and environmental needs. Therefore, it is the most promising concepts (Koster et al., 2003) of the six classes of 4th generation (Gen IV) advanced technologies. In general, the pebble-bed reactor (PBR) is a pyrolytic graphite-moderated and helium gas-cooled nuclear reactor that achieves a requisite high outlet temperature while retaining the passive safety and proliferation resistance requirements of Gen IV designs (Gougar et al., 2003). A description and more details about this pebble-bed nuclear reactor is given by Abdulmohsin (2013).

The efficiency of the pebble-bed reactor is dependent upon how the coolant removes the generated heat from the dynamic core of this reactor. Therefore, to reliably simulate the thermal–hydraulic phenomena, and hence the performance in the dynamic core of nuclear packed-pebble bed reactors, the coolant gas dynamics and heat transport processes must be characterized (Abdulmohsin and Al-Dahhan, 2011a,b; 2012). In addition, the experimental investigation of the thermal–hydraulic characteristics of pebble beds is an issue of high importance when selecting the core geometry and evaluating the performance and safety of such types of reactors (Rimkevicius and Uspuras, 2008). Furthermore, understanding the dispersion and mixing in the longitudinal direction is important when temperatures are rapidly

Abbreviations: AARE, average absolute relative error; ADM, axial dispersion model; CFD, computational fluid dynamics; CSTR, continuous stirred tank reactor; Gen IV, 4th generation of nuclear reactors; HTGR, high temperature gas-cooled reactor; LDA, laser doppler anemometry; MIR, matched index of refraction; PBR, pebble bed reactor; PFR, plug-flow reactor; PIV, particle image velocimetry; PMMA, polymethyl-methacrylate; RTD, residence time distribution; TCD, thermal conductivity detector.

* Corresponding author. Tel.: +1 (573) 341 6941; fax: +1 (573) 341 4377.
E-mail addresses: rsabdulmohsin@mst.edu (R.S. Abdulmohsin), aldahhanm@mst.edu (M.H. Al-Dahhan).
[1] Tel.: +1 (573) 341 7518; fax: +1 (573) 341 4377.

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Nomenclature

Symbol	*Description*
C	concentration of the tracer in the gas phase, mol/m^3
C_{inj}	concentration of the injection tracer, mol/m^3
C_{in}	dimensionless tracer concentration in the gas phase at the plenum outlet
C^*_{in}	dimensionless convoluted tracer concentration in the gas at plenum outlet
C_{out}	dimensionless tracer concentration in the gas phase at the reactor outlet
C^*_{out}	dimensionless convoluted tracer concentration in the gas at reactor outlet
d_h	effective (hydraulic) pebble diameter, m
d_p	pebble diameter, m
D_{AB}	molecular diffusion coefficient, m^2/s
D_c	column diameter, m
D_{ax}	effective axial dispersion coefficient of the gas phase, m^2/s
L	length of the bed (not the column), m
M	total mass of injected tracer, gm
N	the data point number, Eq. (13)
Q	volumetric flow rate of injected tracer, cm^3/s
t	time, s
t_m	mean residence time of the bed, s
V	gas velocity (= V_g/ε), m/s
V_g	superficial gas velocity based on empty column, m/s
Z	axial distance along the bed, m

Greek letters

τ	tortuosity factor
τ_o	residence time in the plenum, s
ε_b	average (mean) voidage of bed, dimensionless
μ	dynamic viscosity of the fluid, kg m/s
ρ	density of fluid, kg/m^3

Dimensionless groups

Pe_D	dispersive Peclet number (= $V_g d_p/\varepsilon D_{ax}$), dimensionless
Pe_M	molecular Peclet number (= $Re_P Sc = V_g d_p/\varepsilon D_{AB}$), dimensionless
Re	Reynolds number (=$\rho V_g d_p/\mu$), dimensionless
Re_P	particle Reynolds number (=$\rho V_g d_p/\varepsilon\mu = Re/\varepsilon$), dimensionless
Sc	Schmidt number (=$\mu/\rho D$), dimensionless

changing with respect to time or axial coordinate due to nuclear reactions and interphase heat transport. Hence, better understanding and model of the gas phase axial dispersion could reduce the uncertainty in local core temperature peaking calculations. Unfortunately, there are no detailed experimental measurements and no reported studies in the literature related to understanding and quantifying the complex coolant gas flow structure and dynamics in these pebble-bed nuclear reactors (Abdulmohsin, 2013). However, studies have been reported that related to the dispersion of gas and its mixing in two phase gas–solid flow, chemical packed bed reactors with small-sized particles (~1–3 mm in diameter), as discussed by Abdulmohsin (2013).

2. Literature review

In the open literature, there are very few studies related to the flow-field in the packed pebble beds. Among these studies, Hassan and Dominguez (2008) applied particle image velocimetry (PIV) along with the matched index of refraction (MIR) technique to measure the full-field velocity of the liquid phase in the interior region of a small-sized (3 cm × 3 cm × 35 cm) packed bed. They packed the column randomly with 4.7 mm diameter polymethylmethacrylate (PMMA) beads of 1.18 g/cm^3 density, which offer high light transmittance with a refractive of index. It should be noted that Hassan and Dominguez (2008) selected the p-cymene (liquid phase) instead of investigating the gas phase. They correlated the results of the liquid phase to that of the gas phase. Vertical liquid flow structures were identified in some of the pores (voids) between the spheres, while there were some flows with preferential direction in other pores. In general, it was observed that the flow in the pores was of a very complex nature. Even though they used the liquid phase instead of the gas phase, the authors also concluded that the obtained data would be useful for enhancing the understanding of gas flow through a packed bed and for computational fluid dynamics (CFD) code validation. In the study of Lee and Lee (2009), flow-field measurements were taken in a two-dimensional wind tunnel using the particle image velocity (PIV) technique in a very narrow flow channel between the pebbles, and air was used as the gas phase. Also, a small-sized (170 mm × 170 mm × 505 mm) pebble-bed test section was used. The results showed that the presence of stagnation points within the fuel gaps might lead to having hot spots on the surface of the fuel particles. With only these two extant studies, the hydrodynamic phenomena are not yet well understood. Furthermore, most of the reported experimental studies were restricted to understanding the effect of operating conditions on the global parameters, such as pressure drop and overall voidage of the bed (Hassan and Dominguez, 2008).

It is obvious that extensive investigations are required to further advance the knowledge of the coolant gas dispersion and dynamics occurring in packed pebble-bed reactors, which will provide information for the safe and efficient design and operation of these reactors. Accordingly, this work focuses on quantifying for the first time the dispersion and the extent of mixing in the gas phase of a cold-flow pebble-bed unit of 0.3 m diameter, using an advanced gaseous tracer technique developed for this purpose. The deviation of the flow of the gas phase from the plug-flow characteristics in the pebble bed is described using the axial dispersion model (ADM), where such representation is valid if there is not much deviation from an ideal plug-flow reactor (PFR) model. The effect of the gas velocity on the axial dispersion coefficient was investigated using a wide range of flow conditions that cover both laminar and turbulent flow regimes in the studied pebble bed. The degree and extent of mixing in the pebble bed are characterized in terms of the axial dispersion coefficients, and a comparison was made between these measured coefficients at different gas velocities with those predicted by selected correlations.

3. Experimental work

3.1. Separate effects experimental setup

To simplify the experimental work and since the movement of pebbles is very slow compared to the flow of the coolant gas, the pebble-bed reactor was made of fixed-bed particles for the purpose of this study. The cold-flow unit of the pebble bed, which was developed as a separate effect experimental setup, so as to conduct proper gas tracer measurements, consists of a Plexiglas® column of 0.3 m diameter and 0.92 m height. The schematic diagram of the