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Characteristics of convective heat transport in a packed pebble-bed reactor

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HIGHLIGHTS

- A fast-response heat transfer probe has been developed and used in this work.
- Heat transport has been quantified in terms of local heat transfer coefficients.
- The method of the electrically heated single sphere in packing has been applied.
- The heat transfer coefficient increases from the center to the wall of packed bed.
- This work advancing the knowledge of heat transport in the studied packed bed.

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ABSTRACT

Obtaining more precise results and a better understanding of the heat transport mechanism in the dynamic core of packed pebble-bed reactors is needed because this mechanism poses extreme challenges to the reliable design and efficient operation of these reactors. This mechanism can be quantified in terms of a solid-to-gas convective heat transfer coefficient. Therefore, in this work, the local convective heat transfer coefficients and their radial profiles were measured experimentally in a separate effect pilot-plant scale and cold-flow experimental setup of 0.3 m in diameter, using a sophisticated noninvasive heat transfer probe of spherical type. The effect of gas velocity on the heat transfer coefficient was investigated over a wide range of Reynolds numbers of practical importance. The experimental investigations of this work include various radial locations along the height of the bed. It was found that an increase in coolant gas flow velocity causes an increase in the heat transfer coefficient and that effect of the gas flow rate varies from laminar to turbulent flow regimes at all radial positions of the studied packed pebble-bed reactor. The results show that the local heat transfer coefficient increases from the bed center to the wall due to the change in the bed structure, and hence, in the flow pattern of the coolant gas. The findings clearly indicate that one value of an overall heat transfer coefficient cannot represent the local heat transfer coefficients within the bed; therefore, correlations are needed to predict the radial and axial profiles of the heat transfer coefficient.

1. Introduction

A pebble bed-type of very-high temperature gas-cooled reactor (VHTR) is one of the most probable solutions (Goodjohn, 1991) and the most promising concept (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).

In the core of a pebble-bed nuclear reactor, the local fuel temperatures depend not only on the local power generation but on the point heat removal rate (Abdulmohsin and Al-Dahhan, 2012). Hence, for the safe design and efficient operation of packed pebble-bed reactors it is crucial to have detailed information and a proper understanding of the transport of the heat generated during nuclear fission from slowly moving hot fuel pebbles to the flowing coolant gas. All three modes of heat transport (i.e.,

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Nomenclature

Symbol

d_h	effective (hydraulic) pebble diameter, m
d_p	pebble diameter, m
D_c	column diameter, m
n	total number of experimental data points, Eq. (2)
N	the data point number, Eq. (8)
V	interstitial 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

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

Nu	Nusselt number (= hd_p/k), dimensionless
Pr	Prandtl number (= $\mu C_p/k$), dimensionless
Re	Reynolds number (= $\rho V_g d_p/\mu$), dimensionless
Re_h	effective Reynolds number [= $\rho V d_h/\mu = Re/(1-\varepsilon_b)$], dimensionless

List of abbreviations

AARE	average absolute relative error
CFD	computational fluid dynamics
DAQ	data acquisition system
Gen IV	4th generation of nuclear reactors
HTGR	high temperature gas-cooled reactor
HTR	high temperature reactor
KTA	German nuclear safety standard commission (Kerntechnischer Ausschuss)
PBR	pebble bed reactor
US DOE	Untied States department of energy
SCFM	Standard cubic feet per minute
VDI	German Engineers Association (Verein Deutscher Ingenieur)
VHTR	very high temperature reactor

conduction, convection, and radiation) are important to modeling and predicting the pebble-bed core temperature distribution. During nominal operation of the reactor (relatively high Reynolds numbers), the heat transfer mechanism is governed by forced convection (Fenech, 1981). This heat convection can be quantified and characterized in terms of a convective heat transfer coefficient or non-dimensional Nusselt number. At low Reynolds numbers (in the case of an accident), the effects of free convection, thermal radiation, heat conduction, and heat dispersion are on the same order of magnitude as the contribution of the forced convection (Fenech, 1981). However, little information related to pebble-bed heat transfer is available in the open literature, so this mechanism has not yet been fully understood (Stainsby et al., 2010b). Furthermore, the quantification of the heat transfer coefficient between the heated pebbles and the flowing coolant gas using models or correlations to predict the temperature distributions for design, scale-up, and operation is still lacking.

2. Literature review

In the open literature, the heat transfer data were obtained by direct measurements (in which the component particles are heated separately) and indirect means (by involving the transient heating of fluid or mass transfer experiments). On the other hand, the measurement techniques applied for packed pebble-bed heat transfer are as follows: (1) the electrically heated single sphere buried in the unheated packing (Achenbach, 1982, 1995; Schroder et al., 2006; Rimkevicius et al., 2006; Rimkevicius and Uspuras, 2008; Rousseau and Van Staden, 2008); (2) mass transfer analogy and simultaneous heat and mass transfer (Achenbach, 1982, 1995); and (3) the regenerative heating technique, which is based on the concept of unsteady heat transfer of a heated sphere in a packed pebble bed through which a cooling fluid flows (Hoogenboezem, 2007). In addition, semi-empirical methods (Gnielinski, 1978, 1981) and recently computational and theoretical models (Becker and Laurien, 2001, 2003; Yesilyurt and Hassan, 2003; Lee et al., 2007; Stainsby et al., 2008, 2010a; Kim et al., 2010; du Toit and Rousseau, 2012) were used to predict the heat transfer rate and coefficients in pebble-bed reactors. Based on the predetermined criteria or model, it is worthwhile to mention that these experimental/computational determinations of heat transfer coefficients were made under either steady-state and/or transient conditions.

Unfortunately, in these previous studies, it was found that the experimental results are quite different and show considerable departures from one another, particularly at low Reynolds numbers. Achenbach (1995) claimed that the reported results cannot be generalized to represent the convective heat transfer in a randomly packed bed. Schroder et al. (2006) pointed out that inhomogeneous interstitial flow velocities are responsible for the scattering of the heat transfer experimental data of other investigators. In fact, this is due to convective heat transfer influenced by many parameters, such as local flow condition, the nature of the flow regime, bed characteristics, etc. In addition, there are inaccuracies in the heat flux and temperature measuring techniques. For instance, the method of using a single heated sphere requires that the local heat flux and sphere surface temperature be measured accurately in addition to the local gas flow temperature in the gap between the pebbles. In all previous studies, the heat flux was based on the directed energy input method, and the boundary condition of constant surface temperature was assumed. This assumption is unreliable for the boundary condition because the thermal conductivity of the solid is not large enough to lead to an isothermal surface temperature (Kaviany, 1995) and because the thermal conductivity of the solids also influences the temperature field around them. Another key issue in these previous studies is that the surface temperature is approximately obtained, due to both the uncontrolled heat losses via the points of contact with unheated neighboring spheres and the influence of heat transfer by the radiation. The surface temperature was taken to be the arithmetic average of the readings of three or four thermocouples, where their tips were flushed with the sphere surface (Rimkevicius et al., 2006; Hoogenboezem, 2007). In addition, the mass transfer analogy experiments are difficult and not an accurate as direct heat transfer measurements. Finally, an ideal plug flow model was generally assumed in the computational and theoretical approaches, although gas dispersion occurs even at high gas velocities and the actual velocity profile is non-uniform with a pronounced slip at the wall. All these crucial limitations in previous studies inevitably reduce the accuracy of the experimental results. Thus, the selected measurement technique greatly influences the generated heat transfer data.

It is obvious that extensive investigations are required to further advance the knowledge of heat transport occurring in packed pebble-bed reactors which will provide information for the safe and efficient design and operation of these reactors. Accordingly, in this work, the local pebble-to-gas heat transfer coefficient in a 0.3 m diameter cold-flow pebble-bed unit were investigated experimentally using a noninvasive and fast-response heat transfer probe of spherical type. This spherical-type probe reduces the integration errors in previous measurements of local heat transfer in packed