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Experimental analysis of the thermal field and heat transfer characteristics of a pebble-bed core in a high-temperature gas-cooled reactor

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ABSTRACT

Identifying the locations of hot spots in a pebble-bed reactor core and analyzing the thermodynamic characteristics in the core are critical tasks. Although various numerical simulations have been conducted in this regard, experimental analyses are rarely found in the literature. Therefore, in this study, experiments are conducted with the pebbles packed in a face-centered-cubic (FCC) structure inside the test section. The local heat transfer characteristics of a pebble are analyzed, and it is found that the heat transfer varies with the location; areas with $\varphi = 36°$ and $117°$ are the strongest heat transfer zones (φ is the circumferential angle from the z-axis to the hole), while areas with $\varphi = 0°$, $90°$, and $180°$ are the weakest heat transfer zones. The experiments are performed under five different conditions of air inlet velocity, and the corresponding surface thermal profiles and maximum temperature differences between two pebbles are obtained. It is found that the maximum surface temperature difference between two pebbles is 15.3 °C when the Reynolds number is 1.46×10^4 and 7.8 °C when the Reynolds number is 3.30×10^4. In addition, the heat transfer coefficients and the Nusselt number are also obtained and they are correlated with the Reynolds number as $h_{AVG} = 0.03677Re^{0.8}$, $Nu = 0.194Re^{0.8}Pr^{0.4}$, respectively. These findings can not only provide a deeper understanding of the thermodynamics in a pebble-bed reactor core but also facilitate safer reactor design.

1. Introduction

A high-temperature gas-cooled reactor (HTGR) with a pebble-bed core is a Generation IV reactor that converts heat into electricity with higher efficiency than a Generation III reactor and is therefore considered economically competitive. Moreover, it is known for its inherent safety in the case of accidents involving coolant loss. The large amount of graphite in the core provides high thermal inertia and maintains the reactor core within the thermal limit (Lohnert, 1990). When the reactor core becomes too hot, its negative feedback mechanism slows down the fission reactions and the power is reduced. Further, when the reactor is shut down, its passive safety characteristic facilitates the removal of decay heat via heat conduction through the sides of the reactor to the environment. Such advantages promote the wide application of HTGR.

However, researchers have found that one-third of the pebbles fed into the radial outer zone of the AVR reactor core experienced surface temperatures 200 °C higher than those previously predicted by reactor core analysis calculations (Moormann, 2008). Such high pebble surface temperatures may affect reactor integrity and cause serious accidents involving the release of fission products from the fuel elements not only into the reactor coolant system but also into the electricity generation system or the environment. Moreover, the graphite layer of the pebble bed may be destroyed under excessively high temperatures; thus, the control of nuclear reactivity will be lost. Hence, the possibility of local hot spot formation must be reduced for a safe operation of the reactor. Therefore, it is extremely important and useful to not only understand the thermodynamics inside the reactor core but also identify the local hot spot locations.

The fuel elements are randomly packed into a realistic pebble-bed reactor core. Hence, it is difficult to conduct experiments or numerical simulations to analyze the flow regimes or thermal field in such a complex system (Auwerda et al., 2010). To investigate the flow physics and thermodynamics in the core, many studies have chosen to simplify the core to a body-centered cubic (BCC) or face-centered cubic (FCC) structure, even though the actual core

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Nomenclature

A	cross-section area (m^2)
C_p	heat capacity (J/kg/°C)
D	characteristic length of the pebble in the reactor core (m)
h	heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m/K)
L	characteristic length of the pebble in the test section (m)
m	mass flow rate(kg/s)
q"	heat flux (W/m^2)
T	temperature (K)
V	velocity (m/s)
x	distance (m)
Abbreviations	
BCC	body-centered cubic
FCC	face-centered cubic
SC	simple cubic
Surf	surface
Greek letters	
α β	coefficient
γ	ratio
Δ	difference
ε	the porosity of the pebble bed
μ	viscosity (Pas)
ρ	density (kg/m^3)
φ	angle (degree)
Subscripts	
m	model
p	prototype

is a combination of simple cubic (SC), BCC, and FCC structures. Hassan (2008) investigated the flow distribution in an aligned pebble geometry consisting of 27 pebbles by numerical simulation. Shams et al. (2012, 2015) performed numerical simulations via CFD approaches and proposed the flow regime of a single FCC pebble bed. Other studies (Ferng and Lin, 2013; Hassan and Yesilyurt, 2002; Laguerre et al., 2008; Lee et al., 2007a,b) have also simulated the flow field under different turbulence models and pebble distributions. Moreover, studies on thermodynamic analysis (Kim et al., 2008; Sobes et al., 2011; Shams et al., 2013; Li et al., 2012) have also been reported. Lee et al., (2007)a,b compared the heat transfer characteristics of pebbles packed in a BCC structure under mutual contact and separation between the pebbles. Zheng et al. (2012) used both two-dimensional and three-dimensional thermal hydraulic codes to calculate the pressure drop and temperature distribution of a reactor core in the case of an accident involving depressurized coolant loss for the High-Temperature gas-cooled Reactor Pebble-bed Module (HTR-PM) project. However, all the above-mentioned studies have been conducted on the basis of numerical simulation and their results have not been validated experimentally.

Thus far, few experiments on flow pattern visualization of the coolant using PIV have been conducted by Hassan and Dominguea-Onitveros (2008) and Lee and Lee (2008, 2010). The stagnation zones over which the coolant rarely passes have been observed and the near-surface velocity field of the coolant has been derived. Nevertheless, there remains a critical need for experimental investigation of the flow physics. Moreover, the thermal field of the pebble surface and the local heat transfer characteristics in a PBR core merit additional research attention. Accordingly, Chen and Lee (2015, 2016) and Chen et al. (2016) have developed a new set of experiment facilities to measure the surface temperatures of the pebbles that are packed in an FCC structure in a rectangular test rig. Furthermore, in the present study, the pebbles are re-fabricated and newly designed heat flux sensors are employed to intensively analyze the general and local heat transfer characteristics in order to provide a deeper understanding of the thermodynamic behavior of a pebble-bed system. Consequently, the thermal field of the pebbles is derived and correlations of the average heat transfer coefficient and the Nusselt number with the Reynolds number are proposed; local heat transfer intensity of a pebble were also analyzed. Thus, this study makes a useful contribution to the existing literature on the thermodynamics in a pebble-bed reactor core and facilitates safer reactor design.

2. Parameter determination for the experiment

The ongoing High-Temperature gas-cooled Reactor Pebble-bed Module (HTR-PM) project in China aims to generate 200 MWe of power by installing two pebble-bed modular reactors, each of which can produce 250 MW of thermal power. Its main design parameters are listed in Table 1 (Zheng et al. 2009; Wang, 2014), and our experiment setup design is based on its operating conditions; the pebble diameter is scaled up by a factor of 2 as explained in the previous study (Lee and Lee, 2008). To ensure that the flow patterns and thermal field in the model accurately reflect those in the prototype, the Reynolds number and the Nusselt number are considered as the most important factors influencing the design.

Considering one of the purposes of this study is to observe the hot spots which might result in the destruction of a pebble's integrity, therefore, it is better to bring all attention to the hottest pebble in a reactor core. According to a report regarding HTR-10 released by International Atomic Energy Agency in 2013 (IAEA, 2013), the pebbles showing the highest temperature are located near the bottom of the bed, where the average fluid temperature is approximately 830 °C calculated by PHOENICS. It may seem unreliable because it is obviously bigger than the designed coolant outlet temperature, 700 °C, however, simulations using WIMSTER and TINTE show similar results, the reason for discrepancy needs to be clarified, though. Since no experimental results can be referred to thus far, the properties of helium under 830 °C are used in the scaling process. The Reynolds number and the Nusselt num-

Table 1
Design parameters of HTR-PM.

Parameters	Design values
Reactor power (MWt)	250
Active core diameter (m)	3
Active core height (m)	11
Helium pressure of primary loop (Mpa)	7
Helium mass flow rate (kg/s)	96
Inlet/outlet helium temperature (°C)	250/750
Number of fuel elements	420,000