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Experimental study of bypass flow in near wall gaps of a pebble bed reactor using hot wire anemometry technique

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ABSTRACT

Coolant flow behavior through the core of an annular pebble bed reactor is investigated in this experimental study. A high frequency hot wire anemometry system coupled with an X-probe is used for measurement of axial and radial velocity components at different points within two near wall gaps at five different modified Reynolds numbers (Re_m = 2043–6857). The velocity profiles within the gaps verify the presence of an area of increased velocity close to the pebble bed outer reflector wall, which is known as the bypass flow. Moreover, the characteristics of the coolant flow profile are seen to be highly dependent on the gap geometry. The effect of Reynolds number on the velocity profiles varies as the geometry of the gap changes. The time histories of the local velocities measured with considerably high frequency are further analyzed using power spectral density technique. Power spectral plots illustrate substantial spatial variation of the energy content, spectral shape, and the slope of the energy cascade region. A significant correlation between Reynolds number and characteristics of the velocity power spectra is observed.

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1. Introduction

Characterization of the fluid flow behavior within porous media is essential in a wide variety of engineering systems such as chemical engineering fluidized beds, pebble bed nuclear reactors, oil recovery, and filtration systems. Fluid flow through packed bed columns has been studied for decades in the field of chemical engineering and has received significant attention in the field of nuclear engineering due to the extensive research performed on the pebble bed core Very High Temperature Reactor (VHTR) concept. The Pebble Bed Modular Reactor (PBMR) which is a starting point for development of pebble bed VHTRs has an annular core with a solid inner reflector and modified fuel pebble design (Koster et al., 2003). The key design characteristics of pebble bed VHTRs are the application of helium as coolant, graphite as moderator, and refractory coated fuel particles (i.e. TRISO-coated fuel particles) as fuel pebbles. Within the core of a pebble bed VHTR, spherical TRISO-coated fuel particles are randomly stacked in an annular region confined between the inner and outer reflectors. Helium passes through the core of a pebble bed reactor within the paths defined by the fuel pebbles. Heat, mass, and momentum transfer through pebble bed reactor cores is quantitatively correlated to the coolant velocity profile within the bed. Therefore, the study of complex coolant flow behavior in gaps between the spherical fuel elements in the core of pebble bed VHTRs is highly important in the development of such reactors.

Research studies performed on the distribution of the fluid flow through packed beds indicated the complex nature of the flow passing through the gaps between the randomly stacked pebbles. Fluorescent Particle Image Velocimetry (PIV) technique in conjunction with Matched Index of Refraction (MIR) was applied by Northrup et al. (1991, 1993) to measure low flow velocities in a porous medium. The results indicated the existence of intrapore mixing within the porous medium. Hassan (2008) used Large Eddy Simulation (LES) technique to simulate the helium flow within a segment of a pebble bed core reactor where the coolant Reynolds number was 8×10^5. Also, an experimental facility representing the pebble bed core was used to measure the velocity in the fuel gaps. In this experiment, Particle Tracking Velocimetry (PTV) and MIR techniques were used to measure the velocity in the midplane of the packed bed. Both LES and the experimental results show very complex flow structures within the gaps between the fuel elements. Hassan and Dominguez-Ontiveros (2008) applied PIV and MIR techniques to obtain the full-field velocity measurements in the interior region of a pebble bed reactor. Vortical structures were identified in some of the pores between the spheres while in some other pores, flows with preferential direction were observed. Lee and Lee (2009) used PIV to visualize the flow within a scaled up test facility representing the core of a pebble bed high temperature gas cooled reactor. A Reynolds number of 2.1614×10^4 was chosen for this experiment to match the

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Reynolds number in the core of an actual pebble bed reactor. The results show that the presence of stagnation points within the fuel gaps might lead to hot spots on the surface of the fuel particles.

Previous experimental and numerical research studies performed on flow distribution within packed bed columns have indicated that velocity profile within the bed significantly changes in the vicinity of the packed bed wall, reaching a maximum in the near wall region. This peak in the flow velocity profile close to the packed bed wall is known as *bypass flow* (also called *flow channeling*). Bypass flow has been observed in chemical packed beds with different sizes and shapes of the bed and also various sizes and shapes of the packing pellets. In an investigation performed by Schwartz and Smith (1953), the air velocities measured by a hot wire anemometer above a packed bed for different bed sizes and different pellet shapes and sizes illustrated a peak in the velocity at approximately one pellet diameter away from the wall. Hot Wire Anemometry (HWA) technique was applied in a study done by Marivoet et al. (1974) to measure the air velocity above a cylindrical packed bed. The results indicated a region of increased velocity close to the container wall. Johnston et al. (1975) applied Laser Doppler Anemometry (LDA) technique along with MIR technique in a hexagonal packed bed facility to obtain the axial velocity profile of the fluid passing through the bed and larger velocity values were observed in near wall regions. In a research study carried out by Drahos et al. (1982), velocity profiles of the air passing through a packed bed column were obtained at the exit plane of the bed using HWA technique. The velocity profiles indicated a well-pronounced maximum in the vicinity of the wall for spherical and cylindrical pellets. Vortmeyer and Schuster (1983) developed a method for calculation of the flow distribution within packed bed columns through which they obtained a sharp peak in the velocity profile near the wall. Another model for velocity distribution through packed beds was developed by White and Tien (1987). The predictions of this model was in good agreement with previous numerical and experimental results showing the flow channeling phenomena close to the packed bed wall. Moreover, it was indicated that the close-packed beds show a sharper velocity peak in the vicinity of the container compared to looser packed beds. In an investigation done by Ziolkowska and Ziolkowski (1988), the radial profile of the flow inside a packed bed was determined for different pellet sizes by both LDA experiments as well as calculations based on the Dupuit-Drochheimer hypothesis. The air flow profiles obtained through both approaches verified the presence of a region of higher velocity close to the packed bed container wall. Moise and Tudose (1998) obtained the local velocities of air passing through long packed beds ($L/D > 1$) for different pebble sizes and for different Reynolds numbers (Re = 100–400). The velocity measurements in the bed were obtained by a thermo-anemometer passing through a free zone with a 20 mm height. The velocity distributions were shown to be strongly affected by the local porosity, pellet diameter, bed length and diameter, and the Reynolds number. Additionally, the velocity profiles confirm the existence of a region of higher velocity adjacent to the wall. However, a different flow pattern was observed in a study done by Lerou and Froment (1977) in which velocity profiles obtained by HWA technique downstream the packed bed for different air flowrates showed more than one peak. More interestingly, the peak close to the wall was not always the highest one. They emphasized on the fact that rearrangement of the structure of the packing significantly affected the velocity profile and in some cases resulted in obtaining the classical velocity profile with one peak close to the wall.

Many research studies have confirmed that the flow behavior and consequently heat, mass, and momentum transfer through packed beds are directly correlated to the porosity of the bed. In fact, several studies have related the bypass flow phenomena to the increased porosity close to the container wall of the packed bed. Therefore, a variety of theoretical, experimental and numerical techniques have been applied to determine the porosity profiles within packed beds. One of the early experimental porosity studies on packed beds was done by Roblee et al. (1958) where the radial porosity variations within a cylindrical cardboard packed bed was measured for different cases with different types of packing (spheres, cylinders, etc.). The results confirmed that the packed bed wall has a significant effect on the porosity of the bed resulting in a higher porosity value close to the container wall. Other studies such as the investigation done by Goodling et al. (1983) confirmed the results obtained by Roblee et al. (1958) showing a porosity value of one at the container wall which then oscillates around the mean porosity value with a decreasing amplitude. Fluid flow passes within the packed bed through the free gaps between the packing material, i.e. the flow chooses the paths of least resistance between the pebbles to flow through the bed. Therefore, the peak in the velocity profile of the fluid flow corresponds well to the maximum porosity value close to the packed bed wall.

In the present study, HWA technique is applied to obtain high frequency velocity measurements at different points within the near wall gaps of a test section modeling an annular pebble bed reactor. Subsequently, for each gap, the time-averaged velocity profiles are obtained for different Reynolds numbers of the flow passing through the bed. Moreover, the time histories of the velocities obtained at each measurement point are further analyzed utilizing Power Spectral Density (PSD) method to acquire a more in-depth insight of the flow characteristics within the near wall gaps of an annular pebble bed reactor.

2. Experimental methodology

2.1. Experimental set-up

Schematic of the test facility used in this investigation which is designed to model the core of an annular pebble bed VHTR is presented in Fig. 1(a). In addition to the schematic of the whole test facility, a picture of the test section modeling the annular pebble bed reactor core along with pictures of one measurement gap and the location of the HWA probe in the gap is shown in Fig. 1(b). As seen in Fig. 1, the test facility used for this study is an annular bed containing spheres representing the spherical TRISO-coated fuel elements. The outer cylinder is made of clear Acrylic with a height of 2.18 m and an outer diameter of 0.89 m. The radius of the annulus inside the cylinder is 0.27 m. The experimental set-up is designed to accommodate both optical techniques and HWA technique. Therefore, as seen in Fig. 1(b), two different types of spheres are used to stack the annular bed: 1 – Black spheres made of plastic with a diameter of 0.03302 m used in the upper and lower sections of the bed, 2 – Clear spheres made of Acrylic with a diameter of 0.03175 m used in the middle section of the annular bed. The Acrylic spheres are chosen to have nearly the same size of the black plastic spheres to ensure a nearly uniform porosity ($\varepsilon = 0.39$) throughout the bed. Both types of spheres are made of high stiffness material and do not experience any deformation due to the weight loads. In this experiment, air is chosen as the working fluid instead of helium and it is passed through the bed using a high power blower. The velocity of air passing through the gaps between the pebbles is measured in certain locations of the bed using HWA technique. Four evenly spaced sets of holes (columns A–D, as shown in Fig. 1) are made through the circumference of the cylinder. Each set has ten equally spaced holes (0.17 m apart) along the cylinder height which could be used for air velocity measurements within the gaps close to the pebble bed wall. Since the annular bed is randomly packed, it is

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