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Natural convective heat transfer of heated packed beds

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ABSTRACT

Natural convection heat transfer of heated packed bed was investigated. Experiments were performed for a single heated sphere buried in unheated packed beds varying its locations and for packed beds with all heated spheres varying the heights of packed beds from 0.02 m to 0.26 m. Mass transfer experiments using a copper electroplating system were performed based upon the analogy between heat and mass transfer. The diameter of sphere was 0.006 m, which corresponds to Ra_d of 1.8×10^7. For the single heated sphere cases, the measured results agreed well with the existing natural convection heat transfer correlations for packed beds and even with those for a single sphere in an open channel. For all heated sphere cases, the average heat transfers decrease with increasing packed bed heights.

1. Introduction

The natural convection heat transfer in the fluid-saturated high temperature packed beds has been widely studied due to its various applications ranging from solar collectors to high temperature gas cooled reactor. The phenomenon has been gaining interest, as the coupled mechanism of conduction, natural convection and thermal radiation in packed beds improves the cooling performance of many applications [1]. The natural convection heat transfer was known to be affected by Ra_d, Pr [2] and especially dominated by the temperature difference between solid spheres and fluid [1].

The measurements of temperature and velocity in packed beds are difficult due to the randomly packed structure of packed beds. Also, the uniformly heated condition for all spheres in packed beds is very difficult to realize in experiments. The natural convection heat transfer in packed beds has been studied as the porous media. This, in general, is the case encountered in packed beds, which are made up of roughly uniform particles [3]. The existing studies have been performed for two largely different heat source conditions: First, the packed beds are not heat source and the heat sources are located inside or outside of the packed beds [4–16]. Second, parts of the packed beds worked as the heat source [1–2,5,17–22]. In the former cases, the existing studies focused on the fluid behavior by the heat source in so-called porous media. Most studies for the former case were performed for side wall or below heating conditions [4–13]. Other studies were aimed at the measuring the temperature or flow field around a concentrated heat source embedded in the porous media [14–15]. In the latter cases, the existing studies focused on the heat transfer between the heat source and fluid by heating the parts of the packed beds. In this case, the natural convection heat transfer was mainly carried out for the single heated sphere condition varying the heat flux of sphere in unheated packed beds [2,17–22]. Other studies investigated the temperature distribution in packed beds for all heated spheres condition [1,5,16]. Relatively less studies were performed for all heated spheres in packed bed.

In this study, experiments were performed in two parts: first, the single heated sphere buried in unheated packed beds and second, packed beds with all heated spheres. First, the experiments were performed the single heated sphere buried in unheated packed beds varying the axial and radial locations of the heated sphere. Second, the experiments were carried out varying the heights of packed beds for all heated spheres.

Based on the analogy concept, mass transfer experiment was performed instead of heat transfer experiments by adopting an electroplating system. In the copper sulfate-sulfuric acid ($CuSO_4$–H_2SO_4) electroplating system, the cathode acts as the heated surface as the reduction of cupric ions results in the decrease of fluid density and hence induces buoyancy. Thus the cathode copper sphere simulates the heated sphere.

2. Theoretical background

The porous media modeling was adopted to predict the fluid flow or heat transfer due to the complicated flow through a packed bed [23]. The porous media modeling simulate the packed beds in two aspects: first, in the fluid flow aspect, the fluid flow in packed bed is simulated

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Nomenclature

C	Molar concentration [mol/m^3]
D	Diameter of duct [m]
D_m	Mass diffusivity [m/s^2]
d	Diameter of sphere [m]
F	Faraday constant, 96,485 [Coulomb/mol]
Gr_d	Grash of number ($g\beta\Delta Td^3/\nu^2$)
g	Gravitational acceleration, 9.8 [m/s^2]
H	Height of packed beds [m]
h_h	Heat transfer coefficient [W/m^2 K]
h_m	Mass transfer coefficient [m/s]
$I_{\lim}$	Limiting current density [A/m^2]
K	Permeability [m^2]
k	Thermal conductivity [W/m K]
Nu_d	Nusselt number ($h_h d/k$)
Pr	Prandtl number (ν/α)
R	Radius of duct [m]
Ra_d	Rayleigh number ($Gr_d Pr$)
r	Distance from centerline of duct [m]
Sc	Schmidt number (ν/D_m)
Sh_d	Sherwood number ($h_m d/D_m$)
T	Temperature [K]
t_n	Transference number
U_x	Uncertainty of x
z	Distance from the bottom of packed beds [m]

Greeks symbols

α	Thermal diffusivity [m/s^2]
β	Volume expansion coefficient [1/K]
γ	Dispersion coefficient
ε	Porosity
μ	Viscosity [kg/m s]
ν	Kinematic viscosity [m^2/s]
ρ	Density [kg/m^3]

as high viscous flow due to the large friction between spheres and fluid [24]. Second, in the heat transfer aspect, the local thermal equilibrium was considered between the fluid and solid spheres and a single volume-averaged temperature is used to predict the ambient temperature in packed beds [7].

When the packed beds are not heat source but merely media, the permeability (K) which is a measure of the ability of a material to transmit fluids was considered as an important parameter in natural convection heat transfer in packed beds. In packed beds, the natural convection on side wall or bottom plate heating condition, was mainly studied varying porosity (ε), working fluid, heat flux of heat source, the material and size of the media [4–13]. Some studies suggested the empirical correlations based on the test results [6–8]. Other studies investigated the temperature or velocity distributions in natural convection with concentrated heat source in unheated media varying the permeability (K) and heat flux of heat source [14–15].

When the parts of the packed beds acted as the heat source, either the single heated sphere or all heated sphere in packed bed, the boundary layer and temperature difference between heat source and fluid were considered importantly. In the natural convection of packed beds for heated sphere condition, the heat transfer was characterized by Ra_d, Pr and not by ε. The Nu_d increases with the Ra_d as the buoyancy increases [2,17,25]. The Nu_d increases with the Pr due to the decrease of the thermal boundary layer thickness. The porosity, ε is an important parameter for the forced convection heat transfer of packed beds but not for the natural convection heat transfer of packed beds [2]. Relatively less studies have been reported to this heat source condition.

International Working Group on Gas Cooled Reactors (IWGGCR) [16] investigated experimentally and numerically the temperature distribution of the packed pebble bed with carbon spheres with the heated pipe at the center of the packed bed, simulating the condition of loss of cooling benchmark of the SANA-1(Selbsttätige Abfuhr der Nachwärme-1). The diameter of the sphere was 0.07 m. The packed beds diameter and height were 1.5 m and 3.2 m respectively. Numerical analysis was carried out under conditions with and without convection and compared with the experimental results. Fig. 1 shows the experimental and numerical temperature distributions in packed beds. Horizontal axis (Radius) is the distance from the heated pipe and vertical axis is the temperature. All the results show that the temperatures were highest at the center and decreased toward the walls of packed beds and higher at the top and lower at the bottom. The numerical results without convection did not depend on top, middle and bottom cases. The experimental results show that each temperature for all axial positions was lower than both numerical results at the small radius. While, the temperature for all axial positions was larger than both numerical results near the wall. The working group concluded that the natural convection occurs in the SANA-1 as the experimental results and numerical results with convection showed similar trends.

Zhang et al. [1] carried out the numerical works on the temperature distribution of the cylindrical enclosure packed beds by carbon spheres with the heated pipe at the center which is the same geometry with SANA-1 test. The spheres were stacked randomly in packed beds. The volume averaged model and the pore scale model in the numerical results were compared with the experimental results. The former used of the averaged porosity in porous media, while the latter used the distribution of porosity. They reported that the pore scale model was more similar to the experiments. As expected, the temperature is the higher near the centerline and lower toward the wall of the packed beds. When the heat flux of heated pipe increases, the temperature difference from center to wall are increased.

Karabelas et al. [17] carried out the natural convection mass

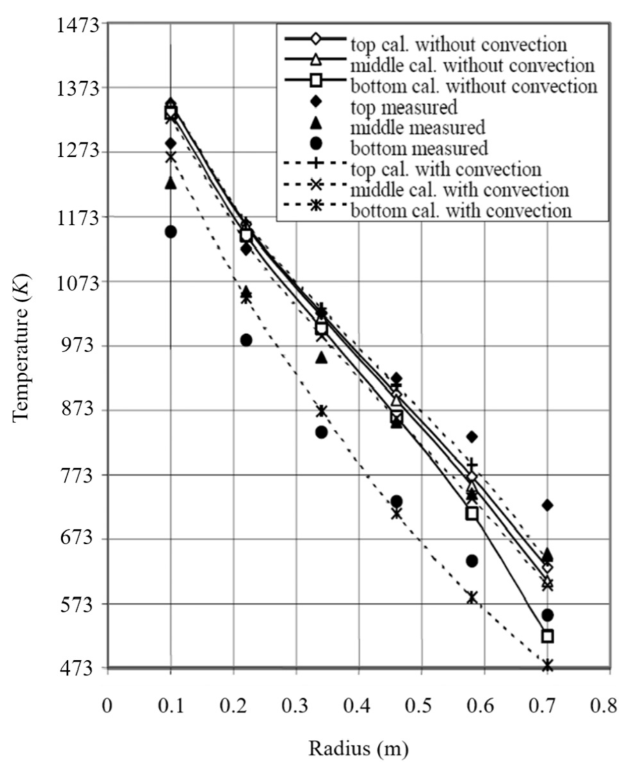

Fig. 1. Comparison of experimental and numerical results for SANA-1 [16].