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# Effect of magnetic fields on thermal conductivity in a ferromagnetic packed bed

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ABSTRACT

Parameters like solid particle conductivity, shape, size, contraction/expansion and porosity along with saturating fluid conductivity and pressure are important parameters when studying effective thermal conductivity of a porous bed. This paper introduces a novel heat transfer enhancement method for ferromagnetic material particle beds by exposing them to an external magnetic field. Two materials were experimentally studied: magnetite ($Fe_3O_4$) and iron filings (random composition of iron oxides). A series of twelve trials were performed using different magnetic field configurations and intensities. The magnetic fields which were used include non-uniform, semi-homogeneous and non-homogeneous fields which formed by four different magnet configurations with magnetic intensities from 819 Gauss to 4667 Gauss. In all the cases it is shown that applying magnetic fields increases the heat transfer rate in particle beds. The improvement rate is 7–15% for most cases studied. However, the configuration and intensity of the field determined the extent of improvement while non-homogeneous fields produced the greater effect.

## 1. Background

Particulate beds have been the subject of study for many years because of their different applications. Some applications of porous media include catalytical and chemical particle beds, mass separator units, thermal insulation, and debris beds [1]. Likewise, the beds which consist of magnetic particles find their application in magnetic fluids, catalysis, magnetic resonance imaging, and data storage.

Magnetic particles are produced from different sources like iron oxides ($Fe_3O_4$ and $\gamma - Fe_2O_3$), pure metals (Fe and Co), and alloys ($CoPt_3$ and FePt). Magnetic particles are chemically very active [2]. Another important characteristics of these particles is that, upon exposure to a magnetic field, they show the properties of supermagnetic materials and each particle acts as a small magnet.

Several studies are available in literature that measure the heat transfer and flow in particle beds. Some of the references are discussed here. Schroder et al. [3] measured the local heat transfer in wooden and slate porous beds. They measured both the particles and the filling gas temperatures in vicinity of the particles and used the data to calculate the local heat transfer coefficient. They also studied the effect of radiation by using a one-dimensional statistical model. Xu et al. [4] performed experiments to study the fluid flow and effective thermal parameters in a column of randomly sized particles. Under a constant wall temperature condition, they studied the axial and radial temperature distributions. The parameters which they considered in their study included particle diameter, particle thermal conductivity and fluid velocity. They suggested that a proper selection of good thermal conductive filling material is important for enhanced heat transfer rates in a particles bed. They also concluded that increased flow rate of the filling gas increases the effective thermal conductivity of the bed while smaller particle size has a significantly negative effect on thermal conductivity of the bed.

Nsofor and Adebiyi [5] performed experimental measurements of the forced convection gas-particle heat transfer coefficient in a packed bed. They suggested a correlation for convective heat transfer in high temperature packed beds while remained concentrated on uncertainty analysis to ensure accuracy of their correlation. Srinivasan and Raghunandan [6] used a packed bed as a heat exchanger while a solid propellent gas generator was used to supply room temperature gas to the bed. They experimentally studied the transient temperature response of the bed with varying inlet gas temperatures under turbulent gas flow regime. They suggested a procedure for calculating unsteady gas temperature at the outlet

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of packed bed for engineering applications. Kapischke and Hapke [7] presented a measuring technique for oscillating temperature changes in a packed bed. Their technique is appropriate for measuring effective thermal conductivity in a non-permeated container. They also suggested that thermal conductivity of a porous bed is dependent on the concentration, pressure and the temperature of the filling gas.

Wen and Ding [8] studied and modeled transient and steady state thermal behavior of the filling gas in a packed bed under constant wall temperature. They derived the effective thermal conductivity and convective coefficients for steady state heat transfer both from experimental measurements and modeling. Their model yielded good results for axial heat transfer in the bed. Laguerre et al. [9] modeled two transient heat convection approaches in a bed and compared their results with experimental results. They developed a method based on dispersed particles approach which included air-particle convection, conduction and radiation. The results of their approach were in good agreement with experimental results.

Wyczolkowski and Musial [10] demonstrated that inside a bundle of long elements, convection does not practically exist and the problem of heat transfer in the system could be simplified to analyzing its thermal conductivity. In such a case the need for solving a differential equation for the motion of filling liquid is eliminated and a simple criterion relation would suffice to determine the thermal conductivity of the system. They suggested that this model could be implemented as a numerical procedure in thermal modules for integrated heat treatment process modeling.

Woodside and Messmer [11] studied the effect of thermal conductivity of a two phase system considering the conductivities and volume fractions of each component. Their study included conductivity measurement on three quartz sand packs, a glass bead pack, and a lead shot pack. Their results show that conductivity is contingent on porosity, solid particle conductivity, saturating fluid conductivity, and the pressure of the saturating gas.

Presley and Christensen [12,13] discussed the impact of particle shape and size, and bulk density on thermal conductivity under low pressure. Based on their studies, particles of irregular shape form loose beds with lower density and lower thermal conductivity compared to spherical shaped particles of the same size. Consequently, lower density of the bed decreases the thermal conductivity. It is also stated that thermal conductivity of a mixture of different sized particles tends to be closer to that of the larger particles while it remains independent of the mixture composition. In another work [14], the same authors showed that increasing the pressure will increase the conductivity of a particulate bed. They suggested that, under vacuum, conductivity of a packed bed is proportional to the cube of temperature gradient.

Matsushita et al. [15] applied some previously proposed methods to calculate the effective thermal conductivity of a porous bed. They concluded that the results from previous methods neglected the expansion and contraction of particles and eventually do not match the experimental data. They proposed a model to calculate the effective thermal conductivity including the effect of expansion and contraction on the bed.

In all of the above studies, the fluid and thermal measurements were performed in a particle bed with or without heat transfer enhancement techniques. In the present work, the authors studied the effect of magnetic field on improving the heat transfer on particle beds by applying an external magnetic field. Addition of magnetic field aids in compaction of the bed and hence increase the contact area between the particles, which in turn aid in increasing effective thermal conductivity of the bed.

Magnetic fields can exert a force on materials with magnetic properties and manipulate them without being in touch with that material [16]. Manipulating magnetic particles by a magnetic field has a wide variety of applications including magnetohydrodynamic pumping in microchannels, fluid mixing, stabilizing or agitating a magnetic particles containing fluid, and supporting bioreactions in microchannels [17]. Most of the studies evaluating the thermal conductivity improvement in the presence of magnetic field focused on magnetic nanofluids [18–30]. It was found from these studies that presence of magnetic field enhances the thermal conductivity of magnetic nanofluids and was found to depend on concentration of particles, magnetic intensity and temperature range. However, none of the studies so far have evaluated the effect of magnetic field on improving the effective thermal conductivity in a porous particle bed. The current work presents the experimental results obtained under different magnetic intensities and configurations in a particle bed. The test setup, parameters used and results obtained are presented in the following sections.

## 2. Experimental setup and procedure

### 2.1. Test chamber

Fig. 1 shows the test chamber used for the experiments. A quartz container with a height of 10 cm and a diameter of 5 cm is used with a phenolic plate at the top and an aluminum plate at the bottom from where heat is supplied. Four K–type thermocouples were installed at the center of the container to measure one-dimensional heat transfer. The distance between each two thermocouples is 1 cm while the lowest one in the bundle touches the bottom aluminum plate of container from inside. A circular ultra-thin sheet heater with a maximum power of 31 W and electrical resistance of 461 W was attached to the setup at the bottom to provide the heat. The voltage of the heater was controlled by an AC voltage controller (variac) and was adjusted such that the maximum temperature is limited to stay below 323 K (50 °C). The setup is insulated around the periphery of the container. A thin sheet heater like the one used here will propagate heat on both sides. In a normal experiment where a magnet is placed below the heater, the magnet provides a thermal resistance which impacts heat loss from setup. A schematic of the container and thermocouple locations is presented in Fig. 1. To avoid the noise from magnetic fields, the thermocouples were covered by braided magnetic shield and noise suppressors were used on both ends. In addition, other equipment was placed at such a distance that there was no magnetic flux measured around them.

The test chamber was filled with either magnetite or iron filings. The particle shapes of the iron filing and magnetite are

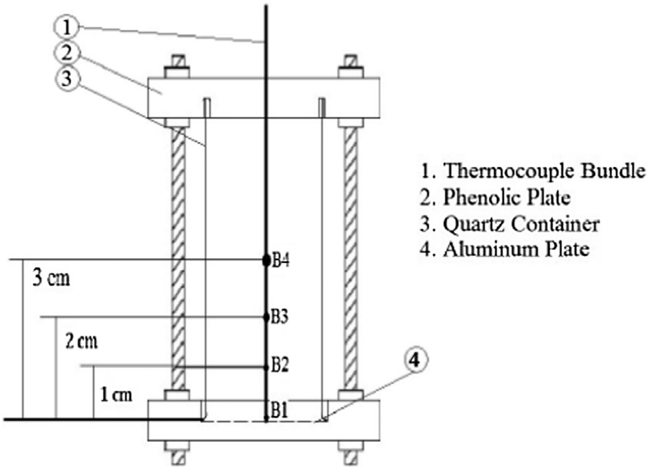

**Fig. 1.** Schematic of the container and thermocouple locations.