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Experimental investigation of effects of grain size, inlet pressure and flow rate of air and argon on pressure drop through a packed bed of granular activated carbon

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ABSTRACT

Considering the wide range of applications of the activated carbon in different applications, the behavior of fluid flow through a packed bed of irregular shaped activated carbon grains has significant importance. Hence, an experimental investigation is conducted on axial-horizontal flow of air and argon through 5 different packed beds of granular activated carbon (GAC) with different grain sizes. Investigations are done different flow line pressure and flow rates. Based on the previous studies, a simple correlation is proposed and results are presented in terms of dimensionless friction factor versus Reynolds number. Results are presented for different grain sizes and the correlation coefficients have been estimated with excellent curve fitting to the experimental data. Outcomes of this study could be used to design the systems in which the pressure drop through a packed bed of GAC is required.

1. Introduction

Understanding the behavior of fluid flow during its transportation through porous media has a great importance due to its effects on different characteristics of heat and mass transfer. There are variety of porous materials like rock, wood, concrete, foam and more. Some sort of porous media are constructed from granular materials such as a bed of sand, silica gel, carbon and so on. These kinds of granular porous materials have a wide range of application in various industries including, but not limited to, chemical engineering [1, 2], petroleum refinery [3], desalination and water treatment [4], adsorption [5], heat pumps [6], cooling and air conditioning [7, 8].

Activated carbon (also called activated charcoal), as a new kind of granular material, is a form of carbon processed to have small, low-volume pores that increases the surface area available for adsorption or chemical reactions. Due to its high degree of micro porosity, granular activated carbon (GAC) has found a great usage and importance in different scientific and engineering applications. GAC is traditionally implemented in filtration, chemical purification, catalytic convertors, thermal generators, refrigeration cycles, agriculture, water/air treatment and medical applications. For instance most of water treatment systems contain a GAC filter to purify water and adsorb its contaminants. GAC is also used in some adsorption refrigerators used in the trucks transportation systems [9, 10]. In gas plants, GAC can be implemented in the purification process of the natural gas to separate methane from the other hydrocarbon components. Based on these applications, thermal behavior and hydrodynamic characteristics of fluid flow through GAC is important to be investigated in order to design a new system using GAC.

In order to be able to study these topics, it is important to find out the effect of different parameters of GAC's on the thermal and hydrodynamic characteristics of flow through it. One of the most essential parameters representing fluid flow behavior through a packed bed of porous medium, such as GAC, is the pressure drop, which has a great importance in designing systems containing porous materials. Different characteristics of GAC such as its grain size, density, porosity, type of the carbon, surface roughness and also different conditions of fluid flow like its direction, flow rate, type of the fluid and its temperature can affect the pressure drop caused by GAC porous bed.

Various research studies have been performed to study and analyze

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fluid flow through a packed bed of porous medium using numerical, analytical and experimental approaches. Allen et al. [11] studied experimentally the pressure drop of air flow through different packed beds (rough spheres, smooth cylinders, cubes and crushed rock) and showed that particle shape, size distribution, packing arrangement and roughness can influence the pressure drop. Wang and Wang [12] performed an experimental study on the influences of gas pressure and temperature on the permeability and steady-state time of a Chinese anthracite coal. A similar work was done by Wu et al. [13] to find the effect of geological pressure and temperature on permeability of a volatile bituminous coal. Li et al. [14] conducted an experimental investigation to analyze the effect of effective stress increase, matrix shrinkage/swelling due to gas desorption/adsorption, gas slippage and other factors on the gas permeability of coals.

In addition to experimental studies, a vast range of numerical studies have been done in this area. Liu et al. [15] present a straightforward mathematical model for studying the behavior of fractured porous media. Zhao et al. [16] simulated two immiscible fluids flow in 2D porous media with a specific investigation on some fluid characteristics.

Because of the broad variety in types of porous media and high dependency of its characteristics to the condition of testing, there have been many experimental studies for various porous media in different testing conditions in order to find an estimate for the pressure drop caused by the packed bed of the porous medium. For instance, some experimental studies have been done to evaluate the permeability of concrete [17, 18], salt [19], pebbly sand [20], natural graphite [21] and anthracite coal [22]. More other similar investigations exist aiming to study fluid pressure drop when flowing through different substances and among them [23–26] can be cited. In addition, Chikhi et al. [27] presented an empirical study to account the pressure drop of two-phase flow through the porous media constructed with single size beads.

In order to find heat and flow characteristics of GAC, similar studies have to be performed on its bed. Most of the studies about GAC focused on adsorption properties of activated carbon such as the works done by Ahmed et al. [28] and Saha et al. [29]. Wang et al. [30] also focused on thermal conductivity and adsorption performance of consolidated composite activated carbon, they also accounted its permeability for specific conditions used in their experiment. Considering the wide range of applications of GAC in different problems, it's necessary to perform experimental investigations in order to evaluate pressure drop of fluid flow through packed beds of GAC and propose proper correlations depending on GAC characteristics. But to the authors' knowledge, such an experimental study to find the pressure drop of fluid flow through a packed bed of GAC has not been done and according to the literature, most of the works in this field focused on particles with regular shapes in bounded conditions. For regular shaped particles, fluid behavior can be easily described by existing equations like, Ergun [31] relation. But for irregular shaped particles, these equations don't have fine accuracy [11], hence, it is necessary to find proper correlations for GAC in different conditions.

Many parameters such as the fluid pressure (or density), flow rate, carbon type, its grain size and the flowing fluid can substantially affect the fluid pressure drop through the packed bed of GAC. This study aims to perform an experimental research to investigate fluid pressure drop through a packed bed of irregular shaped granular activated carbon, when fluid flows axial-horizontal inside the bed. Measurements are reported for two different gases (air and argon) and different flow rates through packed beds of GAC with different pore size diameters in various line pressures (the entrance pressure). Results are presented in terms of friction factor as a function of Reynolds number and new correlations are proposed for each grain size.

2. Correlations to predict pressure drop

Various models have been presented to describe the pressure drop when fluid flows through a porous region. The primary model expressing pressure drop as a function of the fluid velocity and the porous material permeability is Darcy's law [32]:

$$\mathrm{V} = -\frac{k}{\mu}\frac{\Delta p}{L} \tag{1}$$

where V is the Darcy velocity defined assuming cross-section of the bed is empty. μ is the fluid viscosity, Δp represents the pressure drop through the packed bed, and k is the permeability of the porous medium. Darcy's law is confined to very low Reynolds numbers and is usually employed to model fluid flow through low permeable rocks in petroleum reservoirs [33, 34].

One of the most commonly used correlations to describe pressure drop in granular porous materials was proposed by Ergun. Ergun's relation can be employed to account fluid pressure drop when flows through beds of spherical shapes with diameter of D_p, but for irregular shaped grains D_p have to be estimated by measurement of pressure drop [31].

$$-\frac{\Delta p}{L} = 150\mu\frac{V}{{D_p}^2}\cdot\frac{(1-\epsilon)^2}{\epsilon^3} + 1.75\rho\frac{(1-\epsilon)}{\epsilon^3}\frac{V^2}{D_p} \tag{2}$$

In the above equation ϵ is the porosity. By definition of the dimensionless particle friction factor (f_p), Ergun's relation can be rewritten as follows:

$$f_p = \frac{150}{Re}\cdot\frac{(1-\epsilon)^2}{\epsilon^3} + 1.75\frac{(1-\epsilon)}{\epsilon^3} \tag{3}$$

where f_p and Reynolds number are defined by:

$$f_p = -\frac{\Delta p}{L}\frac{D_p}{\rho V^2} \tag{4}$$

$$Re = \frac{\rho V D_p}{\mu} \tag{5}$$

Ergun's relation has also some limitations and Allen et al. [11] in a comprehensive survey stated that this relation deviates from the true pressure in finite packed beds in some situations and could not provide accurate results for all granular materials. After Ergun's relation, many other new correlations have been introduced and continue to be developed and a detailed literature survey and comparison of these models have been performed by Erdim et al. [35] and interested readers are referred to this review paper. Table 1 summarized some correlations presented by other researchers and their range of applicability, but none of these works is done on GAC.

According to the investigation and comparison of different correlation between friction factor and Reynolds number, Erdim et al. [35] proposed the following form of equation to make a correlation between friction factor and Reynolds:

$$f_p\frac{\epsilon^3}{(1-\epsilon)^2}Re = A + B\left(\frac{Re}{1-\epsilon}\right)^C \tag{6}$$

Since in our study, ϵ is a function of pore size of the GAC bed, it can be considered as a coefficient depending on the pore size diameter and by some algebraic manipulations, this equation can be rewritten in the following simple form:

$$f_p = \frac{a}{Re^b} \tag{7}$$

in which a and b are constant parameters depending on the grain size of GAC in the packed bed.