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Hydrodynamic behavior in a moving granular bed filter for modeling on char separation during the biomass fast pyrolysis process

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ABSTRACT

Moving granular bed filters (MGBFs) are the promising approach to improve the quality of pyrolysis oil by removing char particles from fast pyrolysis vapor streams. To minimize the commercial MGBF system, the inner MGBF structures were modified, resulting in differential granular media velocities between inlet and outlet gas stream. The modified structure was applied to increase the removal efficiency under the same superficial gas velocity. The experiments were conducted at room temperature and the designed parameters included the insert length and angle of inserted plates in the bottom of MGBF. In this study, the insert plates were used to distinguish the MGBF into two particle flow streams in the same section. The section area was the function of particle response angle, insert length, insert angle, and angle of the MGBF boundary plate. An accurate equation for determining the mass flow rate of the bed material particle and section area was proposed in this study. In addition, cold model filter tests were conducted on differential designs for three sets of flow fields. These results show that differential flow field designs can effectively enhance filtration efficiency. Under the same filtration pressure decline or loss, the filtration efficiency can be increased from the baseline of 95.4% to 99.9%.

1. Introduction

The biomass fast pyrolysis process is a method for converting biomass into liquid fuel. During the fast pyrolysis process, products in various states or patterns are generated, including condensable oil vapor, char, and non-condensable gas. Condensable oil vapor is recovered as liquid fuel through cooling condensation.

After biomass fast pyrolysis, a comparatively greater amount of ash is present. Alkali metals (potassium and sodium) and alkaline earth metals (magnesium) tend to accumulate in char, fulfilling the role of catalysts by accelerating secondary pyrolysis reactions and reducing the fuel or oil production rate. Additionally, the inorganic materials in biomass also can accumulate on the generated fine char particles during the pyrolysis process; these particles were then mixed into the bio-oil during oil vapor condensation. This phenomenon promotes unstable condensation of the oil products, which polymerize into long chain gel-like materials, leading to deterioration in the quality and increased viscosity of the oil product [1].

The previously stated effects which are disadvantageous to oil products cause issues in subsequent applications, such as clogging or corroding boilers, internal combustion engines, and gas turbines. To avoid mixing fine char particles into the bio-oil and to enhance the stability of the oil, generated char must be separated from the oil vapor in a high-temperature environment before pyrolysis oil vapor condensation.

The solid char content resulting from biomass fast pyrolysis is typically approximately 12–25 wt.% of the feeding biomass [1,2]. These reports described that solid char content is significantly higher than the fine dust created by regular burning systems. Eliminating char in the high temperature environment of the fast pyrolysis process necessitates the effective removal of char with small granular diameter (<10 μm) to reduce the solid residue content in the oil product, thereby lowering the likelihood and risk of the oil products degradation.

Several particle separation technologies, such as cyclones and ceramic fabrics, have been applied to separate particles from vapor or gas in high temperature process [3]. Ceramic fabrics can be utilized as high-efficiency separator; but a short operating cycle and high material cost are major disadvantages. Besides, the particles collection efficiency of cyclones deteriorates rapidly when the particle size is smaller than 10 μm.

Moving granular-bed filters (MGBFs) are separators that utilize solids such as quartz sand, gravel, or limestone as a filter medium. In recent decades, MGBFs have been employed to remove dust from high-temperature gases [4,5] and have several advantages, such as the ability to operate in high-temperature gases, high collection efficiency for fine particles, low operational cost, and

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Nomenclature

A_1	the cross-section filter area of bed material particles on the left side of the MGBF pass through as shown in Fig. 3 (m^2)
A_2	the cross-section filter area of bed material particles on the right side of the MGBF pass through as shown in Fig. 3 (m^2)
C_{in}	the masses of particles in the particle-release device (kg/h)
C_{out}	the masses of particles in the particles collected after MGBF (kg/h)
LL	the insert lengths of the inserts of left side as shown in Fig. 3 (mm)
LR	the insert lengths of the inserts of right side as shown in Fig. 3 (mm)
M_1	particle mass flow rates on the gas inlet sides of the MGBF as shown in Fig. 3 (kg)
M_2	particle mass flow rates on the gas outlet sides of the MGBF as shown in Fig. 3 (kg)

Greek symbols

α	the static angle of repose of the bed material particles (°)
β	the MGBF storage tank design angle as shown in Fig. 3 (°)
θ_1	the inclination angles of left side (°)
θ_2	the inclination angles of right side (°)
ϕ_A	the area ratio between the left and right sides for the moving particles, A_1/A_2
ϕ_M	the ratio of particle mass flow rates on the left and right sides for the moving particles, M_1/M_2
η	filtration efficiency of the MGBF, $1-(C_{out}/C_{in}) \times 100\%$ (%)

long operating lifetime. The bed medium can capture solid particles from the gas stream via the mechanisms of inertial impact, diffusion, and gravity.

MGBFs can be employed to filter solid particles, especially fine particles with diameters below 10 μm. Brown *et al.* [6] and Brown and Glover [7] presented that an MGBF can operate with high collection efficiency, typically exceeding 99%, and low pressure drop without the need for periodic regeneration through the use of a continuous flow of fresh granular filter medium in the filter.

When the particulate loading in the MGBFs, which is contributed to biomass fast pyrolysis process, is relatively high, filtration pressure becomes comparatively large. The char-cake can be removed to control the system pressure within a certain range by increasing the movement speed of the bed material, but the increase in the movement speed of the bed material reduces the particulate removal rate [8]. However, The complex hydrodynamics of granular flow is still not fully understood in the MGBF.

Wu *et al.* [9] studied the flow characteristics of solid particles in a two-dimensional moving bed. They found that the mass velocity of the solid particles and the placement of baffles in stagnant zones have no effect on the flow pattern. The sharpness, size, and angle of repose of the particles affect the flow pattern greatly. Hsiau *et al.* [10] and Tai *et al.* [11] have developed that a MGBF was inserted a louver into the bed to guide the gas flow pattern to increase the path length in the filter and the particle collection efficiency.

To resolve these issues and to consider the feasibility of amplifying the MGBF system, we investigated the effects on the design of inserting an asymmetric plate in the bottom of a MGBF which results in different particle flow pattern for the gas inlet side (front section of the filtration area) and the gas outlet side (back section of the filtration area). Our aim is to simultaneously reduce the decline in filtration pressure and enhance the filtration efficiency.

2. Experimental

2.1. Moving granular bed filter (MGBF) and bed material

The MGBF cold model used in this study consisted of a bed material particle storage bin or tank, the MGBF main body, and a grain circulation and separation system. The main body structure of the MGBF included an inserted plate, louver, gas/particle inlet, gas/particle outlet, and boundary, as shown in Fig. 1. The schematic diagram of the whole MGBF system is shown in Fig. 2.

The MGBF operation is as follows: a gaseous flow with solid particles entered and left from the sides, whereas bed material particles (quartz sand) flowed from the top down through the main body of the granular bed. The solid particles in the gas flow contacted the downward moving bed material. Through interception, collision, and filtration mechanisms, the particles were intercepted by the bed material and discharged from the particle

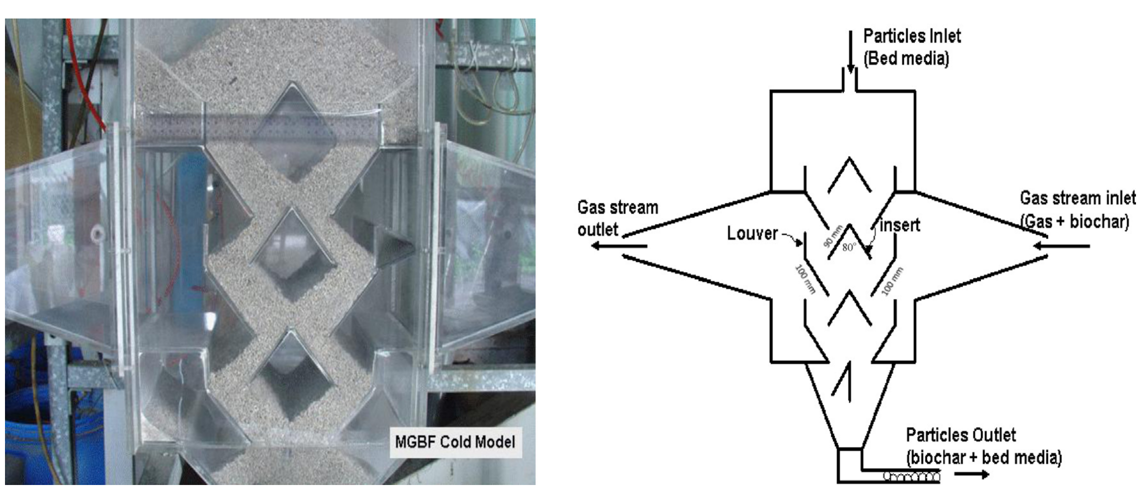

Fig. 1. Cold model of the moving granular bed filter (MGBF).