Advanced Magnetically Assisted Stabilized Bed for the Separation of Solid Waste in Microgravity and Hypogravity: Filtration Modeling

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Abstract

Development of efficient means for the recovery of valuable resources from solid waste materials is a critical requirement for future Advanced Life Support (ALS) systems that will be needed to support long-duration manned mission in space. Of particular importance are technologies that may be employed in hypogravity and microgravity environments. Currently three solid waste processing technologies, including supercritical water oxidation (SCWO), microwave powered combustion and fluidized bed incineration, have been tested for the conversion of solid waste. However, none of these technologies are compatible with microgravity or hypogravity operating conditions. To meet these needs, Gradient Magnetically Assisted Stabilized Bed (G-MASB) technology is under development to serve as an operating platform for fluidized bed operations in the space environment. The G-MASB technology has been specifically tailored for microgravity, hypogravity and variable gravity operating conditions. The operation of G-MASB was successfully tested in two series of zero-g flight experiments on board NASA's KC-135 aircraft. In this paper, we present a mathematical model describing the filtration of micron-sized solid waste particles from a liquid stream. This model is compared with experimental results obtained in the G-MASB while operated at 1g. The experimental data are in good agreement with the theoretical predictions.

Keywords: Filtration; Fluidization; Magnetic Fluidized Bed; Magnetic Field; Microgravity

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1. Introduction

The application of an external magnetic field in fluidized bed operation of ferromagnetic particles is well known in conventional two-phase, gas-solid or liquid-solid fluidization. The uniform external magnetic field significantly changes the fluidized bed fluid dynamic behavior, and if creatively used, may enhance the bed performance. A number of studies and research projects [1-7] have been done to improve fluidization operation for various possible industrial applications. However, no study of liquid-solid fluidization has ever been done in microgravity or variable gravity conditions (e.g., Space Station, Moon or Mars). The possibilities for the development of fluidized bed applications in space may include Advanced Life Support Systems, In Situ Resource Recovery, biochemical reaction processes, and energy conversion.

Separation of solid particles (waste) from liquid waste streams and subsequent conversion of solids into useful resources are important elements of the life support system envisioned for long duration missions and habitation in space. Upon the successful development of the G-MASB [8], which can be operated in the absent of gravity, the G-MASB is proposed as a platform for solid waste destruction in a closed-loop life support system. This study, therefore, focuses on the feasibility of fluidization operation as a renewable filter used in the absence of a gravitational field.

2. Theory and filtration modeling

In either a conventional fluidized bed or a magnetically stabilized fluidized bed, the fluidization conditions result from the interaction of forces acting on fluidized particles. This can be illustrated through a balance of three characteristic forces, the gravitational force, $\mathbf{F_g}$, the buoyancy force, $\mathbf{F_b}$, and the drag force, $\mathbf{F_d}$, as shown in Fig. 1.

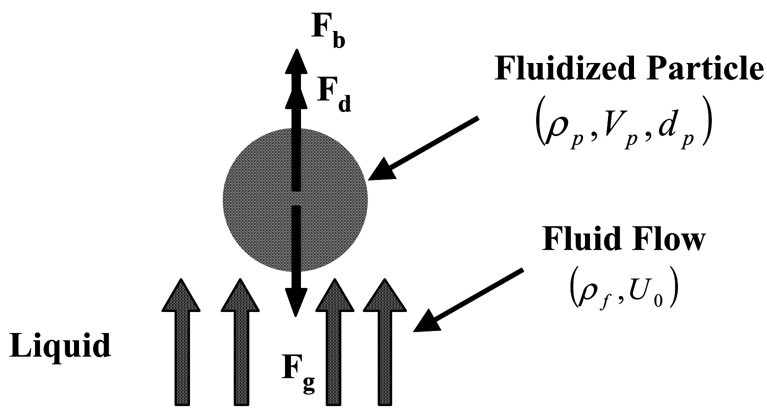

Fig. 1. The balance of forces acting on a fluidized particle in a conventional fluidized bed (liquid media-solid particles).

However, an addition magnetic force can be added to this balance of forces. The magnitude and orientation of this force depends primarily on the orientation, strength and gradients of the field as well as on the magnetization properties of the fluidization particles. Simple quantitative analysis of these forces points to some obvious consequences. For example, to sustain the same quality of fluidization (eg. similar voidage distribution) due to an additional magnetcic force in the same direction as the gravitional force, one has to increase fluid velocity in order to create sufficient drag force to balance the magnetic force. This, in turn will increase the relative velocity of particles and fluid, which should increase mass transfer [7].

The additional magnetic force plays an important role in the operation of fluidized beds in hypogravity and microgravity environments. Under microgravity conditions where the gravitational force is no longer significant, the drag force still acts on the fluidized particle as shown in Fig. 2a. Under these conditions the balance of forces no longer exists, and the particles in the fluidized bed will immediately be swept away in the direction of the fluid flow. Fluidization conditions can be restored by introducing an additional force, such as a magnetic force, $\mathbf{F_m}$, to reinstate the balance of forces on the fluidized particle. Such a magnetic force acting on the ferromagnetic particles can be created simply by placing magnetically susceptible particles into a non-uniform magnetic field, as shown in Fig. 2b.

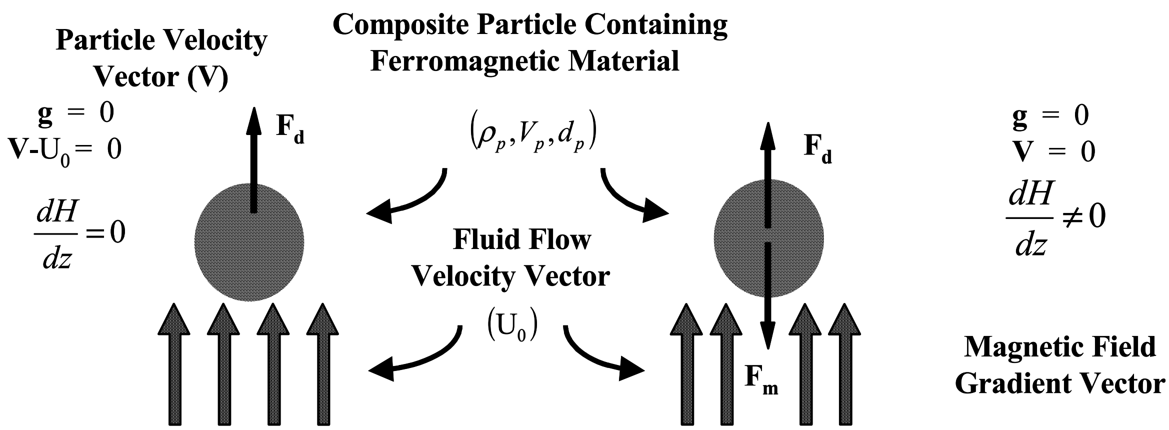

Fig. 2. Balance of forces acting on a fluidized particle containing ferromagnetic material in, a) a fluidized bed in microgravity in the absence of a magnetic field, and b) a gradient-magnetically assisted stabilized bed in microgravity.

Our work has shown that, given a suitable variable field profile, the resulting magnetic field gradient can create sufficient magnetic force acting upon the ferromagnetic particles to replace or supplement the gravitational force. Therefore, the application of suitably designed magnetic field gradients makes feasible a fluidization operation in the absence of gravity, or a creative enhancement of fluidized bed performance in normal or variable gravity.

In this study, we used the G-MASB as a renewable filter to separate solid particles (waste) from liquid waste streams. A schematic representation of the G-MASB filtration process is shown in Fig.3. System boundary (I) represents the region of the experimental apparatus (including holding tank, pump and flow meter) where only the biomass waste particles are present. It is assumed that in this volume the fluid is very well mixed and hence the biomass concentration is uniform. System boundary (II) is the section of our system where the filtration process takes place.

The material balance in both system boundaries can be written in the form of partial-differential equations in the axial symmetric filter bed as the followings:

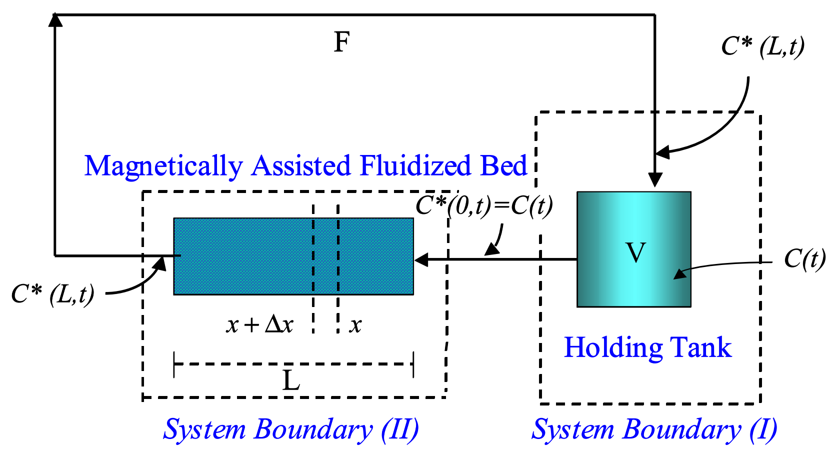

Fig. 3. Schematic diagram of the filtration system.

System boundary (I): $$FC^*(L,t) - FC^*(0,t) = V_{tank}\frac{\partial C^*(0,t)}{\partial t} \quad (1)$$

Initial Conditions: $C^*(0,0) = C_0$

System boundary (II): $$-v\frac{\partial C^*(x,t)}{\partial x} - a'\frac{\partial \sigma}{\partial t} = \frac{\partial(\varepsilon C^*(x,t))}{\partial t} \quad (2)$$

Initial Conditions: $C^*(x,0) = 0; \quad t = 0, \quad 0 < x \le L$

Boundary Conditions: $C^*(0,t) = C(t); \quad x = 0, \quad t > 0$

$C^*(0,0) = C(0); \quad x = 0, \quad t = 0$

The rate of filtration $$\frac{\partial \sigma}{\partial t} = \frac{k_1}{a'}C^*(x,t) - k_2\sigma \quad (3)$$

Initial Conditions: $\sigma(x,0) = 0; \quad 0 \le x \le L$

In the above equation, $C^*(x,t)$ and $\sigma(x,t)$ are the concentration of the biomass particles in the liquid phase and on the media particle surface, respectively. During the filtration process, biomass waste particles are captured and some of them are detached from the filter. Therefore, we have k_1 which is the accumulation coefficient, and k_2 which is the detachment coefficient in equation (3). a' is particle surface per unit volume of the bed, t is time, v is interstitial fluid velocity, V_{tank} is total volume in the holding tank and ε represents the liquid phase volume fraction of the bed. In our study, we assume that once the biomass particles are deposited on the surface of the particle media, they will form a thin layer of biomass waste around the bed surface, hence, the actual bed diameter increased as the biomass was deposited. The variation of bed diameter can be expressed as the following equation:

$$d_p(x,t) = d_p(x,0) + \frac{\sigma(x,t)}{\rho_{\text{straw}}} \quad (4)$$

The voidage of the bed at any given time can be presented as below.

$$\varepsilon = 1 - (1 - \varepsilon_0)\frac{d_p^3(x,t)}{d_p^3(x.0)} \tag{5}$$

With the help of equation (4) and (5), Equation (2) can be written as

$$-v\frac{\partial C^*(x,t)}{\partial x} - a'\frac{\partial \sigma(x,t)}{\partial t} = \left[1 - (1 - \varepsilon_0)\frac{d_p^3(x,t)}{d_p^3(x,0)}\right]\frac{\partial C^*(x,t)}{\partial t} - \frac{3(1-\varepsilon_0)}{\rho_{straw}}\frac{d_p^2(x,t)}{d_p^3(x,0)}\frac{\partial \sigma(x,t)}{\partial t} \tag{6}$$

Equations (1), (3) and (6) are solved numerically, and accumulation and detachment coefficients, k_1 and k_2, are evaluated using an optimization procedure.

3. Experimental section

The filtration experiments were conducted in a closed recirculating G-MAFB system with a constant magnetic field gradient. During the filtration process, the bed was kept in a packed condition and biomass waste particles were deposited in the void spaces among ferromagnetic particles. A pictorial diagram of the experimental apparatus used in the filtration experiments (1g) is shown in Figure 4.

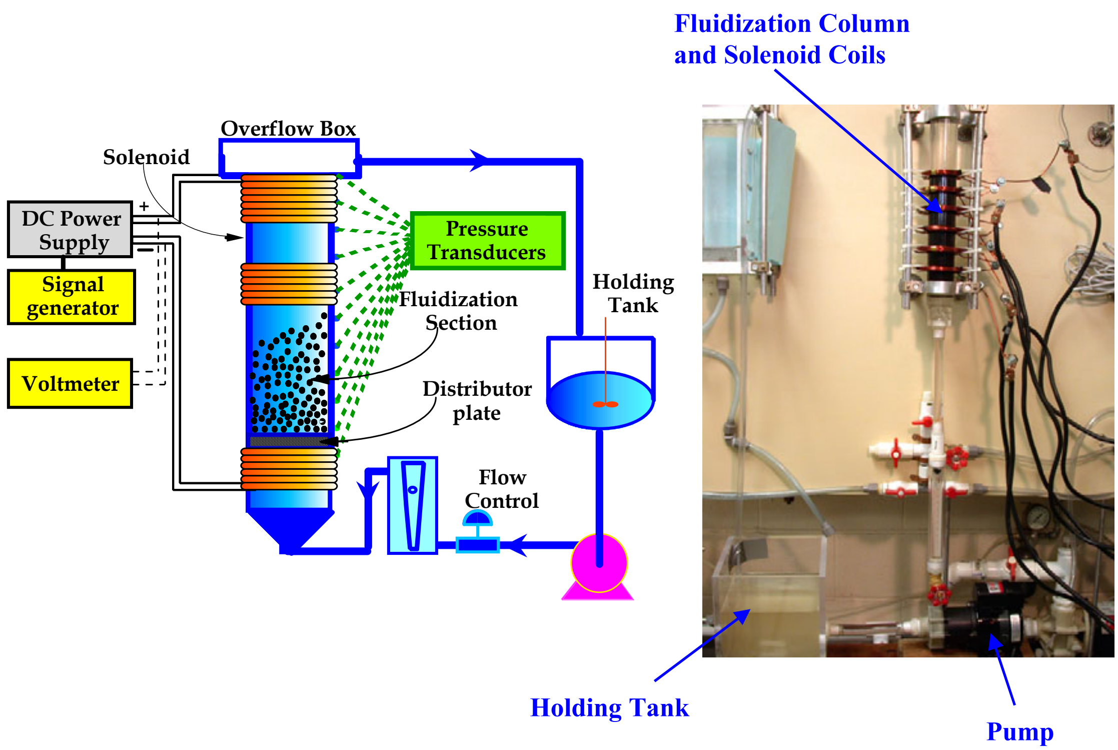

Fig. 4. G-MAFB apparatus used in filtration experiments

The fluidization column is made of polycarbonate, allowing for visual observation through the wall. The column has an inside diameter of 5.04 cm and an outside diameter of 5.80 cm. A distributor plate is located at the bottom of the bed, and can be easily removed or repositioned to any location along the column. Two different sizes of ferromagnetic particles (D_p = 2.5 mm and 3.5 mm, 20%wt ferrite) were used as the magnetically consolidated filtration media. The magnetic field generator is composed of three direct current (DC) power supplies connected to six parallel Helmholtz rings (solenoid). The Helmholtz rings can be positioned at any point along the fluidization column. The overall magnetic field intensity within the fluidized bed is the summation of the magnetic field intensities generated from each Helmholtz ring. Two sizes of biomass waste particles ($149\mu m<D_p<180\mu m$ and $180\mu m<D_p<295\mu m$) were suspended in water. The concentration of biomass particles in the holding tank was monitored online using a laser-photodiode detector.

4. Experimental results and discussion

A series of filtration experiments was conducted using a fixed magnetic field gradient and flow velocities varying between 0.54 and 1.34 cm/s. A magnetic field inside the filter column was created such that the field intensity was highest at the bottom of the bed, and then decreased linearly toward the top of the column (see Figure 5). This arrangement produced a direct magnetic force on the ferromagnetic filter medium which was oriented downward toward the distributor late and fixed the bed in position. Biomass (wheat straw particles) suspended in an aqueous stream were recirculated between a holding tank and the magnetically consolidated filter bed under fixed flow rate and magnetic field intensity. Loading of the filter was monitored by the reduction in particulate concentration within the holding tank as a function of time, as determined by changes in optical density of the suspension. Results for a typical filtration experiment is presented in Figure 6. From these results, we concluded that at a given magnetic field intensity and gradient, the filtration rate increased as the fluid superficial velocity increases. In these experiments, the concentration of the solid waste particles was substantially decreased during the filtration process. However, the concentration of solid waste particles remains constant after it reaches the maximum capacity of the bed. Therefore, the filtration process can be characterized by the rate of accumulation of waste particles in the bed and the rate of detachment of already-filtered particles. The results of filtration experiment were fitted to a filtration model to determine numerical values of the accumulation and the detachment coefficients. These two parameters are related to several mechanisms involved in the deposition of straw particles onto the surface of the magnetic beads, including: diffusion deposition, direction interception and inertial impaction. Therefore, both coefficients are expected to vary as a function of hydrodynamic and geometric parameters of the filtration system such as velocity of fluid, average straw particle size and bed particle size.

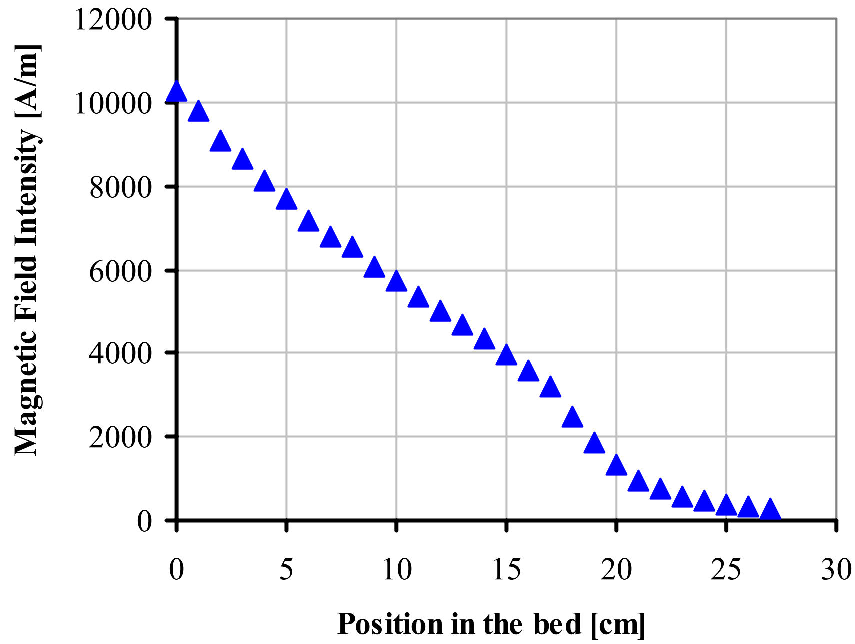

Fig. 5. Magnetic field profile used in filtration experiments

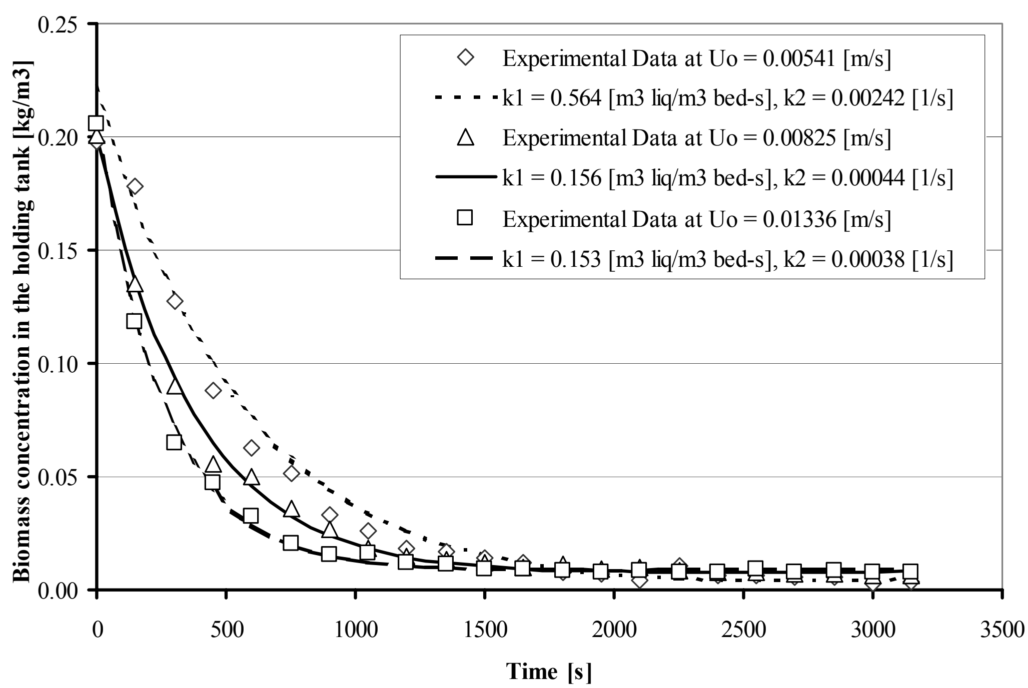

Fig. 6. Change of biomass waste concentration versus flow rate,
d_p = 3.5 mm and Dp = 180μm<D_p<295μm

5. Conclusion

The feasibility of the Gradient Magnetically Assisted Stabilized Bed (G-MASB) as a renewable filter, utilizing magnetic force to achieve stable fluidization, has been successfully demonstrated in our study. This technology, using magnetic force to substitute for the gravitational force in hypogravity and microgravity environments, has many potential areas of application. Filtration experiments conducted in the laboratory have shown that G-MASB based methods can successfully separate biomass waste particles from a recirculating liquid stream. Within the range of fluid velocities used in the filtration experiments, we found that the rate of filtration increases with the fluid velocity. In future work, this G-MASB filtering unit will be integrated into a complete solid waste destruction process.

Nomenclature

a'	Particle surface per unit volume of the bed (m^2 surface/m^3 bed)
$C^*(x,t)$	Concentration of biomass in the bed filter (kg/m^3)
D_p	Straw particle diameter (m)
d_p	Ferromagnetic particle diameter (m)
$\mathbf{F_b}$	Buoyancy force exerted on the particle (N/m^3)
$\mathbf{F_g}$	Gravitational force exerted on the particle (N/m^3)
$\mathbf{F_m}$	Magnetic force exerted on the particle (N/m^3)
$\boldsymbol{g}$	Gravitational acceleration (m/s^2)
$\mathbf{H}$	Magnetic field intensity (A/m)
k_1	Accumulation coefficient (m^3 liquid/m^3 bed-s)
k_2	Detachment coefficient {1/s)
$\mathbf{U}$	Velocity of fluid phase (m/s)
$\mathbf{V}$	Velocity of particle phase (m/s)
v	Superficial fluid velocity (m/s)
x, y, z	Cartesian coordinates

Greek letters

ρ_{straw}	Straw density (kg/m^3)
ε	Void fraction of bed (/)
σ	Concentration of biomass on the bed particles (kg/m^2 surface)

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