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Operation of magnetically assisted fluidized beds in microgravity and variable gravity: experiment and theory

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Abstract

The conversion of solid waste into useful resources in support of long duration manned missions in space presents serious technological challenges. Several technologies, including supercritical water oxidation, 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. In this paper, we present the gradient magnetically assisted fluidized bed (G-MAFB) as a promising operating platform for fluidized bed operations in the space environment. Our experimental and theoretical work has resulted in both the development of a theoretical model based on fundamental principles for the design of the G-MAFB, and also the practical implementation of the G-MAFB in the filtration and destruction of solid biomass waste particles from liquid streams.

Keywords: Microgravity; Fluidized beds; Solid biomass waste; Space life sciences

1. Introduction

Typically, the operation of a conventional fluidized bed relies on the balance of gravitational, $\boldsymbol{F_g}$, buoyancy, $\boldsymbol{F_b}$, and drag forces, $\boldsymbol{F_d}$. However, in the absence of normal gravity, or under microgravity and variable gravity conditions, the gravitational force must be replaced with an alternative force to restore normal fluidization, otherwise the particles in the fluidized bed will be immediately swept away in the direction of fluid flow (Fig. 1(a)). The gradient magnetically assisted fluidized bed (G-MAFB) technology, particularly developed for microgravity, hypogravity and variable gravity operating conditions, takes advantage of a magnetic force, $\boldsymbol{F_m}$, created on magnetically susceptible media in a non-uniform magnetic field. Magnetic field and magnetic forces provide the basis for fluidization under a variety of gravitational environments, including microgravity, as shown in Fig. 1(b). 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 ferromagnetic granular media can be fluidized in either microgravity or hypogravity conditions.

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-MAFB (Jovanovic et al., 1999), which can be operated in the absence of gravity, the G-MAFB

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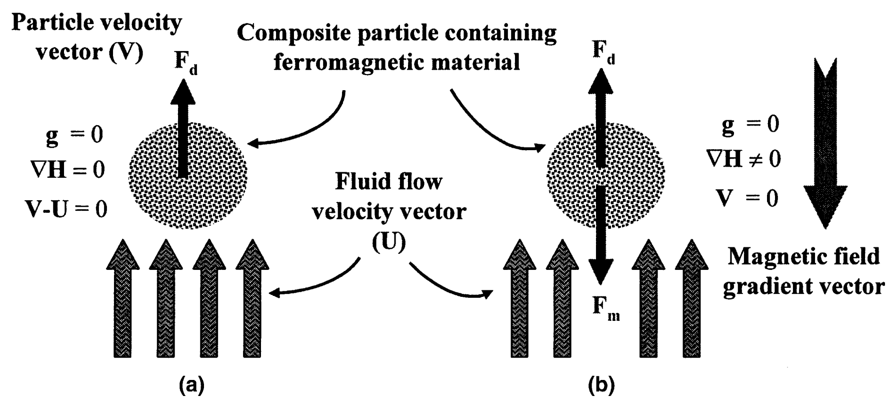

Fig. 1. Balance of forces acting on a fluidized particle containing ferromagnetic material in: (a) a fluidized bed in microgravity in the absence of a magnetic field and (b) a gradient magnetically assisted fluidized bed in microgravity.

is proposed as a platform for solid waste destruction in a closed-loop life support system. In this paper, we report the experimental results describing filtration of micron-size biomass waste particles in the G-MAFB. In addition, a mathematical model of biomass collection in the G-MAFB filter is developed. The model predicts the change of waste particle concentration in a liquid suspension with time.

2. Experimental apparatus and material

Experiments were conducted both on-board NASA's KC-135 aircraft for microgravity magnetic force demonstration and in the laboratory environment (one-*g*) for filtration studies. The experiments in microgravity were conducted in a two-dimensional, square cross-section, tapered fluidization column, as shown in Fig. 2. The tapered shape was introduced to provide additional stability to the fluidization particles. The magnetic field in the G-MAFB was created by a set of Helmholtz rings along the fluidization column. The magnetic field intensity and field gradient were kept constant for all experiments. The height of the bed, at different flow rates, was recorded by a digital camcorder.

The apparatus used for laboratory filtration experiments is a cylindrical bed with constant cross-sectional area, as shown in Fig. 3. The fluidization column is made of Plexiglas, allowing 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, which can be easily removed or repositioned to any location along the column. The micron-size biomass waste particles (149 μm $< d_p <$ 180 μm) were suspended in water, and the ferromagnetic particles were used as filter media.

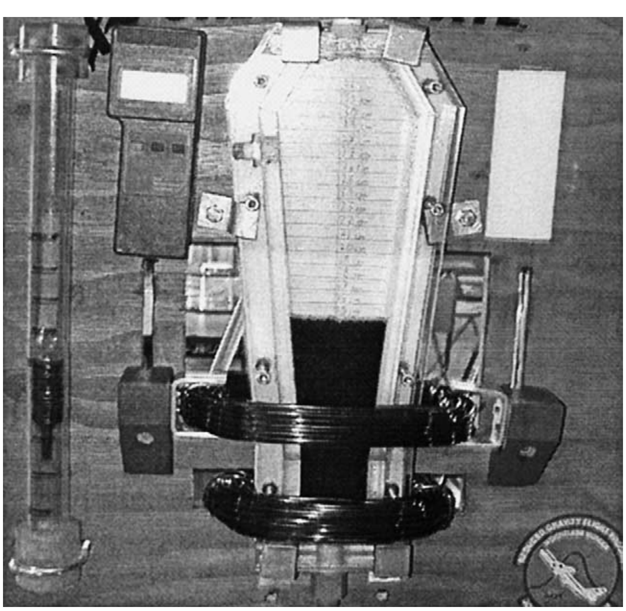

Fig. 2. Experimental apparatus used in microgravity experiments.

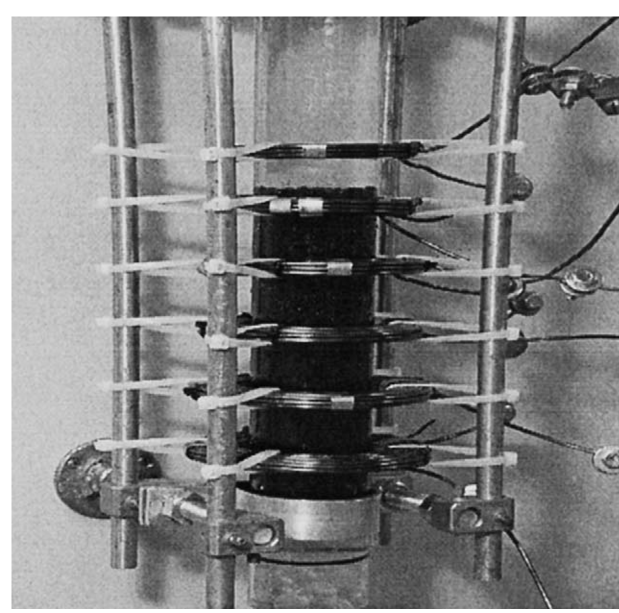

Fig. 3. Experimental apparatus used for filtration experiments (one-*g*).

The magnetic field generator used in these experiments is composed of a direct current (DC) power supply connected to six Helmholtz rings. The overall magnetic field intensity, (***H***), within the fluidized bed is the superposition of the magnetic field intensities generated from each Helmholtz ring. The electromagnets are positioned such that the magnetic field intensity is strongest at the bottom of the bed, and decreases toward the top of the bed. The concentration of biomass particles was monitored online using a laser-photodiode detector.

3. Experimental results and discussion

3.1. The effect of magnetic force ($\boldsymbol{F_m}$) in the G-MAFB under microgravity

The magnetic force acting on ferromagnetic particles is computed with the assumption that the fluidization particles contain a soft (i.e., easily magnetized and demagnetized) ferromagnetic material. The ferromagnetic particles used in this study indeed contain soft ferromagnetic materials. The composition and the manufacturing procedure of the ferromagnetic particles can be found elsewhere (Atwater et al., 2001, 2003). The magnetization of the fluidized bed as a whole, M_b, is assumed to be collinear with the magnetic field intensity. Rosensweig (1979) defined the magnetic body force acting on a magnetic medium in a non-uniform magnetic field as follows:

$$\boldsymbol{F_m} = \mu_0 M_b \nabla H. \tag{1}$$

The ferromagnetic particles ($D_p = 2.4$ mm, 30%wt ferrite) were fluidized in the G-MAFB using a magnetic field intensity gradient as shown in Fig. 4. Microgravity fluidization experiments were conducted over a range of aqueous flow rates. The relationship between height of the bed and fluid flow rate is shown in Fig. 5. These experiments clearly demonstrate that magnetic forces can be used to achieve stable fluidization in the absence of gravity, which otherwise would not be possible. Detailed analysis and experimental results related to the fluid dynamic behavior of the G-MAFB both in microgravity and the one-*g* environment are presented in Sornchamni (2004).

3.2. Filtration experiments and mathematical modeling

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 either a packed or an incipient fluidization condition and biomass waste particles were deposited in the void spaces between ferromagnetic particles. Two different sizes of ferromagnetic particles ($D_p = 2.5$ and 3.5 mm, 35%wt ferrite) were used as filter media. A mathematical model for solid waste collection in the G-MAFB filter was developed to represent the experimental results. A schematic representation of the G-MAFB filtration process is shown in Fig. 6. 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 axially symmetric filter bed as follows:

System boundary(I) :

$$FC^*(L,t) - FC^*(0,t) = V_{\text{tank}} \frac{\partial C(0,t)}{\partial t}, \tag{2}$$

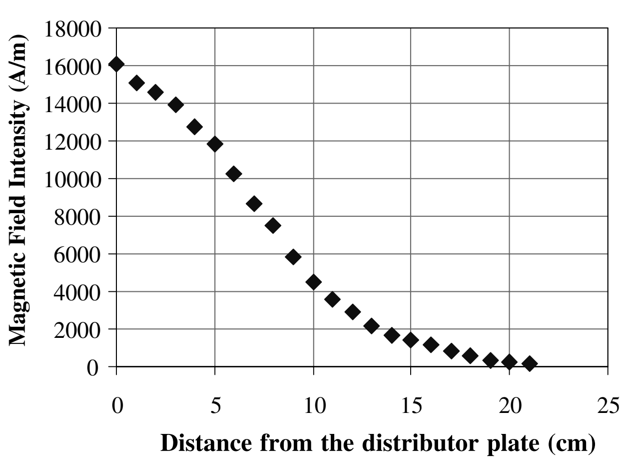

Fig. 4. Magnetic field profile used on-board NASA's KC-135 aircraft during microgravity experiments.

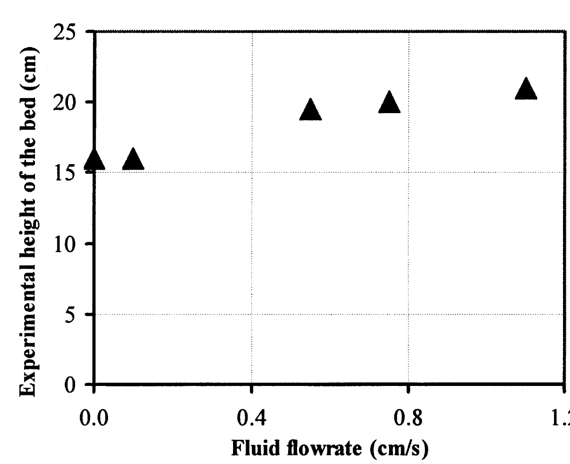

Fig. 5. Height of the bed at different flow rates in the G-MAFB microgravity experiments on-board NASA's KC-135 aircraft, $L_0 = 16$ cm.

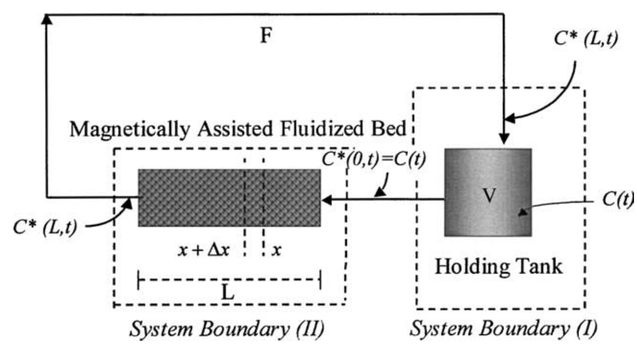

Fig. 6. Schematic diagram of the G-MAFB filtration system.

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

System boundary(II) :

$$-U_0\frac{\partial C^*(x,t)}{\partial x} - a'\frac{\partial \sigma}{\partial t} = \frac{\partial(\varepsilon C^*(x,t))}{\partial t}, \tag{3}$$

$$\begin{aligned}
&\text{Initial condition} &&: C^*(x,0) = 0; \quad t = 0, \quad 0 < x \leqslant L,\\
& &&\ C^*(0,0) = C_0; \quad t = 0, \quad x = 0,\\
&\text{Boundary conditions} &&: C^*(0,t) = C(t); \quad t > 0, \quad x = 0,
\end{aligned}$$

$$\text{The rate of filtration}: \ \frac{\partial \sigma}{\partial t} = \frac{k_1 C^*(x,t)}{a'} - k_2\sigma, \tag{4}$$

$$\begin{aligned}
\text{Initial conditions}: \ &\sigma(x,0) = 0; \quad t = 0, \quad 0 \leqslant x \leqslant L,\\
&C^*(x,0) = 0; \quad t = 0, \quad 0 < x \leqslant L.
\end{aligned}$$

The variation in the nominal diameter of the filtration media as the waste mass is deposited can be expressed as

$$D_p(x,t) = D_p(x,0) + \frac{\sigma(x,t)}{\rho_{\text{biomass}}}. \tag{5}$$

The voidage of the bed, ε, at any given time, is given by

$$\varepsilon(x,t) = 1 - (1 - \varepsilon_0)\frac{D_p^3(x,t)}{D_p^3(x,0)}. \tag{6}$$

In the above equations, $C(t)$ is the biomass concentration [kg/m^3 liquid] in the holding tank. C^* [kg/m^3 liquid] and σ [kg/m^2 surface] are the concentration of the biomass particles in the liquid phase and on the media particle surface, respectively. k_1 (m^3 liquid/m^3 bed-s) is the accumulation coefficient and k_2 (1/s) is the detachment coefficient. a' is particle surface per unit volume of the bed (m^2 media surface/m^3 bed), F is the flow rate of liquid containing solid waste (m^3 liquid/s), t is time (s), U_0 is fluid velocity (m/s), V_{tank} is total volume in the storage tank (m^3) and ϵ represents the liquid phase volume fraction of the bed (dimensionless). With the help of Eqs. (5) and (6), Eqs. (2)–(4) are solved numerically, and accumulation and detachment coefficients, k_1 and k_2, are evaluated using an optimization procedure. Figs. 7 and 8 show the filtration results for both sizes of ferromagnetic particles at different fluid flow rates.

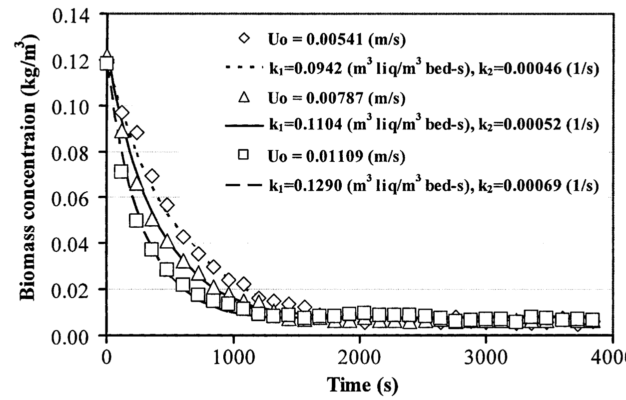

Fig. 7. Change of biomass concentration in the holding tank, D_p = 2.5 mm, and $C_0 \sim 0.12$ [kg/m^3], and packed bed condition.

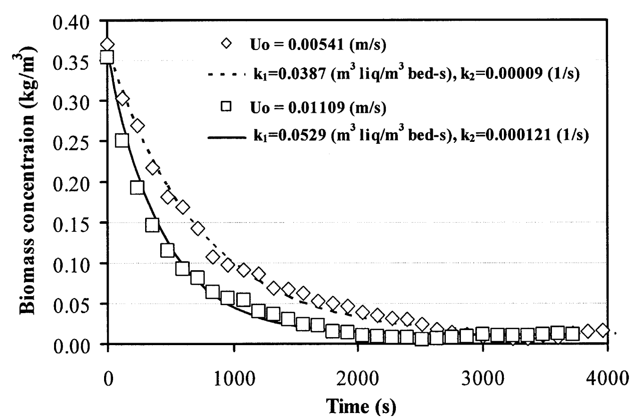

Fig. 8. Change of biomass concentration in the holding tank, D_p = 3.5 mm, and $C_0 \sim 0.35$ [kg/m^3], and packed bed condition.

4. Conclusion

A novel microgravity and hypogravity compatible engineering platform (G-MAFB), utilizing magnetic force to achieve stable fluidization, has been successfully demonstrated on-board NASA's KC-135 aircraft. Here magnetic forces augment or substitute for the gravitational field. This enabling technology may find many potential areas of application. Filtration experiments conducted in the laboratory have shown that G-MAFB based methods can successfully separate biomass waste particles from a recirculating liquid stream. Within the range of fluid velocity used in the filtration experiments, we found that the rate of filtration increases with the fluid velocity. In future work, this G-MAFB filtering unit will be integrated into a complete solid waste destruction process.

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