行政院國家科學委員會專題研究計畫成果報告

軟粒子之固液分離－子計劃一：軟粒子之特性及其薄膜分離機構之研究

Solid/Liquid Separation of Soft Particles: Sub-project 1
Characterization of Soft Particle and Its Separation by Membrane

計劃編號：NSC 89-2214-E-002-014
執行期限：88 年 8 月 1 日至 89 年 11 月 30 日

主持人：呂維明 教授
執行機構：台灣大學 化學工程學系

一、中文摘要：

本研究以可變形之水凝膠 Sephadex G50S 粒子與海藻膠酸鈣(Ca-alginate)粒子泥漿以及不可變形之聚氯乙烯(PS)粒子泥漿為樣品，探討軟膠體粒子之恆壓過濾機構。為了探求其過濾理論，因此對濾餅內之局部性質進行動態解析。此解析方式考慮粒子間的面接觸、暫態壓縮及其變形，可獲得濾餅內局部孔隙度、過濾比阻、及固體壓縮壓力之分佈。研究結果發現水凝膠 Sephadex G50S 粒子由於具有受壓後滲水之現象，因此造成其體積的縮小改變。由 dt/dv 對 v 圖上可發現，Sephadex G50S 粒子之過濾行為可分為兩個時期。前期符合 Ruth 之行為，後期則為粒子產生相當大的變形。此外，經由和可變形不變體積的 Ca-alginate 粒子作比較後可以發現，可變體積的粒子因受壓後體積變小，對外部空隙的佔據量小於不變體積的粒子。吾人亦可從單球試驗的結果推論得知，此即意謂: 不可壓縮粒子會在濾材表面形成一緻密阻力層，其阻力大於由可變體積的水凝膠粒子所形成的者，使得在 dt/dv 對 v 關係較為陡峭，並且前者濾液量明顯少於後者。

關鍵詞：軟粒子、膜過濾、薄膜、濾餅局部特性質、生化分離

ABSTRACT

Constant pressure filtration tests of rigid particles (polystyrene), incompressible gel particles (Ca-alginate), and swollen gel particles (Sephadex G50S) have been conducted. The filtration results have showed that the filtration resistance of incompressible gel particles was larger than swollen particles. It was possibly because the liquid of inside the Sephadex particles would migrate from the matrix under compression; however, Ca-alginate particles, like all other incompressible particles, remain their volume unchanged during the loading process. As a result, when a incompressible gel bead was highly compressed, it become pretty flat and therefore occupied more void space in the bottom layer of the cake than a swollen gel particle. Hence the filtration of the incompressible particles Ca-alginate was more difficult to conduct than the swollen particles Sephadex G50S.

Keywords: Soft particle, Membrane filtration, Membrane, Local cake properties, Bioseparation

二、緣由與目的

近年來由於在醫藥及生物技術等領域上有著相當程度的發展，對於其相關產品製造和廢棄物處置等問題也即漸行重要。這當中所必須處理的物質，其組成及結構實屬相當多樣且複雜。而高壓縮性的多孔軟粒子 hydrogel(水凝膠)，因本身具可變形及可變體積的特性，在以往的過濾理論當中，較少被研究；並且在實際的物料當中，佔有相當大的比例，故對該物種的性質有徹底瞭解的需要。而由於此類潤脹性水凝膠物質的性質及過濾試驗，複雜度遠高於剛性及不可壓縮性粒子，故其相關研究進展並不順遂。關於剛性，不可壓縮及潤脹性粒子的受壓變形型態，可用圖一示意之。

為了將過濾技術有效率地應用於精密化

工程序中，本研究針對含軟膠體之難濾泥漿之恆壓過濾機構進行微觀解析，並對濾餅之成長及其局部性質進行詳盡之探討，使研究成果能應用至需求日般之精密分離。

三、研究方法

理論分析

(1)單球壓縮模式

針對不可壓縮的凝膠粒子的受壓變形，Lu(2001)曾經推導出一通式表之：

$$\frac{2}{3}\pi\delta^{2}(3R-\delta)=\pi\left\{\left[\sqrt{R^{2}-(R-\delta)^{2}}+U\right]^{2}-\left[R^{2}-(R-\delta)^{2}\right]\right\}\times 2(R-\delta)$$

其中δ為壓陷深度，R 為粒子半徑，U 為徑向的擴張量=f(δ)。然而，對潤脹性凝膠粒子而言，由於在受壓過程中，粒子之內含液體會循孔隙而滲出，造成體積的改變，故必須對 Tung 所建立之模式加以修正，並將基於以下之假設作為出發點：(a)操作前所有的凝膠粒子皆已達膨脹平衡。(b)液體易為凝膠所吸收。(C)粒子內流出之液體量等同於粒子的體積改變量。(D)為求簡化，當球體體積減少之後，此球本身將收縮，並且成唯一較小之不可壓縮物體。

(2)濾餅過濾之理論分析

傳統的過濾理論是基於粒子為點接觸的假設作為出發點。然而對於可變形粒子來說，粒子與粒子間的接觸已不再是點對點的方式，取而代之是面與面的對應；並且對於具黏彈性的潤脹性凝膠粒子而言，存有明顯的暫態壓縮(transient compression)的現象。因此，要探討此類粒子的過濾行為及特性，例如孔隙度的變化，以及濾餅的阻力之相關問題等，勢必要對傳統的過濾理論進行修正，否則容易產生極大的誤差。

實驗方法

(1)單球壓縮試驗

本實驗部分為量測巨觀的球體壓縮變化，作為推論潤脹性粒子受壓改變模式的方法。實驗裝置為一組直徑 0.144m 之活塞壓縮設備。實驗物料使用一不可壓縮和一多孔可吸水之大球。

(2)濾餅表面孔隙度量測

濾餅表面之孔隙度可由 Haynes (Lu, 1968)所設之低壓過濾裝置量測之。

(3)恆壓過濾

本裝置為參考 Lu(2000)所設立之恆壓過濾裝置。唯其濾室之直徑改變為 0.026m。

(4)實驗物料

剛性粒子：Polystyrene 粒徑分佈在 53 至 61 μm 之範圍。不可壓縮粒子：Ca-alginate 其平均粒徑為 60μm。令其體積在壓縮過程中保持固定。潤脹性水凝膠粒子：Sephadex G50S 其平均粒徑為 60μm，在擠壓的過程當中，液體將會由粒子中滲出，為一可變形可變體積之粒子。

四、結果與討論

(1).單球壓縮試驗：

圖二為不可壓縮和潤脹性球體受壓後側向變化比較的情形。其結果顯示潤脹性球體側向變化之長度小於不可壓縮球體者。其理由可推論為在受壓後，吸水性球體內之含水滲出，使總體積減小之故。下式為根據量測結果導出之潤脹性球體最終體積與壓陷深度變化之關係式。

$$\frac{V'}{V}=-0.134\left(\frac{\delta}{R}\right)^{3}-0.5471\left(\frac{\delta}{R}\right)^{2}-0.2026\left(\frac{\delta}{R}\right)+1.008$$

(2).濾餅表面孔隙度之量測：

量測結果如表一所示。

(3).恆壓過濾之實驗結果：

圖三為對polystyrene 進行不同壓力條件下之恆壓過濾結果 dt/dv 對濾液量 v 之關係圖。由圖三可知剛性 polystyrene 粒子，其過濾行為相當符合 Ruth 之理論而呈線性分佈。圖四及圖五為分別對不可壓縮的 Ca-alginate 和 Sephadex 泥漿之恆壓過濾實驗結果圖。由此兩圖形上看出，Ruth 的行為並不適合針對此兩種膠體粒子作論述，因兩者在 dt/dv 對 v 的關係圖上，都表現出非線性之關係。而比較此兩種膠體粒子可發現，由 Sephadex 所構成之濾餅，其阻力小於 Ca-alginate 所成濾餅之阻力。圖六顯示 Sephadex G50 粒子所形成之濾餅，由 SEM 所拍攝出的濾餅內粒子受壓後之變形情況。另外，不同於 Ca-alginate 的 dt/dv 之單調遞增現

象，Sephadex G50S 之過濾行為可分為兩個時期：(a)過濾前期：其 dt/dv 對 v 關係成線性，與 Ruth 之行為相符。(b)過濾後期：圖形之斜率增加，表示此水凝膠粒子已開始產生相當大的變形量。

由圖上可以得知，Sephadex G50S 較 Ca-alginate 有更明顯的暫態現象，這可以在過濾初期的關係圖上發現。另外由圖五也可得知，當施予較高壓力時，圖形較趨於線性。由現象應可看出在較高的壓力之下，粒子比在低壓的條件下更快地填充累積於濾材上，因而形成一厚層。此厚層將施加於濾餅的壓力分擔掉，故其底層的粒子之變形程度和低壓下的結果並不相同。

圖七為三種粒子在同濃度同壓力條件下之 dt/dv 對 v 比較圖。很顯然地，Ca- alginate 之濾餅阻力較 Sephadex G50S 濾餅阻力來得大。因而在此可得一結論：Sephadex G50S 為可變體積之粒子，在經過壓縮之後，因粒子本身之含水滲出，使得其體積縮小；然對 Ca-alginate 粒子來說，經過壓縮之後，該粒子體積依舊保持不變，所以將會造成其粒子比可滲水的 Sephadex G50S 粒子佔據較多的外部孔隙體積，結果便使其在濾材表面的阻力增加，濾液量減少。

五、結 論

水凝膠 Sephadex G50S 粒子由於具有受壓後滲水之現象，因此造成其體積的縮小改變。由 dt/dv 對 v 圖上可發現，Sephadex G50S 粒子之過濾行為可分為兩個時期。前期符合 Ruth 之行為，後期則為粒子產生相當大的變形。此外，經由和不可壓縮的 Ca-alginate 粒子作比較後可以發現，可變體積的粒子因受壓後體積變小，對外部空隙的佔據量小於不變體積的粒子(如圖一所示)。吾人亦可從單球試驗的結果推論得知，此即意謂：不可壓縮粒子會在濾材表面形成一緻密阻力層，其阻力大於由可變體積的水凝膠粒子所形成的者，使得在 dt/dv 對 v 關係較為陡峭，並且前者濾液量明顯少於後者。

六、計劃成果自評

本研究針對含水凝膠之難濾泥漿之恆壓過濾機構進行微觀解析，並對濾餅之成長及其局部性質進行詳盡之探討。除達成計劃之原訂目標外，研究成果並能發表在學術性期刊及應用至需求日般之精密分離程序中。

七、參考文獻

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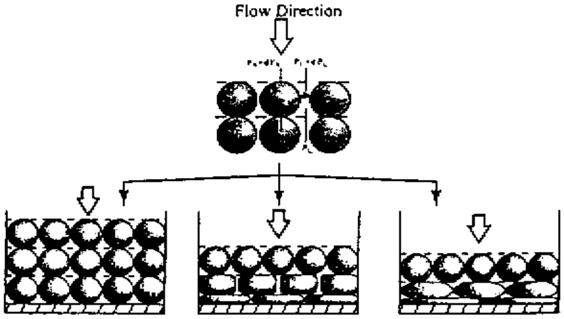
圖 表

Table1 Water content of each particle and Porosity at cake surface(slurry conc.=1.0%)

Material	Polystyrene	Ca-alginate	Sephadex G50S
Water Content X_w	0	0.831	0.775
Porosity ε_i	0.52	0.505	0.733



(a) Rigid particles (b) Swollen gel particles (c) Incompressuble gel particles

Fig.1 Schematic representation of the deformation of rigid, swollen gel and imcompressible gel particles during filtration process.

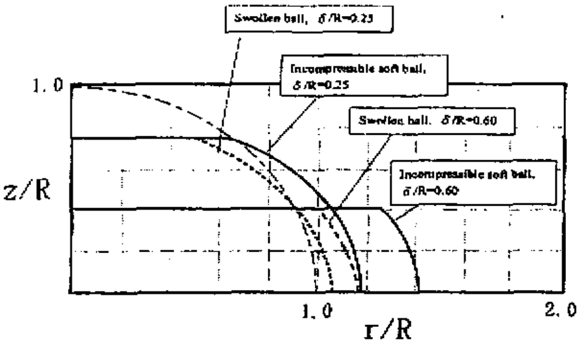


Fig.2 Comparison of the lateral expansion of swollen ball and incompressible ball.

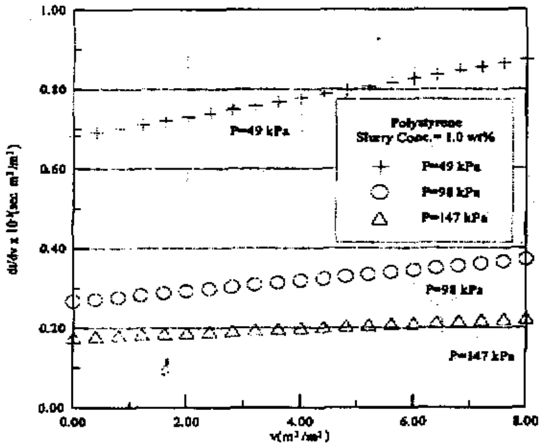


Fig.3 dt/dv vs. v data of rigid particles(polystyrene)

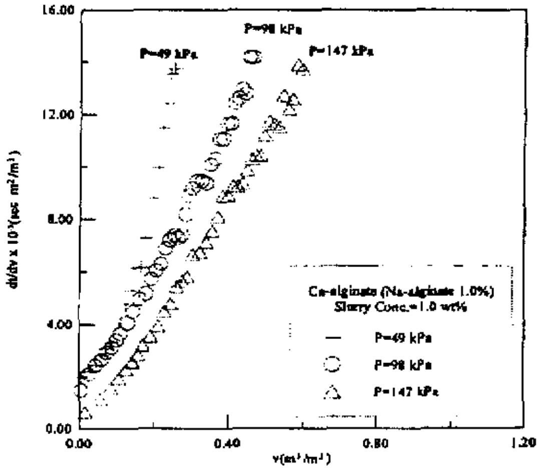


Fig.4 Constant pressure filtration results of incompressible gel particlés(Ca-alginate)

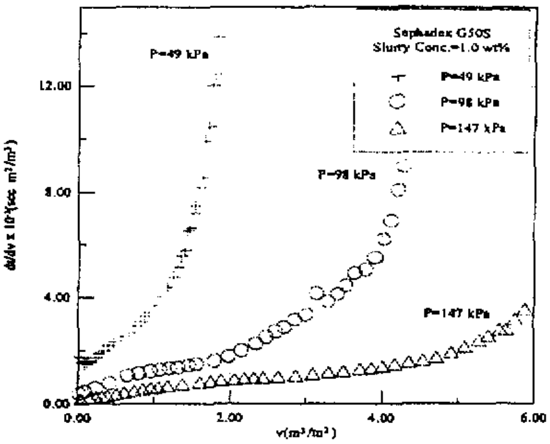


Fig.5 Constant pressure filtration results of incompressible gel particles(Sephadex G50S)

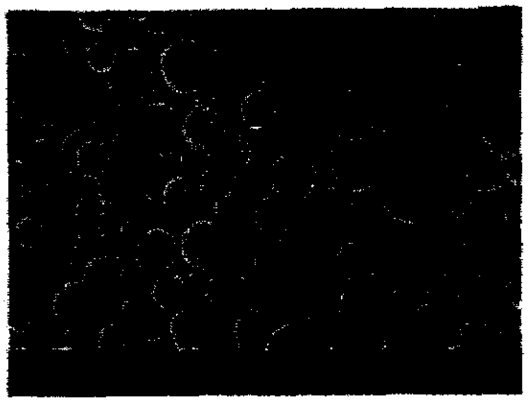


Fig.6 A scanning electron micrograph (SEM) of a fracture surface showing

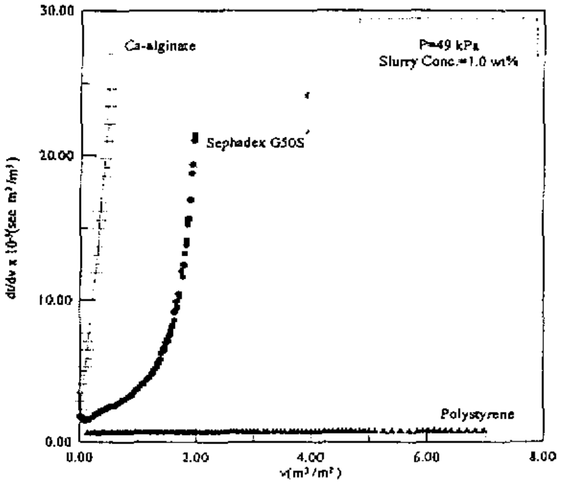


Fig.7 Comparison of the constant pressure filtration results

參加第八屆世界過濾會議報告

報告人：　呂維明 (台大化工系)
會議名稱：　第八屆世界過濾會議
8th World Congress of Filtration
地點：*Brighton, United Kingdom*
日期：April 3~7 , 2000
發表論文題目：
(1) Dynamic Analysis on Crossflow Microfiltration of Soft Particles
(2) Dynamic Analysis on Constant Pressure Filtration of Soft Gel Particles

一．參加會議經過

世界過濾會議(World Congress of Filtration)為國際間最具規模的過濾技術會議，每四年舉行一次。第八屆世界過濾會議由英國化工學會主辦，在Brighton舉行，本人被邀請參與為International Scientific Committee member之一。此次會議有40多個國家近600人參加，並有300篇以上論文之發表，論文發表時間每篇在15~20分鐘，並併行海報發表。會期共五天，並於3日舉行歡迎酒會，及6日舉行盛大之大會宴。我國這次共有近十人參加，發表了12篇之論文；大陸亦有20人左右出席，有11篇文章之發表。

二．與會心得

在本屆會議中所發表的之章，應用的論文佔了相當多之篇數，而基礎研究佔約1/3，題目涉及澄清過濾，濾餅過濾，膜分離，濾材、泥漿之特性，及濾機之發展等。本人發表可變形粒子之恆壓過濾理論及掃流過濾特性。由於發表內容相當新穎，引起不少與會人士之注意及詢問。

在另一領域---空氣之淨化與過濾方面，因空氣污染及半導體工業之需求，在此方面之所需已為過濾技術領域注意之重點，約在1/3之論文探討了此方面之研究。

在本屆會議中舉辦之過濾設備展，展示了不少量測設備及濾材方面之產品，碳化濾材及高溫用濾材之展示也代表了空氣淨化之需求之方向。

下屆世界過濾會議之地點，由不少國家爭取後，決定由美國過濾協會負責在New Orleance 舉行。

三．攜帶資料

大會專輯兩冊(存於台大化工系流體操作實驗室)

四．附件

發表之論文兩篇

DYNAMIC ANALYSIS ON CROSSFLOW MICROFILTRATION OF SOFT PARTICLES

Wei-Ming Lu,* Chun-Hsi Pan and Kuo-Lun Tung†

Dept. of Chemical Engineering, National Taiwan University, Taipei 106, Taiwan
†Dept. of Chemical Engineering, Chung Yuan University, Taoyuan 320, Taiwan

Abstract

Crossflow filtration experiments of *Saccharomyces cerevisiae* and PMMA were conducted to examine the structure of flux limiting layer formed by soft particles. A dynamic analysis proposed by Lu and Hwang (1995) was modified to investigate cake formation during crossflow filtration of soft particles by taking the transient effect of cake compression and the effect of area contact between particles into consideration. Effect of particle deformation due to frictional drag and mass of cake on the reduction of porosity was studied to examine how this variation led to the increase in filtration resistance. Results showed that as the cake formed by soft particles exhibits a rapid increase in flow resistance or decrease in porosity due to area contact between particles, a high resistant flux limiting layer is formed next to the filter medium during filtration. Neglecting the area contact effect between particles will lead to an over-estimated of gel layer thickness; and neglecting the transient effect of cake compression during gel layer formation will result in a under-estimated of gel layer thickness.

Keywords: crossflow microfiltration, soft particle, fouling, particle deformation

Introduction

Crossflow microfiltration is an essential mode of filtration operation for the production or recovery of valuable chemical and biological materials. Generally, biosolids contain much water and are regarded as deformable. Although many materials are deformable as subjected to a hydraulic drag force in fine chemical processing, a fundamental understanding of the mechanism of filtration of deformable particles remains elusive. It always results in a dramatic error prediction on filtration rate by using the conventional cake filtration theory. Various gel-layer models which based on mass transfer theory have been proposed to describe the phenomena of crossflow filtration for deformable biosolids. Although these models can accurately predict the steady-state flux for some biosolids, the regressive values of the parameters used often result in considerable discrepancies with the physical facts. Gatenholm et al. (1988) compared the performances of a MF membrane and an UF membrane during cell harvesting of *E. coli* and observed the membrane after filtration with SEM and TEM. They founded that the thickness of cake layer on the MF membrane was ten times of that on the UF membrane. The thickness difference was that the cells could not adhere to the UF membrane because the membrane surface is too smooth for the microorganism cells. In this article, Crossflow filtration experiments of *S. cerevisiae* and PMMA were conducted to examine the structure of flux limiting layer formed by deformable particles. A microscopic analysis using a force balance model was applied to investigate cake formation in crossflow filtration of deformable gel slurry. The effect of particle deformation due to friction drag and mass of cake on the reduction of porosity was studied to examine how this variation leads to the increase in filtration resistance.

Theoretical Analysis

Calculation of Flow Field. A crossflow microfiltration system Laminar flow of fluid through this 2-D system is governed by continuity and momentum balance equations with the following boundary conditions: $x = 0,\ 0 < y < H,\ u = u(y),\ v = 0, 0 < x < L_1,\ y = 0,\ u = 0,\ v = 0$

$0 < x < L$, $y = H$, $u = 0$, $v = 0$ and $L_1 < x < L$, $y = \delta(x)$, $u = u_w(x)$, $v = v_w(x)$, where $v_w(x) = \Delta P_x / [\mu(R_m + R_c)]$ and $u_w(x) = \Delta P_x / (\mu R_c)$, for $0 < y < \delta(x)$.

Force Analysis. The particles in slurry are transported onto the cake surface by carrier fluid. The major forces exerted on particles are analyzed as : the tangential force (O'Neill, 1986) $F_t = 1.7009 \cdot 3\pi\mu d_p u|_{y=d_p/2}$, the normal drag force (Goren, 1978) $F_n = 3\pi\mu d_p (q - v_L) \left[R_m d_p / 3 + (1.072)^2\right]^{1/2}$, the values of lateral lift velocity, where, v_L, can be obtained by (Drew, 1991): $v_L = 0.036 \rho_f (d_p/2)^3 \tau_w^2 / \mu$, and the net gravity force $F_g = \pi(\rho_p - \rho_f) g d_p{}^3 / 6$.

Dynamic Analysis on Cake Properties. The continuity equation of cake compression can be expressed as

$$\left(\frac{\partial q}{\partial x}\right)_t = \left(\frac{\partial \varepsilon}{\partial t}\right)_x \tag{1}$$

The effective specific surface area of deformable, S_o', is a function of cake porosity and can be regressed as the following equation by theoretical derivation of the compression of simple cubic packing:

$$\frac{S_o'}{S_o} = \frac{1 - \exp(-17.35\varepsilon)}{1 + 13.75\exp(-17.35\varepsilon)}. \tag{2}$$

Where S_o is the specific surface area of a incompressible spherical particles with the same volume. The filtration equation can be expressed by Kozeny equation. For the cake formed by deformable particles, the Kozeny's constant should be modified according to Sparrow and Loeffler (1959) to take a extremely low porosity value below 0.259 in to consideration. For the cake formed by deformable particles, the equilibrium cake porosity is not attained instantaneously with changing pressure. The time-dependent behavior of the cake structure shows that the cake can be regarded as a viscoelastic material and the porosity can be estimated by the following equation

$$\frac{\varepsilon_x - \varepsilon_o}{\varepsilon_f - \varepsilon_o} = 1 - \exp(-t/\tau), \tag{3}$$

where τ is the retardation time, ε_o is the porosity of filter cake before compression, and ε_f is the equilibrium cake porosity. In the traditional derivation of the drag equations, it was usually assumed that particles are in point contact. In a cake composed of deformable particles, there is a small area of contact $A_c = cA$ between particles as shown in Fig. 1. Tiller and Huang (1961) analyzed the case for finite contact area and presented the following equation which reduced to traditional relation when contact area vanishes, i.e. $A_c / A = 0$.

$$P_s + (1 - \frac{A_c}{A}) P_L = P \tag{4}$$

The known conditions from analyses and experimental measurements include a set of v vs. t data, cake surface porosity, filter medium resistance, flow rate of fluid at the cake surface, and the mass of cake formation.

Procedures for analyzing local cake properties. The details of the calculation procedures for analyzing the local cake properties can be referenced to the work of Tung (1998).

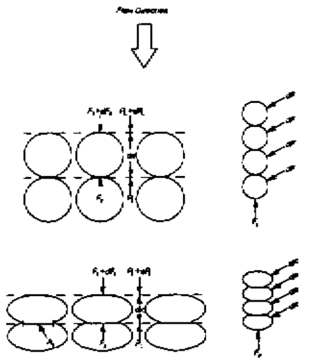


Fig. 1 Compressive force due to frictional drag.

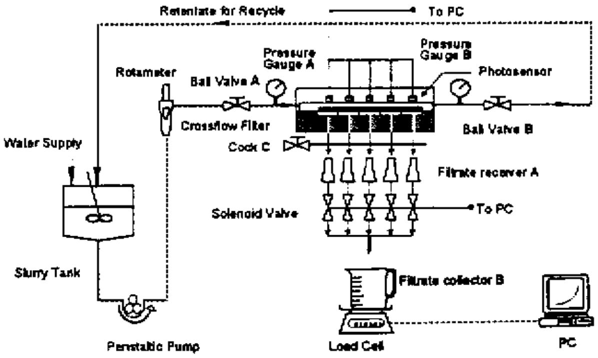


Fig. 2 A schematic diagram of crossflow filtration system.

Experimental

A schematic diagram of the crossflow filtration system is shown in Fig. 2. Two parallel plates with a clearance of 3.1*mm*, 20*mm* wide, and 0.1*m* long were assembled to construct a crossflow filter. The upper plate was made from a transparent plexiglass to facilitate observation. Ten photo-interrupters were placed in the upper plate to measure the variation of local cake thickness. The signal from each photointerrupter was sent to a PC through an AD/DA converter. The lower plexiglass plate was divided into five sections, each having a filtration area of $4 \times 10^{-4} m^2$. The latex particle of polymethyl meth-acrylate (PMMA) is an incompressible spherical particle with an averaged particle diameter of 5.365 μm (ρ_s=1,200 kg/m^3). As a deformable particle, *S. cerevisiae* was suspended in 0.86% NaCl solution, the average particle diameter of yeast is 4.324 μm (ρ_s=1,150kg/m^3).

Results and Discussion

Figure 3 shows the experimental result of cake thickness variation during a crossflow microfiltration process for both non-deformable PMMA particles and deformable *S. cerevisiae* particles. The steady thickness of cake layer formed by PMMA particles is six times of that formed by *S. cerevisiae* particles. The interpretation of the thickness difference is that the flow of fluid through *S. cerevisiae* particles cake layer produces a highly non-uniform structure with a tight skin of low porosity next to the supporting medium. The flux-limiting layer not only attenuates the filtration rate but also constricts the growth of filter cake. The experimental results of flux decline during a crossflow filtration process for both non-deformable PMMA particles and deformable *S. cerevisiae* particles are shown in Fig. 4. At the beginning of filtration, the filtration rate decreases quickly due to the growth of filter cake and the compression of the formed cake.

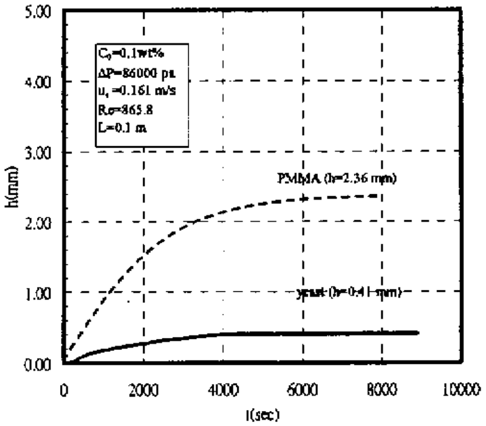


Fig. 3 Experimental result comparison of cake

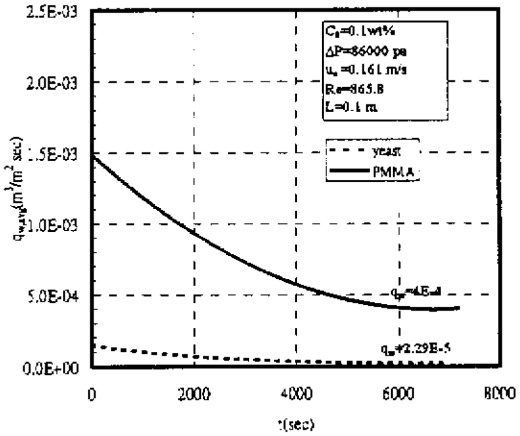


Fig 4 Experimental results of the time coarse of

growth with filtration of PMMA and yeast slurry.

permeate flux with filtration of PMMA and yeast.

Figure 5 illustrates the simulated distribution porosity within cake layer for both non-deformable PMMA particles and deformable *S. cerevisiae* particles. Comparison of the porosity distribution in filter cake formed by non-deformable PMMA particles and deformable *S. cerevisiae* particles shows that there is a sharper decrease in the porosity profile near the filter septum for *S. cerevisiae* cake layer than that of PMMA cake layer. This discrepancy is mainly due to the difference of deformability of particles. The *S. cerevisiae* particles are deformed in cake layer under the applied stress and results in a tight skin layer. This phenomena can be certified by such a extremely low porosity value of 0.19 next to the supporting medium as shown in Fig.5. In Fig. 6, the values of specific filtration resistance increase toward the filter septum due to the decrease of porosity near the septum.

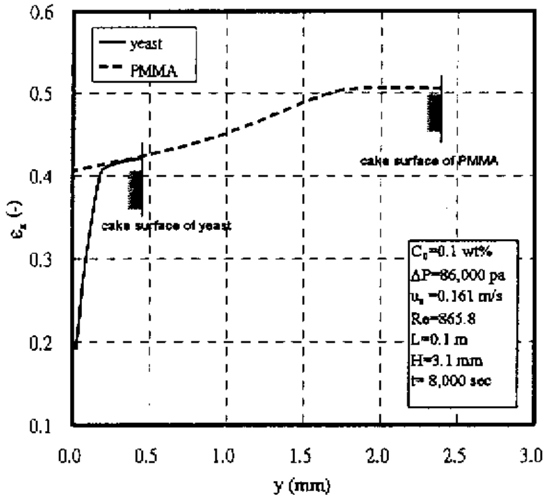


Fig. 7 Simulated result of porosity profiles along dimensional y location.

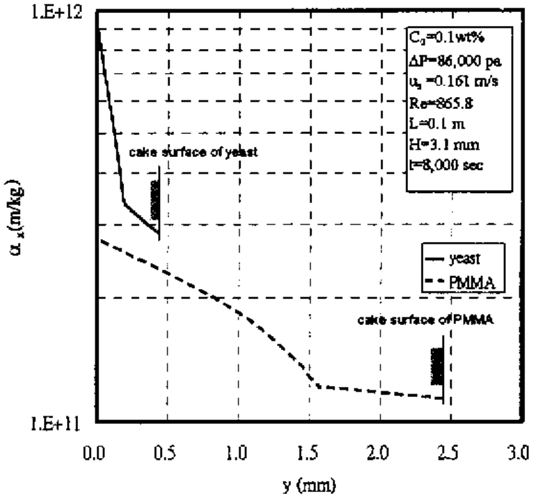


Fig. 8 Simulated results of specific filtration resistance along y direction.

Conclusion

Crossflow filtration experiments of *S. cerevisiae* and PMMA were conducted to examine the structure of flux limiting layer formed by deformable particles. A microscopic analysis using a force balance model was applied to investigate cake formation in crossflow filtration of deformable gel slurry. The effect of particle deformation due to friction drag and mass of cake on the reduction of porosity was studied to examine how this variation leads to the increase in filtration resistance. Results show that as the cake formed by deformable gel particles exhibits a rapid increase in flow resistance or decrease in porosity, a thin skin layer, resistant material is formed next to the filter medium during filtration.

Acknowledgment

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DYNAMIC ANALYSIS ON CONSTANT PRESSURE FILTRATION OF SOFT GEL PARTICLES

Wei-Ming Lu*, Kuo-Lun Tung, Shu-Mei Hung and Jia-Shyan Shiau

Dept. of Chemical Engineering, National Taiwan University, Taipei 106, Taiwan

Abstract

A dynamic analysis is extended to investigate cake formation in constant pressure filtration of soft gel slurry. For soft particles, the traditional filtration equations based on the assumption of point contact were modified to include the effect of the contact area into consideration. Effect of particle deformation due to frictional drag and mass of cake on the reduction of porosity is studied to examine how this variation affects the in filtration resistance. Results show that as the cake formed by soft gel particle exhibits a rapid increase in flow resistance or decrease in porosity due to area contact between particles and deformation of the particles. A thin high resistant layer is formed next to the filter medium during filtration.

Keywords: cake filtration, soft particle, local cake properties, particle deformation

Introduction

Separation of deformable particles from liquid is frequently encountered in the biomass processing and in the chemical/biological waste treatment. The deformation of particles during a separation process complicates the processing of a variety of materials including gels, foods, blood cells, bacteria, microorganisms, and chemical/biological waste products. Although many materials of industrial interest are deformable as subjected to a hydraulic drag force, a fundamental understanding of the mechanism of filtration of deformable particles remains elusive. Numerous investigators (Tiller and Green, 1973; Tiller et al., 1987; Jönsson and Jönsson, 1992; Fane et al., 1993) claimed that flow through highly compactible cakes produces a highly non-uniform structure with a tight skin of low porosity next to the supporting medium. This skin layer leads to adverse effects in which increasing filtration pressure has little effect on flow rate or average porosity. Jönsson and Jönsson (1992) developed a model to describe both static and dynamic behaviors of fluid flow through viscoelastic deformable materials. However, no attempt has been made on the investigation of contact area variation among deformable particles during a course of cake filtration microscopically. In this study, the dynamic analysis proposed by Lu and Hwang (1993) is modified by considering the variation of contact area among the particles to investigate cake formation in cake filtration of deformable slurry. For deformable particles, the traditional filtration equations based on the assumption of point contact must be modified to include the effects of the contact area and transient compression into consideration. Effect of particle deformation due to frictional drag and mass of cake on the reduction of porosity is studied to examine how this variation leads to the increase in filtration resistance.

Theoretical Analysis

Dynamic Analysis on Cake Properties. The continuity equation of cake compression can be expressed as

$$\left(\frac{\partial q}{\partial x}\right)_t = \left(\frac{\partial \varepsilon}{\partial t}\right)_x \tag{1}$$

The effective specific surface area of deformable, S_o', is a function of cake porosity and can be regressed as the following equation by theoretical derivation of the compression of simple cubic packing:

$$\frac{S_o'}{S_o} = \frac{1 - \exp(-17.35\varepsilon)}{1 + 13.75\exp(-17.35\varepsilon)}. \tag{2}$$

Where S_o is the specific surface area of a incompressible spherical particles with the same volume. The filtration equation can be expressed by Kozeny equation. For the cake formed by deformable particles, the Kozeny's constant should be modified according to Sparrow and Loeffler (1959) to take a extremely low porosity value below 0.259 in to consideration. For the cake formed by deformable particles, the equilibrium cake porosity is not attained instantaneously with changing pressure. The time-dependent behavior of the cake structure shows that the cake can be regarded as a viscoelastic material and the porosity can be estimated by the following equation

$$\frac{\varepsilon_x - \varepsilon_o}{\varepsilon_f - \varepsilon_o} = 1 - \exp(-t/\tau), \tag{3}$$

where τ is the retardation time, ε_o is the porosity of filter cake before compression, and ε_f is the equilibrium cake porosity. In the traditional derivation of the drag equations, it was usually assumed that particles are in point contact. In a cake composed of deformable particles, there is a small area of contact $A_c = cA$ between particles as shown in Fig. 1. Tiller and Huang (1961) analyzed the case for finite contact area and presented the following equation which reduced to traditional relation when contact area vanishes, i.e. $A_c / A = 0$.

$$P_c + (1 - \frac{A_s}{A})P_L = P \tag{4}$$

The known conditions from analyses and experimental measurements include a set of v vs. t data, cake surface porosity, filter medium resistance, flow rate of fluid at the cake surface, and the mass of instantaneous cake formation.

Procedures for analyzing local cake properties. The details of the calculation procedures for analyzing the local cake properties can be referenced to the work of Tung (1998).

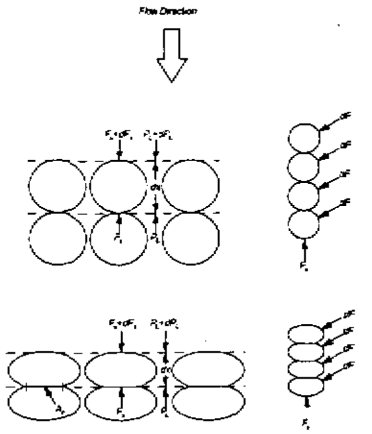

Fig. 1 Compressive force due to frictional drag.

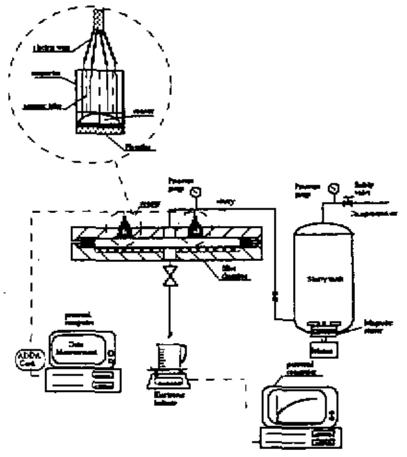

Fig. 2 A schematic diagram of filtration system.

Experimental

A schematic diagram of the experimental apparatus used in this work is shown in Figure 2. The slurry was agitated in the slurry supply tank with a magnetic disk and was kept well mixed by pumping the slurry at a moderate rate through pressure filter. In each experiment, the filtration pressure was supplied by compressed air and was adjusted to a given value by a pressure regulator. The increase of the weight of filtrate was detected by a load cell and recorded on a personal computer. The filtration data, e.g., v vs. t, were used to simulate the growth and compression of cake during the filtration. An optical *in situ* technique by reflection type photointerrupter was adopted to measure the dynamic cake thickness during each cake filtration experiment. Variations of cake thickness were recorded by the transverse value of voltage signal with an accuracy of $10\,\mu m$. In this study, constant pressure filtration experiments of $5\,\mu m$ calcium-alginate particles, *Saccharomyces cerevisiae* and PMMA were conducted to examine the structure of flux limiting layer formed by deformable particles. The latex particle of polymethyl methacrylate (PMMA) particle is an incompressible spherical particle with an average diameter of $5\,\mu m$. It has a narrow size distribution, a slightly negative charge and a high dispersibility. It was suspended in deionized water for filtration experiments and the suspension was pretreated for 30 min with ultrasonic dispersion to minimize particle aggregation. As a deformable particle, *Saccharomyces cerevisiae* was purchased from Sigma Chemical Co., Ltd. and suspended in 0.86% NaCl solution (physiological saline). The yeast diameter ranged from 4 to $5\,\mu m$. The modeled deformable particles, calcium alginate gel particles, with averaged diameter of $5\,\mu m$ and density of $1{,}070\,kg/m^3$ were used in volumetric concentration, ϕ_s, of 0.2%. The gel particles were prepared by dropping 0.5, 0.75, or 1.0% sodium alginate solution into 0.1M $CaCl_2$ solution from spraying nozzle.

Results and Discussion

From constant pressure filtration experiments on a surface filter, Ruth et al. (1933) found for various industrial slurries that the dependence of *v* on time *t* was described closely by a parabolic profile, i.e. a linear profile in *t/v* vs. *v* plot. Figure 3 shows the experimental result of *dt/dv* vs. *v* data for rigid PMMA particles and for deformable Ca-alginate particles of various particle strengths. All the particles show a non-Ruth behavior. As indicated in Figure 3, increasing the filtration pressure will result in a more curvous profile. In Figure 3, constant pressure filtration of PMMA slurry shows a perfect linear profile in dt/dv vs. v plot indicates a Ruth behavior, while, constant pressure filtration of deformable Ca-alginate particles and *Saccharomyces cerevisiae* show non-linear behavior in dt/dv vs. v plots. The discrepancy of filtration behavior between rigid and deformable particles will be further discussed in the following sections based on the local variation of cake properties. Figure 4 shows the variation of hydraulic pressure distribution during a course of constant pressure filtration. Apparent creep effect has also been observed. Such a factor has never been systematically studied in filtration discipline, regardless of the classical theory or the multi-phase theory.

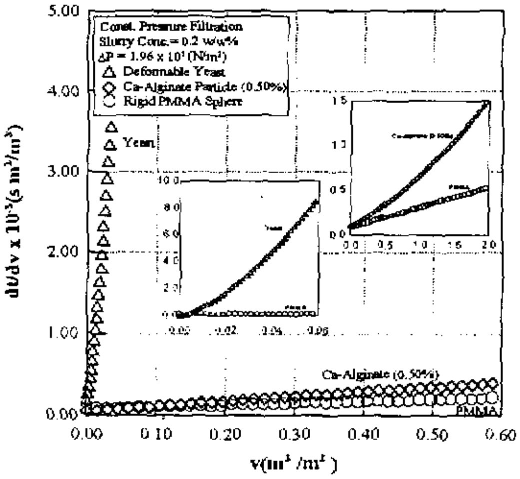

Fig. 3 dt/dv vs. v for constant filtration pressure (PT=98000 Pa).

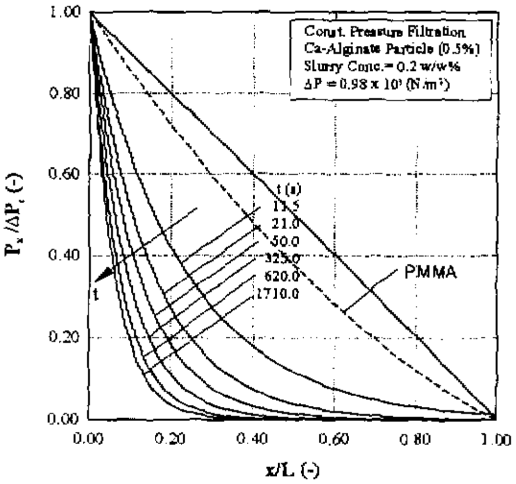

Fig 4 Variation of hydraulic pressure distribution during constant pressure filtration.

Figure 5 reveals the variation of local cake porosity distribution with three different values of τ. There is a sharp decrease in the porosity profile near the filter septum for Ca-alginate cake layer. Result also shows that neglecting the transient effect of cake compression during gel layer formation will result in an underestimate of gel layer thickness. Furthermore, Fig. 6 depicts the comparison results of ε_{av} vs. t from dynamic simulation based upon point contact mode and area contact mode, respectively. Results show that neglecting the area contact effect between particles will lead to an over-estimated of gel layer thickness.

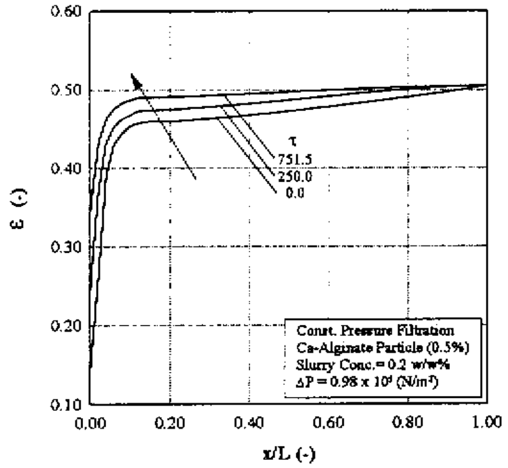

Fig. 5 Variation of local cake porosity distribution with τ value.

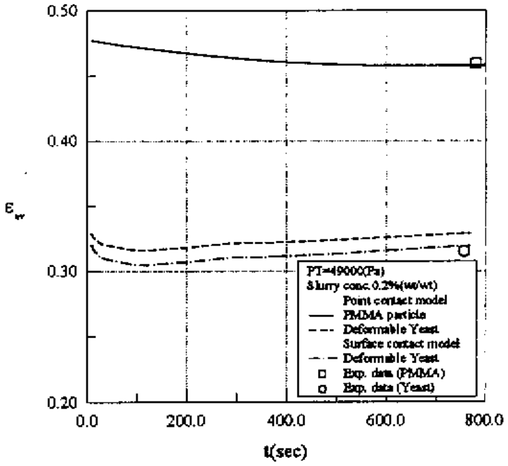

Fig. 6 ε_{av} vs. t for constant pressure filtration: effect of contact mode.

Conclusion

A dynamic analysis is proposed to investigate cake formation in cake filtration of deformable gel slurry. For deformable particles, the traditional filtration equations based on the assumption of point contact must be modified to include the effect of the contact area into consideration. Effect of particle deformation due to friction drag and mass of cake on the reduction of porosity is studied to examine how this variation leads to the increase in filtration resistance. Results show that as the cake formed by deformable gel particles exhibits a rapid increase in flow resistance or decrease in porosity due to area contact between particles, a thin skin layer, resistant material is formed next to the filter medium during filtration. Furthermore, neglecting the area contact effect between particles will lead to an over-estimated of gel layer thickness; and neglecting the transient effect of cake compression during gel layer formation will result in an underestimate of gel layer thickness. The results show that the data obtained from dynamic analysis for filtration of deformable particles can provide a well prediction with an average deviation of around 6% for low applying pressure to 10% for high applying pressure.

Acknowledgment

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