Estimation of Floc Permeability and Porosity (short communication)

膠羽透過率及孔隙率的預測（短文）

doi:10.6967/JCICE.200303.0275

Journal of the Chinese Institute of Chemical Engineers, 34(2), 2003

中國化學工程學會會誌, 34(2), 2003

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頁數/Page： 275-280

出版日期/Publication Date：2003/03

J. Chin. Inst. Chem. Engrs., Vol. 34, No. 2, 275-280, 2003

Short communication

Estimation of Floc Permeability and Porosity

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Abstract—This paper briefly reviewed the progress made recently to the estimation of hydrodynamic permeability of sludge flocs, which is essential for determining the extent of advection flow through the floc interior. The large pores mainly contribute the hydrodynamic permeability of sludge floc through which the fluid could readily flow. Permeability models that assume a homogeneous floc interior normally yield marked uncertainties in model outputs. Wu et al. (1998) proposed a hydrodynamic approach for estimating the hydrodynamic permeability that considers the response of the sludge floc when moves toward a flat plate. The floc permeability for waste activated sludge was noted higher than the cupric hydroxide sludge, while the polyelectrolyte flocculation and fluid shear could reduce the permeability. The bubble-tracking technique describes the fluid flow field around and through the floc interior. The existence of advection flow is noted unexceptional. The misuse of permeability model has been demonstrated with a case study leading to the floc porosity based on free-settling test.

Key Words : Floc, Permeability, Hydrodynamics, Bubble-tracking, Advection flow, Porosity

INTRODUCTION

The knowledge about the hydrodynamic drag force exerted on the floc is necessary for predicting its motion. The drag force exerted on a floc requires the information about several unknowns, e.g., drag coefficient (Huang, 1993), primary particle density (Lee, 1994), and the correction factor for advection flow (Li and Ganczarczyk, 1988). A detailed discussion about the present status of the knowledge on these terms is available in Lee et al. (1996). The hydrodynamic force exerting on a floc of diameter d_f (m) moving at a steady velocity of V (m/s) is

$$F_s = \left(\frac{\pi}{4} d_f^2\right)\left(\frac{1}{2}\rho V^2\right)\Omega C_D, \qquad (1)$$

where C_D and ρ are the drag coefficient (-), fluid density (kg/m^3), respectively. Meanwhile, the correction factor Ω (-) takes account of the advection flow through the floc's interior, which is unity for impermeable floc, and less than unity for a porous floc. The hydrodynamic permeability of a hypothetical "point" in a porous medium, k (m^2), could be defined as

$$k = -\frac{\mu}{\nabla p}\vec{V}_{rel}, \qquad (2)$$

where $\vec{V}_{rel}$ (m/s) is the relative velocity of liquid and the solid phases, p (Pa), the local pressure, and μ (Pa-s), the liquid phase viscosity (which is not necessarily identical to the bulk solution). Hence, the permeability controls the extent of the advection flow. Restated, with a low permeability, the floc interior could be regarded impermeable and the effects of advection could be safely neglected. On the other hand, an object with a high permeability would experience a strong advection flow through its interior while the correction factor is far less than unity.

To evaluate the correction factor, the floc permeability k is required to be known a priori. However, since the floc is very fragile and tends to break down under shear, the floc interior permeability cannot be accurately evaluated by the conventional column test (Note: a column test is widely employed in determining soil permeability, which is made in a filled column with flow-through fluid.). Indirect methods are required to estimate the floc permeability.

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PERMEABILITY MODELS

In literature, empirical models usually evaluate the floc permeability. Matsumoto et al. (1978) employed Davies correlation for estimating the floc permeability. Li and Ganczarczyk (1992) compared the permeabilities calculated from Carman-Kozeny equation and Davies correlation. Huang (1993) employed Brinkman model on permeability estimation. Lee et al. (1996) summarized the six among the other widely employed permeability models: Brinkman, Carman-Kozeny, Happel (sphere), Happel (fibrous), Davies and Iberall, which are all of the same form: $k = f(\varepsilon) \times d_p^2$, where ε (-) is the floc porosity, and d_p (m), the diameter of primary particles that constitute the floc. As addressed in Lee et al. (1996), however, these two quantities are not available for a real sludge process and are usually taken as fitting parameters. Rogak and Flagan (1990) also proposed an expression for permeability based on the fractal nature of floc. Chellam and Wiesner (1993) examined theoretically the fluid collection efficiency in relation to the fractal dimension and noted an enhanced advection flow when the fractal dimension is less than two. Veerapaneni and Wiesner (1996) proposed a radially varying permeability model to describe the advection flow. The significance of the advection through the floc interior affects the flocculation efficiencies (Li and Logan, 1997a, 1997b).

Sludge flocs are recognized as a fractal-like object in which pores of all sizes (less than that of the floc size and greater than that of the primary particles) exist (Li and Ganczarczyk, 1987, 1989, 1990, 1992; Huang, 1993; Lee, 1994). However, moisture tends to flow through the path of the least resistance. Restated, water would unlikely flow into the tiny pores in the microflocs but rather through the large pores among the microflocs. This observation suggests a highly heterogeneous nature of the floc interior. Permeability herein measured thereby is mainly attributed to the structures of the large pores (Lee, 1996). However, in literature most permeability models assume a homogeneous floc interior structure. For a specific floc, the k values calculated based on various permeability models can vary by two to three orders of magnitudes. Caution must be paid, therefore, to any conclusion drawn from the floc permeability information obtained from permeability models.

FLOC MOVING TOWARD A PLATE

Wu et al. (1998) presented a trial to experimentally estimate the floc interior's permeability. The underlying concept is simple: the response for a porous floc when moving towards an impermeable plate should differ from that for a nonporous object. Comparing their responses allows us to obtain information regarding the floc interior permeability. For instance, when a floc is released from the distant top end and moves freely towards (downwards) a bottom flat plate under the action of gravity, if only the floc Reynolds number is not sufficiently large (<50, say), the transient effect could be safely neglected and the process assumed to be in a pseudo-steady state. Under such a circumstance, the sum of gravity force, buoyancy force and the drag force vanishes. Restated, at any instant along the travel of floc, whose diameter is d_f and moving speed is V, then $F_{\text{gravity}} - F_{\text{buoyancy}} = F_{\text{drag}} = \Omega F_s$, where F_s is defined in Eq. (1). The gravity and buoyancy forces remain unchanged for a given floc, consequently, the product ΩF_s is constant along the floc's travel towards the plate. To keep a constant product of ΩF_s when the floc approaches the plate, the floc must decelerate to reduce the corresponding F_s. Meanwhile, the correlation between the corresponding drag force and the change in moving velocity could be obtained either using theoretical estimate (Payatakes and Dassios, 1987) or by numerical calculations (Wu and Lee, 1998a, 1998b) as a function of floc permeability. Hence, by comparing the measured floc velocity with the distance to the wall, the floc permeability could be estimated. Figure 1 demonstrates the sequential photos for a floc moving toward a flat plate.

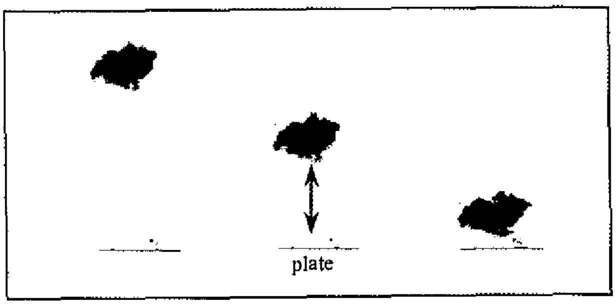

Fig. 1. Floc approaching toward a flat plate.

Following Wu et al.'s proposal, the floc permeability for a waste activated sludge was estimated ranging 2.5×10^{-9}-9×10^{-6} m^2 over a size range of 150-10,000 μm in floc diameter (Wu et al., 2000a). Meanwhile, the cationic polyelectrolyte flocculation would reduce floc permeability to 3×10^{-9}-7×10^{-7} m^2 over a size 560-2,710 μm (Wu et al., 2000b), indicating a more compact interior for flocculated flocs. The permeability for cupric hydroxide flocs is lower than the activated sludge flocs. After shearing the permeability would be further reduced, probably owing to the breakage and reconstruction of floc interior structure during shearing (Wu et al., 2001).

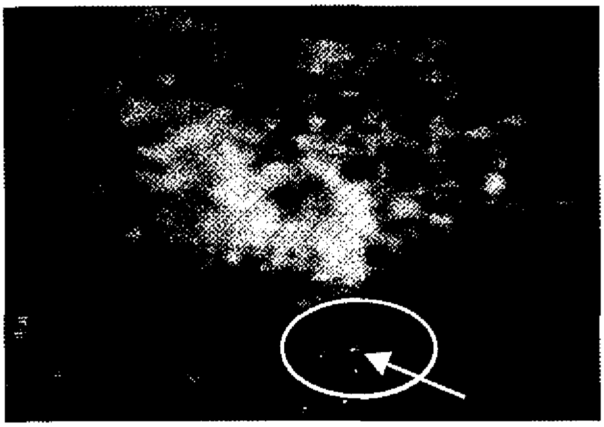

Fig. 2. Interactions between the falling floc and the rising hydrogen bubbles. The arrow indicates the bubbles just beneath the floc and will penetrate into the floc interior.

BUBBLE-TRACKING TECHNIQUE

Although Wu et al.'s proposal seems promising to estimate the floc interior permeability without the deterioration of the fragile structure during settling, it is an indirect estimate based on the response of moving floc subjected to hydrodynamic environment changes. Direct observation on the fluid flow field around and through the floc interior could directly estimate the extent of the advection flow. When a porous floc moving in a liquid pool, ahead of the moving there is a fluid tube of diameter ω (m) within which the fluid will flow through the interior of the floc, while outside this tube the fluid will flow around the floc. Clearly, for an impermeable sphere $\omega/d_f = 0$, that is, no fluid could flow through the sphere's interior. At another extreme with "no floc", or a floc with infinitely large permeability, $\omega/d_f \to 1.0$, that is, the approaching fluid could flow through the sphere interior without any interference. The collection efficiency, η (-), was defined as $(\omega/d_f)^2$. For a porous floc of permeability k, η would range between 0 and 1, depending on the easiness of fluid flowing through the sphere interior.

Tsou et al. (2002a, 2002b) employed the bubble-tracking technique for measuring the collection efficiency of a moving floc. Hydrogen bubble chains were generated and allowed to rise from the chamber bottom and meet with the falling floc in the mid-way of the chamber. Since the bubble size is generally much smaller than the flocs under investigation, the streamlines around the floc, whence the collection efficiency, could be accordingly estimated.

Figure 2 reveals the falling floc and a few rising bubbles from the first bubble chain. The bubbles indicated by the arrow locate just beneath the floc. It is apparent that the floc interior is loosely packed and, in observation, some rising bubbles could penetrate into the floc interior and be captured there. Hence, a strong advection flow exists when sludge floc settles. These authors estimated that the permeability for original sludge flocs is $0.52\text{-}5.4\times10^{-7}$ m^2; flocculated flocs, $0.88\text{-}10\times10^{-8}$ m^2; and freeze/thawed sludge flocs, 4.8×10^{-8} m^2. The permeability for sludge flocs correlates that found in hydrodynamic response test proposed by Wu et al. (1998).

Based on the bubble-tracking tests, the advection flow through the floc interior is found unexceptionable in all tests. The extent of advection flow is controlled by the structure of the floc interior, which determines its settling velocity, the rate of collisions with small particles, and the retained moisture in the interior (Thomas et al., 1999). The information of floc permeability is essential to the capability for predicting floc process performance, which is still far from satisfaction to date. However, the misuse of the permeability correlation in application may lead to erroneous conclusion. In the next section we demonstrate such an example.

INSTRISIC AND APPARENT POROSITIES

A common practice for estimating floc porosity is to observe a floc of diameter d_f falling freely in a pool of liquid. The settling velocity and the floc diameter (by various kinds of definition, see Adachi and Tanaka (1997)) are recorded, afterward, the force balance between the drag force (Eq. (1)) and the buoyant weight of floc leads to the following expression:

$$\rho_f - \rho = \frac{3\rho\,\Omega C_D}{4d_f g}V^2 \tag{3}$$

where ρ_f is the floc density (kg/m^3). The density difference, or the effective floc density, relates to the floc porosity with the mass balance expression:

$$1-\varepsilon = \frac{\rho_f - \rho}{\rho_m - \rho}, \tag{4}$$

where ρ_f is the solid density (kg/m^3). Take d_f=634 μm, V=1.15 mm/s, $\Omega = 1$ (no advection flow, as commonly assumed), C_D=34/Re (a commonly adopted expression proposed by Tambo and Watanabe (1979)), and ρ and ρ_m as 1000 and 1500 kg/m^3, respectively. Then ε is calculated as 0.985, a very porous floc interior. This value, in most cases, seems unreasonably high since the visual observation normally suggests a not-so-loose structure (Zartarian et al., 1997).

We demonstrate herein that the unreasonable high porosity (denoted as apparent porosity herein) is attributed to the inappropriate use of the permeability models. Consider a highly heterogeneously structured floc, moving at velocity V, as a cube of size

d_f that consists of N (-) parallel capillary tubes of diameter d (m) and length L (m). The intrinsic porosity of this floc (ε_i) is Nd^2/d_f^2 (<1). (Note: These capillary tubes represent only the big pores that allow easy advection flow, and exclude the contributions of the small pores that the bulk fluid could hardly flow through.) The fluid velocity distribution within a capillary tube could be stated as a function of radius (r) follows:

$$u = 2V_m\left(1-\left(\frac{2r}{d}\right)^2\right), \tag{5}$$

where $V_m=V/\varepsilon_i$. The pressure drop across the tube length (and across the floc length as well) could be stated as follows:

$$\Delta P = -\frac{\tau\pi dL}{\frac{\pi d^2}{4}} = -\left(-\mu\frac{\mathrm{d}u}{\mathrm{d}r}\right)_{r=d/2}\frac{4L}{d} = -\frac{32\mu VL}{d^2\varepsilon_i}, \tag{6}$$

where τ (Pa) is the wall shear stress, μ the liquid viscosity (Pa-s), Using the definition of Eq. (2) the (global) permeability k of the floc could be stated as follows:

$$k = \frac{\varepsilon_i d^2}{32} = \frac{\varepsilon_i^2 d_f^2}{32N}\ . \tag{7}$$

The permeability in Eq. (7) is estimated for a floc containing big pores through which the advection flow occurs. Restated, the floc interior is highly heterogeneous while the fluid flow is mainly confined within only part of the body. On the other hand, most of the commonly adopted permeability models, like the Carman-Kozeny model, assume a homogeneous floc interior. Restated, the fluid has an equal chance to flow through all parts of the floc interior while the friction between the primary particles (diameter d_p) and the flowing fluid controls the extent of the advection flow.

The Carman-Kozeny model for hydrodynamic permeability could be stated as follows:

$$k = \frac{\varepsilon^3}{(1-\varepsilon)^2}\frac{d_p^2}{180}. \tag{8}$$

If one estimates the permeability of a sludge floc assuming a model with homogeneous interior, as commonly done in literature, hence, the apparent porosity could be estimated as follows:

$$\varepsilon^3 - a\varepsilon_i^2(1-\varepsilon)^2 = 0\,, \tag{9}$$

where $a = 45d_f^2/8Nd_p^2$ (-), a parameter characterizing the floc pores. Apparently, ε is not necessarily identical to ε_i.

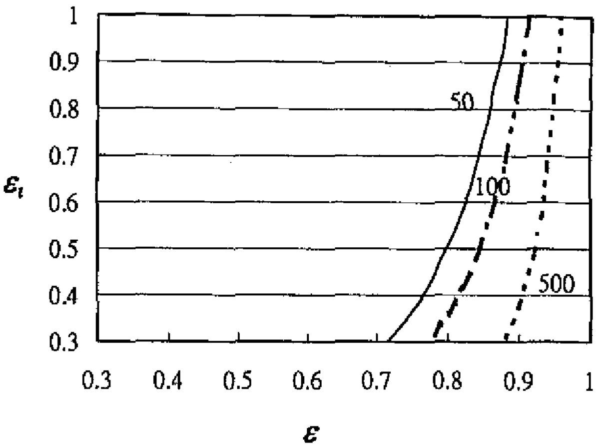

Fig. 3. The intrinsic porosity (y-axis) versus apparent porosity (x-axis) plot. The numeric values in this plot are for a parameter.

Figure 3 demonstrates the ε_i versus ε plots using a as a parameter. As Fig. 3 reveals, ε is a weak function of ε_i, but is dependent of the parameter a. For instance, when the intrinsic porosity (ε_i) changes from 0.4 to 0.99, the corresponding apparent porosity only mildly increases from 0.76 to 0.88 for a =50, or 0.90 to 0.95 for a =500. For a sufficiently large a the derived ε value would all be close to unity regardless of the ε_i value. It is thereby not surprised to note very high floc porosity based on settling technique and some permeability model. The example calculation proposed above yields an apparent porosity of 0.985. This observation suggests that the floc's a parameter should be large, meanwhile, there is no information on what the exact ε_i is based on this settling test. Again, the hydrodynamic permeability of the sludge floc has to be a priori obtained before the accurate floc porosity could be thereby estimated.

CONCLUSION

Sludge flocs comprise pores of all sizes in their interior. Water tends to flow through the path of the large pores, which contribute the most of the hydrodynamic permeability under investigation. Permeability models normally assume a prescribed internal structure, uniform or fractal-like, based on which significant uncertainty exists among the model outputs. This paper briefly reviewed the progress made recently to the estimation of hydrodynamic permeability of sludge flocs. Wu et al. (1998) proposed the first trial on the hydrodynamic response of the sludge floc moving toward a flat plate. Using this technique the permeabilities of the waste activated sludge (original and flocculated) and the cupric hydroxide sludge (original and fluid sheared) were estimated. The bubble-tracking technique was employed for describing the fluid flow field around and through the floc interior. A strong advection flow is noted for flocs in all tests, which markedly influences the floc characteristics like settling, collision rate, and strength. Meanwhile, owing to the heterogeneous nature of the floc structure, permeability correlation could be misused. We demonstrated using a simple model calculation why the literature often reported unreasonably high floc porosity with free-settling test.

NOMENCLATURE

a	parameter in Eq.(9)
C_D	drag coefficient
d	diameter of parallel capillary tube, m
d_f	diameter of floc, m
d_p	diameter of primary particles, m
F_s	hydrodynamic force exerting on a floc, N/m^2
k	hydrodynamic permeability in a porous medium, m^2
L	length of parallel capillary tube, m
N	number of parallel capillary tube
p	local pressure, Pa
R_e	Reynolds number
r	radius, m
u	liquid velocity in capillary tubes, m/s
V	steady velocity of a floc, m/s
V_m	fluid velocity distribution, m/s
V_{rel}	relative velocity of liquid and solid phase, m/s

Greek symbols

ε	apparent floc porosity
ε_i	intrinsic floc porosity
η	collection efficiency
μ	liquid phase viscosity, Pa-s
ρ	fluid density, kg/m^3
ρ_f	fluid density, kg/m^3
ρ_m	solid density, kg/m^3
τ	wall shear stress, Pa
ϖ	diameter of fluid tube, m
Ω	correction factor

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(*Manuscript Received April 26, 2002*)

膠羽透過率及孔隙率的預測

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摘　要

本論文簡短的回顧了近來預測污泥膠羽水力透過率的過程，預測污泥膠羽水力透過率的原因之一乃是爲了測量污泥膠羽中流體可通過的部分，對多孔性污泥膠羽而言，水力透過率代表了污泥膠羽中大孔洞部份影響了流體在膠羽中的流力行爲。以往研究者提出一些透過率模式，進而模擬膠羽的受力情形，但結果往往相差數個數量級。Wu et al. (1998)藉由單顆膠羽在無限流場中逐漸接近一平板的流力方式預測膠羽水力透過率，結果顯示活性污泥膠羽的透過率大於氫氧化銅污泥膠羽，而經過高分子架凝後的膠羽，以及受剪力作用後的膠羽，其透過率皆減小。氣泡追蹤技術描述了膠羽附近的流場，並且顯示確有流體流過膠羽內部及旁邊，本論文更進一步以膠羽自由沉降的觀點證明以往透過率模式的誤用。