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Determination of cake filtration characteristics of dilute suspension of bentonite from various filtration tests

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ABSTRACT

Various types of filtration experiments of dilute bentonite suspension were performed by using the fully automated and computer-driven experimental apparatus equipped with an unstirred batch filtration cell. The filtration tests conducted were the single constant pressure filtration test with an appreciable membrane resistance, a series of constant pressure filtration tests with the negligible membrane resistance under conditions of various filtration pressures, a constant rate filtration test, and a variable-pressure, variable-rate filtration test. The experimental data of the time variation of both the filtration rate and applied filtration pressure monitored throughout the course of filtration enabled us to evaluate the relation between the average specific cake resistance α_{av} of the filter cake and the applied filtration pressure p. The logarithmic plots of α_{av} vs. Δp_c have roughly merged into a unique curve irrespective of the type of filtration tests. The plots were approximated by a straight line over the moderate and high pressure ranges, and approached asymptotically to a constant value as the pressure decreased. The relation between α_{av} and Δp_c was fairly consistent with the empirical equation presented by Tiller et al. and the expression presented in this paper over wide ranges of the pressure.

1. Introduction

Cake filtration has been widely used over many years throughout the chemical and process industries. The major drawback in the use of cake filtration is the increase of the cake resistance ascribed to the formation and growth of the filter cake on the top surface of the filter medium during filtration. The accurate determination of filtration characteristics, especially the pressure dependence of the specific cake resistance α_{av} of the filter cake, is a key factor in the analysis of filtration operations. For this purpose, several laboratory filtration tests have so far been developed, and are classified into three categories according to the time variations of the applied filtration pressure p and filtration rate u_1: constant pressure filtration tests, constant rate filtration tests, and variable-pressure, variable-rate filtration tests.

In constant pressure filtration, the filtration rate decreases with time due to the increase of the cake resistance since the filtration pressure is maintained constant. Whilst the constant pressure filtration test is the method most commonly employed in industrial laboratories due to the ease of the testing method, a set of tests have to be conducted at several different filtration pressures in order to obtain the compressibility of the filter cake [1,2]. In contrast, in constant rate filtration, the applied pressure increases with time because the filtration rate is maintained constant. The pressure dependence of the average specific cake resistance α_{av} can be determined from monitoring the variation of the pressure with time in a single constant rate filtration test [3–11]. In variable-pressure, variable-rate filtration, neither pressure nor filtration rate are maintained constant. The compressibility of the filter cake can be obtained from monitoring the time variations of both pressure and filtration rate in a single variable-pressure, variable-rate filtration test [5,12,13]. As a special case of variable-pressure, variable-rate filtration, step-up pressure filtration consisting of a series of stepped pressures finds favor in determining the filtration characteristics [14,15].

Tiller et al. [16] originally presented the revised filtration theory in which the average specific cake resistance α_{av} varied with time even in constant pressure filtration because of the variation of the pressure drop across the filter cake with time [17,18]. More recently, Vorobiev [19] developed a more general form of the revised filtration theory by accounting for the time variation of the pressure drop across the cake for both incompressible and compressible filter media. Teoh et al. [20] proposed a method for determining α_{av} based on the instantaneous filtration rate in constant pressure filtration by making use of the variation of the pressure drop across the cake with time. Iritani et al. [21] obtained the pressure dependence of α_{av} over a wide range of pressures from the single constant pressure filtration test employing the filter medium with the high flow resistance compared to the resistance of the filter cake, resulting in the observable variation of the pressure drop across the cake with time.

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Nomenclature

a_0	empirical constant in Eq. (16) (m/kg)
a_1	empirical constant in Eq. (18) (m/kg)
k	slope of linear relationship of $d\theta/dv$ vs. v defined in Eq. (6) (s/m^2)
m	average ratio of mass of wet to mass of dry cake (–)
n	compressibility coefficient in Eqs. (13), (14), (16), and (18) (–)
p	applied filtration pressure (Pa)
p_a	empirical constant in Eqs. (16) and (18) (Pa)
p_i	empirical constant in Eq. (14) (Pa)
p_m	pressure drop across membrane (Pa)
p_s	local solid compressive pressure (Pa)
R^2	determination coefficient (–)
R_m	resistance of membrane (m^{-1})
s	mass fraction of solids in suspension (–)
u_1	filtration rate (m/s)
v	cumulative filtrate volume per unit membrane area (m)
Greek letters	
α	local specific cake resistance of filter cake (m/kg)
α_{av}	average specific cake resistance of filter cake (m/kg)
α_0	empirical constant in Eq. (14) (kg^{-n-1}m^{1+n}s^{2n})
α_1	empirical constant in Eq. (13) (kg^{-n-1}m^{1+n}s^{2n})
Δp_c	pressure drop across filter cake (Pa)
ε_{av}	average porosity of filter cake (–)
θ	filtration time (s)
μ	viscosity of filtrate (Pa s)
ρ	density of filtrate (kg/m^3)
ρ_s	true density of solids (kg/m^3)
Subscripts	
m	membrane

In the analysis of filtration operations, it is essential to know the average specific cake resistance α_{av} as a function of the pressure drop Δp_c across the filter cake. Several empirical equations have been proposed for representing α_{av} vs. Δp_c relations [22–24]. Although the power function presented by Sperry [22] has been widely used, it is difficult to relate α_{av} to Δp_c by Sperry equation in the low pressure range. Tiller et al. [23,24] used the analytical expressions which may be applicable over a wide range of pressures.

In the present article, the pressure dependence of the average specific cake resistance α_{av} is evaluated from the experimental data obtained from various types of filtration operations such as constant pressure filtration, constant rate filtration, variable-pressure, variable-rate filtration, and constant pressure filtration with the appreciable membrane resistance. The data are acquired by using dilute suspension of bentonite. The applicability of the existing empirical equations and the expression presented in this paper are tested for relating α_{av} to the pressure drop Δp_c across the cake analytically over a wide range of pressures.

2. Materials and methods

2.1. Raw materials and dispersion preparation

All experiments were conducted with bentonite (Ben-Gel, Hojun Co., Ltd., Annaka, Japan) of the sodium type. Dilute dispersions were prepared by suspending preweighed quantities of the particles in ultrapure, deionized water. Ultrapure, deionized water (resistivity > 18 MΩ cm) for dispersion make-up was prepared by purifying tap water through ultrapure water systems equipped with both Elix-UV20 and Milli-Q SP for laboratory use (Millipore Corp., Tokyo, Japan). The mean specific surface area size of bentonite particles, which is measured by a laser diffraction particle size analyzer (SALD-300 V, Shimadzu Corp., Kyoto, Japan) are 1.66 μm. The true density of the particles measured by the pycnometer is 2.48 g/cm^3.

2.2. Experimental apparatus and procedure

Fig. 1 illustrates a schematic drawing of the fully automated and computer-driven experimental apparatus, which is similar to that developed by Tarleton [7,8]. An unstirred batch filtration cell with an effective membrane area of 19.6 cm^2 was utilized. The filter medium used was mixed cellulose ester microfiltration membranes (Advantec Toyo Corp., Tokyo, Japan) with the nominal pore size of 0.1 μm. The flow resistance of the microfiltration membrane is negligible compared to that of the filter cake. Asymmetric regenerate cellulose ultrafiltration membranes (PLAC, Millipore Corp., Tokyo, Japan) with the nominal molecular weight cut-off (MWCO) of 1000 Da were also used to ensure the high resistance of the filter medium in the single constant pressure filtration test. Either membrane was fully retentive to bentonite particles.

Filtration experiments were carried out by adjusting the applied filtration pressure automatically by a computer-driven electronic pressure regulator by applying compressed nitrogen gas, as shown in Fig. 1. The filtrate was collected in a reservoir placed on an electronic balance (Shimadzu Corp., Kyoto, Japan) connected to a personal computer to collect and record mass vs. time data. The weights were converted to volumes using density correlations. The values of the filtration rate at various times were computed by numerical differentiation of the volume vs. time data.

The single constant pressure filtration experiments using ultrafiltration membranes were performed under conditions of constant pressure of 12, 49, 294, and 490 kPa. The conventional constant pressure filtration experiments using microfiltration membranes were conducted under conditions of constant pressure ranging from 0.59 to 490 kPa. But, the experimental data at constant

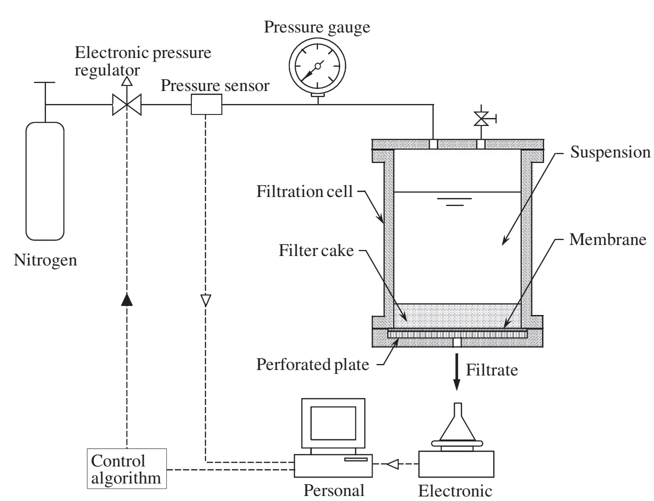

Fig. 1. Schematic diagram of experimental apparatus.