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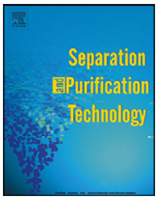

An adhesion model of the axial dispersion in wash columns of packed ice beds

Frank G.F. Qin*, Xiaoxi Yang, Minlin Yang

Research Centre of Distributed Energy Systems, DongGuan University of Technology, 1 University Road, SongShan Lake, DongGuan City, Guang Dong Province, China

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ABSTRACT

Experimental studies on a packed ice bed wash column, which was used for separating ice from ice slurry in the process of freeze concentration or freeze desalination, showed that the transitional mixing zone at the wash front of the ice bed expanded as the ice particle size decreased. It can be interpreted that the smaller the particle size, the greater the axial dispersion coefficient. This conflicts with the general knowledge or understanding of mixing and diffusion in porous media based on current dispersion theory, which predicts an opposite trend. To address this problem, an adhesion model of the axial dispersion coefficient of wash columns is proposed in this work, which correlates the axial dispersion coefficient in liquid phase with the particle size of the ice bed, the bed porosity, the interstitial flow velocity and the viscosity of the liquid. The model gives an analytical perspective of the axial dispersion in operating a packed ice bed wash column.

1. Background

The packed ice bed wash column, also known as the ice counter-washer, is an important part of the freeze concentration process (or freeze crystallization) and desalination for separating ice from ice slurries, which are mixtures of small ice particles and concentrated mother liquids. The primary ice slurry is usually produced from a scraped surface heat exchanger (SSHE), and is transferred to a re-crystallizer (or known as ripener) to start the so-called Ostwald ripening, which takes about 3–10 h to produce matured ice slurries [1,2]. During ripening small ice particles melt away while surviving ice particles grow larger in spherical shape through an adiabatic process.

In the process of washing conducted in this study as described in our previous papers [3,4], matured ice slurry containing more than 65% of mother liquid is fed into the wash column, and then compressed by a perforated piston to form a compact ice bed. Most of the mother liquid is squeezed out of the ice bed leaving only small amounts in the interstices of ice particles. The porosity of the ice bed depends on the applied pressure and the particle size. It was known by the rule-of-thumb that a larger average ice particle size gives a better (or higher) permeability of the ice bed, which is important to the washing performance and a 30–40% bed porosity is required to deliver a satisfactory outcome [5]. A packed ice bed wash column model was recently developed by Qin et al., from which 3 operating criterions were proposed for stabilizing the wash operation [4].

During washing, the cold water displaces the mother liquid top–down in the ice bed, meanwhile the mother liquid passes through the mesh filter/piston at the bottom and leaves the wash column (Fig. 1(a)). When the water moves downward as a plug flow, the interface between the displacing water and the displaced concentrated mother liquid produces a horizontal wash front, which divides the ice bed into two parts: a washed upper section and an unwashed lower section. In fact, the wash front can keep on going until it reaches to the bottom of the ice bed. The displacement of mother liquid with water is the basis of separating ice from ice slurry.

After washing, the clean ice bed can be pushed up by the piston and removed together with the interstitial wash water, so that the ice is separated from the concentrates.

Compared to other methods that may be able to separate ice from ice slurries, such as centrifugation, press or membrane filtration, the wash column offers less product loss and higher energy efficiency [6–9].

As an operational unit for separation however, the wash column is still often considered immature. A horizontal and sharp wash front may not appear, or may somehow disappear during the operation. Problems such as channelling, viscous fingering and ice pack clogging are often seen in practice [5]. When channelling occurs, the wash water runs down through channels and mixes with the concentrated solution. Most channels appear initially close to the wall of the wash column from the top of the bed surface and develop downward until they reach the bottom. This may be attributed to the so-called wall-effect, wherein the outer edge of a packed bed that is close to the walls is generally looser than that in the bulk [10]. Moreover, if the temperature of the environment is above zero

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* Corresponding author. Tel.: +86 0769 22862619; fax: +86 0769 22862619.
E-mail address: qingf@dgut.edu.cn (F.G.F. Qin).

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Nomenclature

a_{ice}	specific area of a individual ice particle ($m^2\,m^{-3}$)
a_{bed}	specific area of the ice bed ($m^2\,m^{-3}$)
d_i	diameter of the individual ice particle (m)
C	solute concentration ($kg\,m^{-3}$)
C_m	solute concentration in the thin film adhering on the ice ($kg\,m^{-3}$)
D_m	molecular diffusion coefficient ($m^2\,s^{-1}$)
D_{eff}	effective diffusion/dispersion coefficient ($m^2\,s^{-1}$)
D_L	longitudinal dispersion coefficient ($m^2\,s^{-1}$)
D_z	axial dispersion coefficient (the same with the D_L in this work) ($m^2\,s^{-1}$)
F	formation factor
F_h	source function of heat ($W\,m^{-1}$)
F_m	source function of mass ($kgm^{-1}\,s^{-1}$)
H	wash front height (thickness of the transitional mixing zone) (m)
J	flow flux ($kgm^{-2}\,s^{-1}$)
K_1, K_2, K_3	constant
l	characterized length of the pore channel (m)
R_f	retardation factor of the porous media
S	cross sectional area of the wash column (m^2)
t	time (s)
u	flow velocity of the liquid phase above the ice bed ($m\,s^{-1}$)
v	flow velocity of the liquid phase in the interstice of ice particles ($m\,s^{-1}$)

Greek

α_L	coefficient
ϕ	porosity of the ice bed
ρ	density ($kg\,m^{-3}$)
μ	viscosity of the liquid (mPa s)
τ	tortuousness of the pore channel (τ=l/d_i)
η	variation transformation ($\eta = z - v_z t$), a moving coordinate in z direction (m)
σ	standard deviation of Gaussian distribution (in this instance it can be interpreted as the thickness of wash front)

degree, the surroundings become a heat source and melting would be most likely to occur in this region. A less compact local region and ice melting are the main reasons that induce channelling. However, the breakthrough of water at the wash front does not necessarily result from thawing ice. Viscous fingering, for example, is caused when the wash front moves unevenly in different areas, channelling and/or ice melting may not occur simultaneously, but the result is a divergence in the interface between water and mother liquid that develops into finger-like shapes, the horizontal wash front then disappears.

Clogging of the wash column can be foreseen to occur under the following two conditions: (1) the ice bed porosity is very low, e.g. <5%. An insufficiently ripened ice slurry contains large amounts of small ice particles, e.g. <10 μm, the porosity and permeability of the ice bed produced from this ice slurry would be very low; and (2) the freezing point of the concentrate is very low, e.g. <−8 °C. The water temperature at the wash front is very close to 0 °C, but the unwashed ice bed is subzero, therefore ice grows when water passes the wash front. This combines the ice particles to form a sinter-like structure. Moreover, if the ice crystallization fills the interstices between the ice particles and blocks the pore canals, or forms dead-end holes, it results in clogging. Clogging may occur only partially in the cross section of the column leading to viscous fingering, or may occur in the overall cross section of the wash front, resulting in the blockage of the wash column.

In addition to these problems, the convective mixing at the interface between water and mother liquid produces a transitional mixing zone, in which the solute concentration in liquid phase shows a variation from zero of the wash water to the original value of the concentrated mother liquid. The thickness of the transitional zone is a measure of the convective mixing. It was interesting to find in experiments that the smaller the ice particle size of the ice bed, the thicker the transitional zone, so that the greater the axial dispersion coefficient. This conflicts with some often used, well known dispersion theory regarding porous media [11,12], which predict an opposite trend. In the rest of this paper, the main focus will be placed on the experimental and analytical work to address this problem. The adhesion of the viscous mother liquid on the ice surface during washing is emphasized in model analysis and establishment aiming to correlate the dispersion coefficient with the particle size of ice, the viscosity and the flow velocity of mother liquids, and the porosity of the ice bed as well.

2. Experiment

Fundamental research regarding the influence of the particle size and the flow velocity of the mobile phase on the interfacial mixing between water and the mother liquid was carried out in this study using a lab scale packed ice wash column, as shown in Fig. 1(a). The wash column was made of a Perspex tube 80 mm in diameter and 500 mm in height. The outside was wrapped with 5 mm thick rubber foam for thermal insulation, in which there was a double glazed window for observation. Fig. 1(b) is the schematic diagram of the continuous wash column, the structural details of which are not shown for the reason of intellectual property.

The ice slurry was poured into the column, in Fig. 1(a), and pressed with a mesh piston from the top to form a packed ice bed underneath. The mother liquid above the ice bed would be drained at the bottom and allow the liquid level to be flush with the top surface of the ice bed. The piston remained in the wash column to keep the pressure against the ice bed, and then a certain amount of water was introduced into the wash column on top. The height of this water layer was 100 mm. A washed ice layer appeared after draining the mother liquid again at the bottom to allow the liquid level to be flush with the surface of the ice bed.

Experiments showed that the mixing zone was strongly influenced by the ripening time of the ice slurry, as shown in Fig. 2. We know the grain size of ice increases with ripening time and has been studied by many [2–4,13,14]. The newly formed ice particles are normally smaller than 20 μm, but gradually grow up to several hundred microns after ripening for more than 3 h. The particle sizes of ice were measured with a biological optical microscope in a cold cabinet which was described in the above-mentioned previous work.

The ice bed that was packed from less aged ice-slurry would produce a larger transitional mixing zone between the washed and unwashed ice bed, as shown in Fig. 2(a). In this instance, chemical deterioration during the ripening time was ignored, i.e. the viscosity of the mother liquid was kept the same. The only element that changes during ripening time is the grain size of ice, which, of course, would have impact on the final porosity of the compressed ice bed (Fig. 3).

In contrast, the wash front became much sharper when the ice slurries were given longer ripening time (Fig. 2(b) and (c)). These results implied that the effective axial dispersion coefficient (D_z) increased greatly as the ice grain size was reduced. This cannot be satisfactorily explained with the current dispersion theory of miscible fluids in porous media, which predicts an opposite trend that the