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Algae-dewatering using rotary drum vacuum filters: Process modeling, simulation and techno-economics

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HIGHLIGHTS

- Mass transport was significantly affected by algal cake-layer compressibility.
- Cake-layer pore sizes were evaluated to determine the bursting pressure.
- Process capital investment and operating costs were assessed.
- The optimal operating conditions and minimum dewatering cost were identified.
- Two cost-sensitive domains were discovered to avoid.

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ABSTRACT

Clean and energy-efficient rotary drum vacuum filtration was selected to conduct algae-dewatering. The dynamic formation of an algal cake-layer on the filter surface was modeled by correlating the cake-layer permeability to the physical parameters of algae and cake-layer. The compressibility of algal cake-layer was taken into consideration in the modeling, and its effect on the algae-dewatering is discussed.

The dewatering process was simulated to determine the process energy demand. Process economics were assessed considering the dewatering cost, which includes capital investment and energy cost and also labor, installation, maintenance and infrastructure. Optimal operating conditions and minimum dewatering cost were achieved by process optimization, and two cost-sensitive zones in operating the filtration were identified. The techno-economics showed that the dewatering cost can be further reduced by scaling up the process.

1. Introduction

Filtration is a mature technology for the removal of particulate matters from fluids. It has found wide industrial applications in water treatment (e.g. turbidity removal) [1–3], food processing (e.g. clarification of beer and liquors) [4–6], air cleaning (e.g. dust and bacteria removal), etc. [7]. At present, various filter media are available for the removal of these small particulates ranging from submicron to 100 μm [8–11]. Filtration is based on size-exclusion, so it does not require large energy input. A low pressure (e.g. 20–30 kPa) can generate a high flux through these well-tuned and highly porous filter media [12].

Microalgae, mostly in the range of 5–20 μm, are now playing a key role in the ongoing endeavors to sustain energy and environment [13]. Cultivation of algae consumes large amounts of CO_2, as a carbon source for algal biomass synthesis. Because algae grow fast and possess high lipid contents, algae have been mass cultivated to provide renewable energy and at the same time mitigate CO_2 emissions [14–16]. The concentration of algae in a culture medium is usually 0.1 w/w%, and this concentration can be enhanced up to 20 w/w% through centrifugal harvesting. The traditional method to dewater this 20 w/w% harvested algae is with thermal energy to evaporate most of the remaining 80% water content [17]. Given the extremely high latent heat of water, algae-dewatering by evaporation requires a very large energy input. Alternative approaches have good potential to improve the energy efficiency of algae-dewatering.

One major objective of our algal biofuel project is to maximize the energy return to help better address energy sustainability. Each operating unit of this process can benefit from use of energy-efficient technology. Energy-efficient filtration with the rotary drum

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vacuum filter (RDVF) was selected to conduct algae-dewatering. Continuous operation of filtration is favored by industry for its flexibility in process scale-up and for not needing extra storage space for intermediate product. In addition, by using the vacuum operation, the amount of filtrate water contained in the porous algal cake-layer can be minimized. Consequently, much of the heating burden can be removed from the subsequent process for algae-drying, which has been identified as one of the bottlenecks limiting the overall energy efficiency of algal biofuel technology [18,19].

To demonstrate the RDVF filtration process for algae-dewatering, a mathematical model was developed to model the filtrate water transport through the algal cake-layer as well as the underneath filter medium. The transport resistances of algal cake-layer and filter medium were correlated to their physical properties. Correlating the cake-layer resistance to its characteristic parameters serves to make the model fundamental, straightforward and readily applicable for simulation. Algae are a soft material, and compression of the algal cake-layer in the filtration process must be taken into consideration in this model, in order to properly simulate the observed behaviors of the algal cake-layer. A value was determined for the equivalent pore size in the cake-layer, which was a parameter required for modeling the algal cake-layer dewatering.

Process economics is an important measure characterizing the viability of a technology. Literature survey shows that little work has been carried out on the cost analysis of algae dewatering [20]. To determine costs of algae-dewatering with the filter, the process capital and operational energy costs were evaluated. Process optimization was performed to demonstrate the potential of reducing this dewatering cost by identifying the best operating conditions. Analysis of the global dewatering cost, which consisted of energy, capital and installation, infrastructure, labor and maintenance, suggests that the proportion of costs can be significantly reduced through appropriate scale-up. Thus, scenarios for further reducing this dewatering cost were also explored by considering overall process scale.

2. An overview of algae-dewatering process

Algae-dewatering using a rotary drum vacuum filter is illustrated in Fig. 1. The rotary drum is partially submerged in the harvested algal feed. Water in the algae feed is drawn into the drum through the filter medium to the low pressure zone through use of a vacuum pump. Algae are thus held and accumulated on the external surface of the filter to form a dynamic algal cake-layer.

The filtrate water passing through the filter and the drain piping is first collected in the vacuum receiver and is finally moved out by a water pump. The algal cake-layer keeps building up on the filter surface until it is carried out of the feed tank as shown in Fig. 1. The water contained in the algal cake-layer is removed in the subsequent algae-dewatering zone under a controlled vacuum pressure during the portion of a drum revolution between exiting the liquid region and prior to arriving at a scraping blade, which removes it from the drum surface. This dewatered algal cake is peeled off the drum filter surface and collected for drying.

3. Modeling of the constant pressure filtration of centrifuge-harvested algae

3.1. Transport of filtrate water through the algal cake-layer

Modeling the dynamic formation of algal cake-layer on the filter surface is a challenge. Some assumptions should first be made, including (i) neglecting the effects of tangential shear induced by filter rotation in the feed tank, on the formation of algal cake-layer atop the filter surface, (ii) neglecting the effects of mixers in the feed tank, and (iii) assuming all the algae moving toward the filter surface with the water in the filtration process are retained, and build up on the filter surface to form a uniform algal cake-layer on the filter surface.

According to Darcy's law, the flow-rate of the filtrate can be written as [21–23],

$$\frac{dV}{dt} = \frac{A \cdot \Delta p_1}{\mu \cdot R} \tag{1}$$

where V is the cumulative volume of filtrate water, A is the effective area for filtration, Δp_1 is the pressure difference across the algal cake-layer as shown in Fig. 2, μ is viscosity of water, and R is the hydraulic resistance of the cake-layer. Algal cake-layer resistance is assumed to be proportional to the cake-layer thickness, ℓ, by,

$$R = \beta(r_{\text{algae}}, \varepsilon) \cdot \ell \tag{2}$$

where β is the specific resistance of the cake-layer, related to r_{algae} and porosity ε of the algal cake-layer.

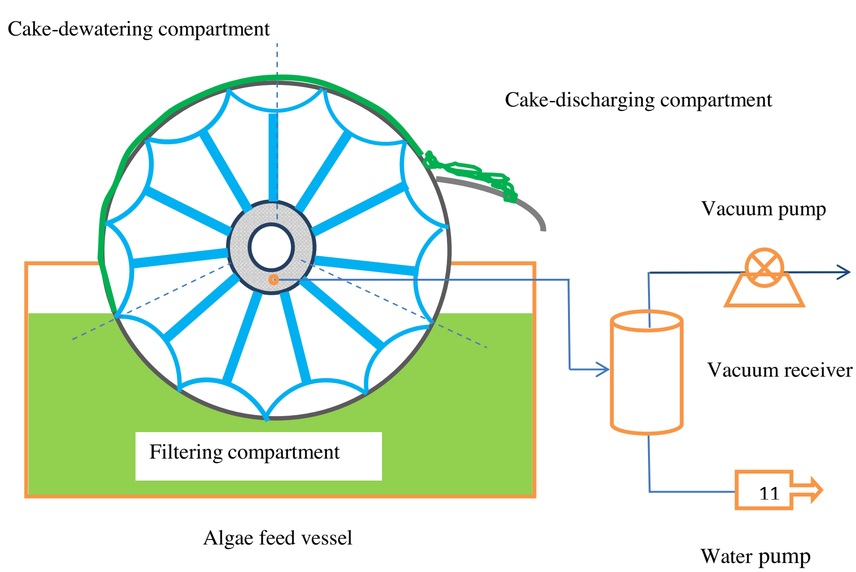

Fig. 1. Flow-chart of algae-dewatering using a rotary drum vacuum filter with three distinctive zones for algae-filtering, algae-dewatering, and algae-discharging.