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Falling film evaporation characteristics of microalgae suspension for biofuel production

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HIGHLIGHTS

- It is the first time a study focused on microalgae dewatering by falling film evaporation.
- Heat/mass transfer properties of falling film evaporation of microalgae were investigated.
- Bubble formation mechanisms of microalgae falling film evaporation was discussed.

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ABSTRACT

Microalgae, one of the important biofuel producers, have received considerable attention recently. Dewatering is one of the bottlenecks for its industrialization due to the dilute nature of the suspensions and the small cell size. Traditional liquid–solid separation processes are not efficient for dewatering of microalgae suspensions. In this study, falling film evaporation was employed for dewatering of microalgae suspension, which is a popular process for concentrating heat sensitive materials. The heat transfer coefficient was as high as 9414.20 W/m^2 K with mass flow rate of 0.233 kg/s, ΔT of 1.21 °C, and microalgae concentration of 60 g/L. The falling film evaporation process can be made highly energy efficient if it is coupled with Mechanical Vapor Recompression (MVR) or Thermal Vapor Recompression (TVR) system. Heat and mass transfer characteristics of falling film evaporation of microalgae suspension have been investigated here. This will provide the fundamentals for future feasibility study of utilizing the falling film evaporation in the microalgal industry.

1. Introduction

In recent years, focuses on microalgae utilization in biofuel production, environmental pollution treatment and remediation, carbon fixation and high-value products manufacturing, have been rapidly expanded [1–3]. Microalgal plants of high-value products and biofuel production have ballooned quickly consequently. Processing steps such as strain breeding, cultivation, harvesting and dewatering, extraction, transesterification and purification are involved in microalgae industries [1,4–6]. Proverbially, microalgae have definitive advantages over conventional bio-resources [7,8], however, due to the very dilute nature of microalgal cultures, microalgal plants are plagued with high costs on the downstream processes, particularly harvesting and dewatering process [5,6]. The utilization of efficient, versatile and feasible harvesting and dewatering technologies is required for production of microalgal biofuels, fatty acids, proteins and other high-value products.

In industries, concentration and dewatering of materials with evaporation has been utilized in air conditioning, refrigeration, chemical, petroleum refining, desalinization, dairy, pharmacy, and biological product industries [6,9]. Heat and mass transfer characteristics are the key features of an evaporation process. As reported previously [6], the authors carried out the first study on the dewatering of microalgae cultures by evaporation, and found that the moisture evaporation rate from microalgae suspension was much

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Nomenclature

A	area (m^2)
d	diameter (m)
g	gravitational acceleration (m/s^2)
h	height (m)
h	effective heat transfer coefficient (W/m^2 K)
H_{vap}	enthalpy of vaporization of water (J/kg or J/mol)
k	thermal conductivity (W/m K)
$\dot{m}$	effective mass transfer coefficient (kg/m^2 s)
Δm	weight the condensate collected during the time range of Δt (kg)
Nu	Nusselt Number
Pr	Prandtl Number
Q	volumetric flow rate (m^3/s)
q	power input (W)
q_{ONB}	heat flux for the onset of nucleate boiling (W/m^2)
r	RADIUS (m)
r_c	critical radius of the micro-grooves on the evaporation column (m)
Re	Reynolds Number
Re_c	critical Reynolds Number
T	Temperature (K or °C)
T_b	boiling temperature (K)
T_{hw}	temperature of the heater external surface (K)
T_l	temperature of the liquid in the evaporation system (K)
ΔT	temperature difference (K)
ρ	density (kg/m^3)
μ	dynamic viscosity (P s)
Γ	mass flow rate (kg/m s)
σ	surface tension (N/m)
ρ_g	gas density (kg/m^3)
γ	surface tension (mN/m)
θ	contact angle (°)

higher than that of water or medium during the vacuum pool boiling evaporation. Microalgae cells might perform as fluid mixing enhancers and nucleate sites in the boiling fluid and help enhancing heat and mass transfer. It is reported that the related fluid properties of the microalgae suspensions are of importance for evaporation [6].

Owing to the high heat transfer coefficient, no refrigerant charge, short residence time and low pressure drop, and also the potential in large saving of energy with MVR and TVR [10], falling film evaporation is one of the most popular concentration processes in food, biomedicine, cosmetic and fine chemical industry [9,11]. The falling film evaporation rate is affected by several parameters, such as fluid properties of microalgae suspension, heat flux, saturation pressure, thermophysical properties of the heater surface, temperature difference between the heater surface and fluid, and power input [12–16]. As presented previously [6], the evaporation characteristics of microalgae suspension has been achieved by means of pool boiling. In the present study, experiments on falling film evaporation with a customized pilot electrically heated falling film evaporator were conducted. The corresponding heat and mass transfer coefficients were obtained. There will provide a good foundation in process design for microalgae suspension treatment in industry.

2. Materials and methods

2.1. Microalgae suspension

The microalgae suspension used for this study was *Nannochloropsis* sp. [17]. All the microalgae cultivation conditions and methods employed were described in the previous study [6,17]. In this work, all experiments were performed with cultures from a single harvest at the stationary phase to ensure the same growth phase and storage conditions in order to minimize any variation that could result from differences in these conditions. The average value of dry mass microalgae concentration was 0.6 g/L. A portion of the suspension was concentrated using a centrifuge (Heraeus Multifuge 3 S-R, Germany) operated at 4500 rpm for 10 min for biomass concentration of 6 and 60 g/L, respectively. Distilled water and fresh modified F/2 medium were employed for the comparative experiments.

2.2. Apparatus

The evaporation was applied with a customized electrically heated pilot vacuum falling film evaporator, which was designed and built by the Biotechnology and Food Engineering Lab in Department of Chemical Engineering of Monash University, Australia [11]. As shown in Fig. 1, the evaporator consists of a stainless steel feed tank (20 L), a circulation pump, a preheater, a flow meter, an evaporation column (1.1 m length), a condensate collection flask and a condenser. All the apparatus were connected using the stainless steel tubes.

2.2.1. Preheater

As shown in Fig. 1, for adjusting the temperature of the fluids prior to flowing into the evaporation column, a preheater was employed. Heating wire (HS0002R, made by Argus, Australia) with a heating rate of 40 W/min was wrapped around the stainless steel tube with a length of 25.7 m per meter of the stainless steel tube. Then silica gel of 732 RTV type (Dowcorning, US) was used to fill the gaps and aluminum sheet was used to cover the heating wire assembly.

Two thermocouples (TT-K-36-SLE-200, Omega Engineering Inc., US) were located in the preheater, for monitoring the temperature of the liquid and the heating wire, respectively. The heating wire and the thermocouples were connected to the preheater PID controller, which set the heating target temperature and the maximum temperature (for safety).

2.2.2. Evaporation chamber and its power input monitoring

The evaporation chamber is the prime equipment, in which falling film evaporation occurs. It consists of a stainless steel top disc, a distributor, a stainless steel electric heater column of BEW 24 type (Helios, Australia), the acrylic isolating tube outside the heater column and a stainless steel base disc. The electric heater column was connected with the base disc with screws and sealed with sealant of a 592 type (Loctite, US). The acrylic tube was set consequently outside the heater column and screwed between the two discs. Liquid film was formed due to the very narrow gap between heating column and distributor cap (as shown in Fig. 1b), once the fluid inflows into the heating column via the distributor. Liquid film is heated quickly during flowing down on the column.

A CMV10E-1 autotransformer (Carroll & Meynell, UK) was used for the heater's power input control. However, for measuring the actual power input, a WT210 digital wattmeter (Yokogawa, Australia) with an accuracy of 0.1% was used.

2.2.3. Liquid–gas separation and condensation

The liquid–gas separator was connected to the customized condenser and was set on the top of the feed tank, which is made of