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Falling film flow of ionic liquid–MEA solution on vertical cooling flat plate and channel

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A B S T R A C T

Visualization experiments on heated Ionic liquid-MEA mixed solution falling film flowing on a uniformly cooled vertical plate and channel (plate with two sidewalls) by using an IR thermal camera were performed for the first time. The effects of the wall-liquid temperature difference and the liquid flow rate on the falling film flow pattern, film width and area were discussed. It is evidenced that the Marangoni effect exists in a channel and has brought quite different flow patterns of the falling film from the plate because of the corner effect. Instead of a string film along the central area of the plate on a flat plate, the falling film presented two wetted strips at the wall corner on a channel because of larger capillary force. A symmetrical and asymmetrical film expansions were presented on the plate and channel, respectively, with the increasing wall-liquid temperature difference. The widest film width and largest film area were reached at a wall-liquid temperature difference of 40 °C and liquid flow rate of 600 mL/min.

1. Introduction

Carbon dioxide is the largest contributor to the increasingly serious greenhouse effect. It is an urgent task to develop carbon dioxide capture and storage technologies with environment-friendly and economic benefits. The most viable near-term approach is chemical absorption capture. Falling film reactor is one kind of attractive and prospective reactors in the application to carbon dioxide (CO_2) absorption due to its excellent heat and mass transfer performance as well as effective gas–liquid reaction. Meanwhile, in recent years, ionic liquid (IL) is strongly proposed to work as an environmentally friendly [1–4] absorbent for CO_2 absorption considering its negligible volatility and significant thermal stability. Unfortunately, the application of ionic liquid has been hindered by its high viscosity and cost. Recent researches indicated that admixture of ionic liquid and amines will head its way to the practical application [5–9]. Camper et al. [8] mixed ionic liquid with amines as absorbent for CO_2 capture and found that using this unprecedented and industrially attractive mixing approach, the desirable properties of room temperature ionic liquids (i.e., non-volatility, enhanced CO_2 solubility, lower heat capacities) can be combined with the performance of amines for CO_2 capture. Zhang et al. [9] mixed ILs with N-methyl-diethanolamine (MDEA) aqueous solutions to form new solvents for the uptake of CO_2. The results indicated that IL greatly raised the absorption rate of CO_2 in aqueous MDEA solutions. However, when the mixed ionic liquid solution is applied into the falling film reactor for CO_2 absorption, different from the stagnant solution, the flow characteristics that results in various film flow pattern will significantly affect heat and mass transfer process in the film, hence the performance of CO_2 absorption. Meanwhile, the physical properties of the mixed ionic liquid solution also give rise to different film flow characteristics [10] from that of the common media. Additionally the thermal Marangoni effect induced by spatially inhomogeneous temperature field at the gas–liquid interface may also deform the falling film during the operation. The Marangoni effect dramatically influences the falling film flow dynamics and thus the heat and mass transfer. On account of this, the Marangoni effect has been widely studied. Sternling et al. [11,12] found the criteria for the Marangoni flow by solving the governing equations of the interfacial turbulence caused by longitudinal variations of surface tension. Schatz and Neitzel [13] summarized recent experimental studies of instabilities in free-surface flows driven by thermocapillarity. Kabov et al. [14] used the solution of 25% ethyl alcohol in water as working liquid and experimentally investigated the effect of a local heat source on a liquid film falling down a vertical plate. The results showed that the non-uniform temperature distribution at the

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liquid–gas interface because of non-uniform heating led to a thermocapillary counterflow which caused a deformation of the film surface having a horizontal bump-shape. This shape deformed into vertical downstream rivulets when the imposed heat flux was over a critical value. Zaitsev et al. [15] made an investigation on the wetting angle on the thermocapillary breakdown of a falling liquid film and showed that no effect of the equilibrium wetting angle on the non-isothermal breakdown of the film was revealed. Zaitsev and Kabov [16] studied the thermocapillary effect on a wavy falling liquid film. Katkar and Davis [17] investigated the bifurcation in a thin liquid film flowing over a locally heated surface for a non-volatile and a volatile liquid. The results showed that the bifurcation is universally observed for both, a non-volatile film and a volatile film. Peng et al. [18] studied the falling film flow dynamics of ionic liquid-water binary solutions on a uniformly heated vertical plate, the results showed that the lateral Marangoni effect influenced the heated film flow significantly. Additionally, a novel flow pattern called as “bifurcate flow pattern” was observed when the mass fraction of IL was 30%. Chinnov [19]studied the temperature distributions and wave characteristics of the water film flowing down a vertical plate with a heater at high Reynolds numbers. It is noted that the existing studies on Marangoni effect mainly focused on the falling film flow over an infinite plate (open plate). However, the falling film flow usually happens on a confined space with restricted sidewalls [20,21] in the practical applications. The falling film flowing over a vertical plate with sidewalls will present quite different flow characteristics from the flow without sidewalls due to the corner effect. The studies on the Marangoni effect in falling liquid film of ionic liquid mixed solution on a vertical plate with sidewalls have not been reported so far.

In the present study, the tetramethylammonium glycinate ionic liquid ([N_{1111}][Gly]) and monoethanolamine (MEA) mixed solution was chosen as the working media, and experiments on falling film flow of heated mixed solution on vertical cooling plate were performed to investigate the influence of Marangoni flow. Considering the practical application, comparably, both a vertical plate and a vertical channel were applied. Furthermore, the effects of wall-liquid temperature difference and liquid flow rate of mixed solution were discussed.

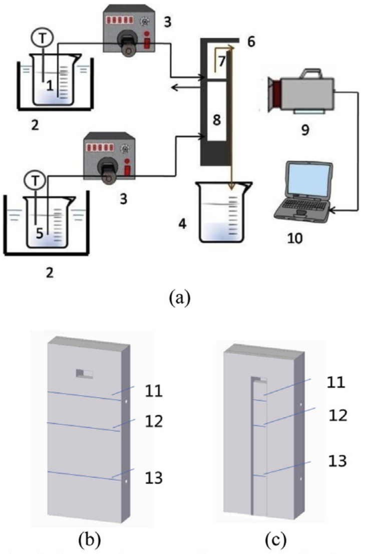
2. Experiment system and approach

2.1. Experimental system and reagents

The schematic diagram of experiment system is shown in Fig. 1(a). The system consisted of an absorbent supply system, a cooling water supply system, a plate falling film reactor and a temperature control and measurement system. The mixed solution of ([N_{1111}][Gly]) (Lanzhou Institute of Chemical Physics-Chinese Academy of Sciences) and MEA (Chongqing Dong Fang Hua Bo Company) with mass fraction of 5% and 15%, respectively, was adopted as the absorbent. The plate falling film reactor made of stainless steel with an overflow liquid distributer on the top and a cooling chamber on the reverse side of the plate. Two types of plates, an open plate with effective size of 0.1×0.04 m^2 (L × W) (Fig. 1(b)) and a plate with a channel of 0.02 m in width and 0.005 m in depth (Fig. 1(c)), were applied to the falling film, respectively.

1- mixed solutions storage tank; 2-electro thermostatic water bath; 3-peristaltic pump; 4-mixed solution recovery tank; 5-cooling water storage tank; 6-falling film reactor; 7-overflow distributer; 8-cooling chamber; 9-IR thermal camera; 10-computer; 11-the upper edge of the cooling chamber; 12-line 1(the distance between the line of 11 and 12 was 0.036 m); 13- the lower edge of the cooling chamber.

The ionic liquid-MEA mixed solution was fed from a storage tank immerging in an electro thermostatic water bath into the overflow liquid distributer by a peristaltic pump (Baoding Longer Precision Pump Company). The overrunning absorbent from the distributer formed a thin falling liquid film down along the vertical plate and was exhausted into a mixed solution recovery tank underneath the plate. The temperature of the vertical plate was maintained at a preset temperature ($T_w = 25$ or 65 °C) by supplying cooling water through a cooling chamber on the back of the plate in an open cycle mode. The shape and temperature distribution of the falling film at the gas–liquid interface were recorded by a highly sensitive IR camera ThermaCAM™ P20 (Flir System Company, USA) and were analyzed by a special software. The spatial resolution of the film temperature is 0.08 °C at 30 °C. The distance between the film and the IR camera was 0.40 m.



1- mixed solutions storage tank; 2-electro thermostatic water bath; 3-peristaltic pump; 4-mixed solution recovery tank; 5-cooling water storage tank; 6-falling film reactor; 7-overflow distributer; 8-cooling chamber; 9-IR thermal camera; 10-computer; 11-the upper edge of the cooling chamber; 12-line 1(the distance between the line of 11 and 12 was 0.036 m); 13- the lower edge of the cooling chamber;

Fig. 1. Schematic diagram of experimental setup (a), falling film reactor with a plate (b), a channel (c).

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